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Lower Jordan River: Phase 1 Report

Prepared for

River Network

Prepared by

SWCA Environmental Consultants

November 2013

LOWER JORDAN RIVER: PHASE 1 REPORT

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EXECUTIVE SUMMARY

The lower Jordan River is listed as an impaired waterbody by the State of Utah for violations of dissolved oxygen (DO) standards protective of aquatic life. Recent results from the Jordan River total maximum daily load (TMDL) identify organic matter loads to be the most important pollutant contributing to reduced DO levels. However, controls on DO levels in streams and rivers are complex and interconnected, and other factors may also influence DO to a significant, though lesser, degree. This report identifies increased flow as a potential mechanism by which DO levels could be improved in the lower Jordan River during the late summer. It explores the effects of flow on DO and some DO-influencing processes using available data and models.

Flow in the lower Jordan River is highly regulated and is slower and less variable than flow in the upper Jordan River; these conditions in the lower Jordan have resulted in an environment that is conducive to particle deposition. The sediments that result from this depositional environment are characterized by relatively high levels of oxygen-demanding substances, specifically organic matter. Depth profiles of sediment cores in the lower Jordan River indicate that this oxygen demand is not limited to surficial sediments, and it has the potential to be even greater in deeper sediments, implying that removal of sediments through scour due to increased flows and/or dredging may not improve DO levels.

Results from a primary data analysis identify a positive correlation between flow and DO in the lower Jordan River. This relationship is attributed to a depth-induced decrease in oxygen-demanding processes and a simultaneous increase in oxygen delivered from upstream reaches. These effects likely outweigh the impacts of depth-induced reductions in reaeration rates and velocity-induced increases in water column oxygen demand due to resuspension of organic sediments.

This report corroborates findings from the primary data analysis with a sensitivity analysis of calibrated models for the lower Jordan River. Results suggest that an increase in flow to the lower Jordan River to approximately 190 cubic feet per second during the summer critical period has the potential to raise DO levels above the instantaneous TMDL target (and chronic standard) of 5.5 milligrams per liter. Based on estimated sediment physical property characterizations, outputs from the hydraulic model indicate that although mobilization of some organic matter is probable under most flow conditions, in general, sediment resuspension may be negligible.

Some data gaps limited the accuracy of the modeling and analysis presented in this report. The greatest uncertainties were the accuracy of reaeration rates used in the water quality model and sediment shear stress values. These parameters have comparatively large impacts on the model outputs presented and tend to be highly site specific. Future studies could more precisely fill in these gaps.

Recommendations for further study were framed into three avenues or threads of exploration: 1) analysis of linkages between base flow and chronic DO violations, 2) analysis of linkages between instantaneous peak flows and acute DO violations (i.e., storm events), and 3) analysis of sediment dynamics and DO. Future work related to the base flow thread is identified as the next step for Phase 2 of the work to be performed by SWCA under guidance from River Network. These recommendations include additional analysis and modeling using continuous dissolved oxygen data collected in 2013 and design and execution of flow experiments in 2014. In addition, SWCA has identified the acute dissolved oxygen and sediment transport threads as potential avenues of pursuit for other teams, but these will not be included in the Phase 2 scope of work. SWCA has provided cost estimates for all potential recommendations and next steps.

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1. DATA ANALYSIS AND LITERATURE REVIEW

The data collected for this report come from a wide range of sources, including the Utah Division of Water Quality (DWQ), the University of Utah, the U.S. Geological Survey (USGS) stream gages and National Water Information System (NWIS), Environmental Protection Agency (EPA) Storage and Retrieval Database (STORET), Salt Lake County, personal communications, and primary literature. In this report, there are many references to specific site locations where flow and/or water chemistry measurements are made. These locations are shown in Figure 1.

For clarity, sections of the Jordan River are often identified by their reach number. In the lower Jordan River, the reaches are defined moving from up to downstream as follows (see Figure 1): Surplus Canal diversion to the 900 South (S) stormwater discharge (Reach 3), 900 S stormwater discharge to South Davis Wastewater Treatment Plant (Reach 2), and South Davis wastewater treatment plant to Burnham Dam (Reach 1). These reaches are slightly different from the three segments defined for purposes of HEC-RAS modeling in section 2.2.

1.1. Flow

Flow in the lower Jordan River is largely regulated by the Surplus Canal diversion at 2100 S. Water diverted into the Surplus Canal is delivered northwest to Farmington Bay Waterfowl Management Area and directly to Great Salt Lake. The canal was constructed to prevent residential flooding in Salt Lake City, which occurs above the flood stage of approximately 700 cubic feet per second (cfs) (see Section 2.2.2). The gate on the canal is operated to satisfy downstream water rights in the lower Jordan River while maintaining the reserve capacity to receive tributary storm inflows. Over the past 10 years, the canal has diverted an average of 60%–70% of the river's flow, but at times of high discharge, it has diverted as much as 99.9% of the flow (e.g., in May 2005). Upstream of the canal, flows tend to peak in early summer (average of approximately 7,800 cfs) and drop off in late autumn/early winter (average of approximately 300 cfs). Just downstream of the canal, however, seasonal variation in flow is significantly attenuated, and the river experiences an average yearly range of only 40 cfs between peaks of 135 cfs and lows of 95 cfs. The flows in the lower Jordan River in late summer (i.e., the period identified in the Jordan River total maximum daily load [TMDL] as the critical period for dissolved oxygen [DO] excursions) range from 100 to 160 cfs, but on average fluctuate around 135 cfs.

The flow regime of the lower Jordan River is effectively characterized by exceedance probability curves, or flow duration curves. These curves show the probability distribution for all flows experienced by the reach of interest and are plotted on semi-log plots. The flow duration curves developed for the lower Jordan River are based on data from 2100 S, 1700 S, and 500 North (N) collected from USGS gages 10170490 (2002–2013), 10171000 (2002–2013), and 10172550 (1974–1986), respectively. A comparison of flow regimes along the lower Jordan exhibits the high level of flow control that the Surplus diversion exerts on the river (Figure 2). Just before the canal (at 2100 S), the river experiences a wide range of flows and has a median flow rate (50th percentile) of approximately 370 cfs. On the other hand, the lower Jordan River downstream of the canal (at 1700 S) experiences a much narrower range of flows on average (roughly 75% of the flows are between 100 and 200 cfs) and has a median flow rate of approximately 125 cfs. Moreover, the sharp drop off on the 1700 S curve at 85% is a display of the ability of the Surplus Canal to divert almost all of the Jordan's flow during flood events.

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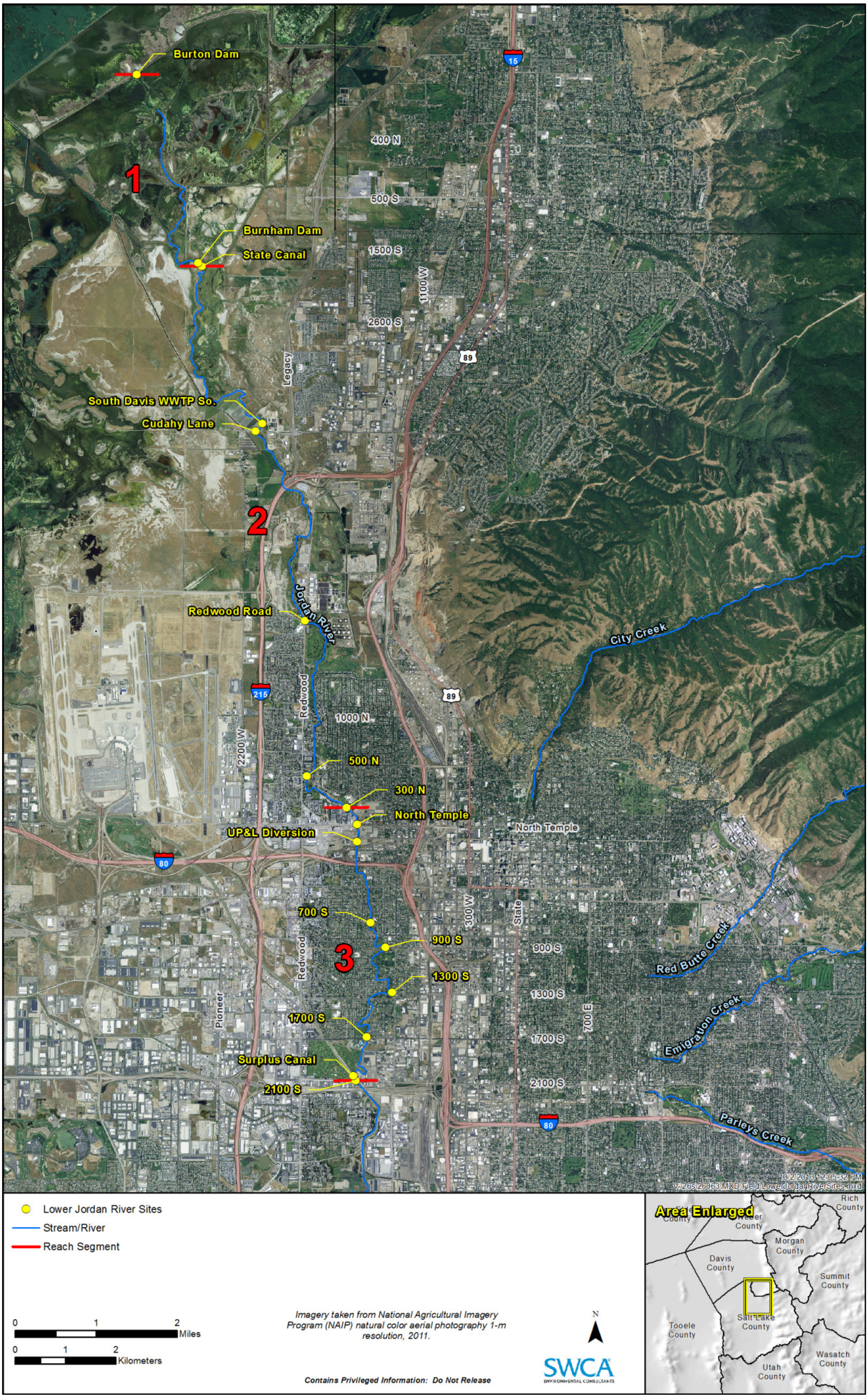

Imagery taken from National Agricultural Imagery Program (NAIP) natural color aerial photography 1-m resolution, 2011.

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Figure 1. Relevant sites along the lower Jordan River.

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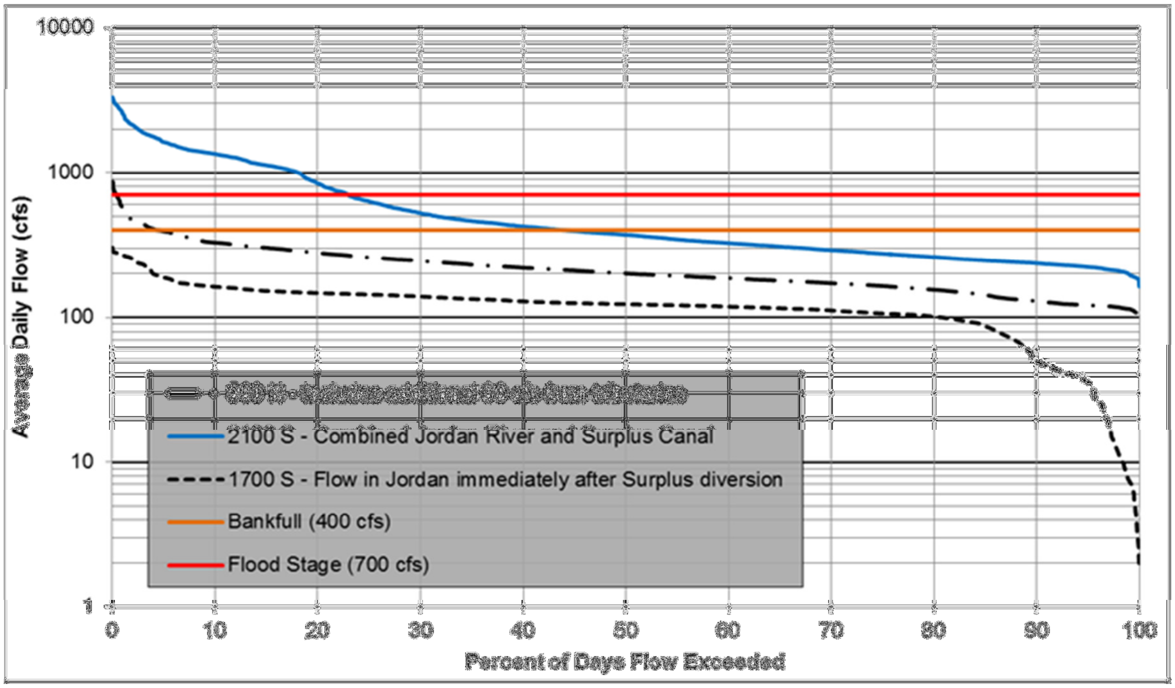


Figure 2. Flow exceedance curves for the lower Jordan River.

The lower Jordan River gains a significant amount of flow as it moves downstream from the Surplus Canal. This is evidenced by the increase in average daily flow between 1700 S and the 500 N (7.5 kilometers [km] downstream) by approximately 80 cfs (see Figure 2). In large part, this increase is due to tributary inflow from four creeks that originate east of the river, though some of the flow is also associated with irrigation return flows from the Jordan and Salt Lake Canal. Three of the creeks, (Parleys Creek, Red Butte Creek, and Emigration Creek) are diverted to a storm conduit that discharges an average of approximately 33 cfs into the Jordan at 1300 S (1980–1988, USGS gage 10172350). Base flow for the 1300 S conduit is closer to 10 cfs, and stormflows range from 25 cfs on average to over 350 cfs during major events (e.g., May 1986). City Creek is also diverted into a storm conduit that discharges an average of approximately 11 cfs into the Jordan at North Temple (1963–1982, USGS gages 10172499 and 10172500). Base flow for the N. Temple conduit is also close to 10 cfs, and peak flows range from 20 to 150 cfs.

Additional contributions to flow in the lower Jordan River include stormwater (7 cfs), diffuse runoff (1 cfs), groundwater (33 cfs), and wastewater discharge from the South Davis wastewater treatment plant (3.5 cfs) (Utah Department of Environmental Quality [UDEQ] 2013).

1.2. Sediment Oxygen Demand

Sediment oxygen demand (SOD) is the sum of biological and chemical oxygen consumption that occurs within the sediments and is frequently reported on an areal basis in units of g O_2 m^{-2} d^{-1} (grams of oxygen per square meter per day). It has been identified as the major contributor to reduced oxygen levels in the lower Jordan River (UDEQ 2013), and therefore is of particular concern in this review. SOD is influenced by a large number of variables, including temperature, water column DO concentrations, sediment organic matter content, sediment grain size, flow velocity, bioturbation (biological disturbance of sediments), and presence of reduced chemical species and molecules that consume oxygen during oxidation. These variables are themselves interdependent, which makes the measurement and interpretation of SOD difficult and complex.

Initial results from a late summer study in the lower Jordan River indicate little correlation between SOD and sediment composition, land use, or point discharges (Hogsett and Goel 2009). In fact, results from this study show that SOD rates in the impaired reaches of the lower Jordan River were comparable to SOD rates in the unimpaired reaches. Furthermore, the lowest SOD rates of the whole river were measured at 1700 S in the impaired reach. On the other hand, average SOD rates for the entire lower Jordan River (reaches 1–3) were close to 50% higher than the average SOD rates for the Jordan River above the diversion (U.S. Highway 73 to 2100 S) (2.22 vs. 1.51 g m^{-2} d^{-1}).

A follow-up study on the fate of organic matter in Jordan River sediments further characterizes SOD rates in the lower Jordan River (Hogsett et al. 2013). Generally, SOD rates were found to increase along the length of the lower Jordan River (from a median of approximately 1.3–2.0 g m^{-2} d^{-1}), and constituted upward of 75% and 95% of the ambient DO deficit in the summer and winter, respectively. This study also identifies a linear relationship between percentage volatile solids (%VS, the percentage of dried sediment that is combustible, i.e., a rough indicator of sediment organic content) in the upper 2 centimeters (cm) of sediment and SOD:

$$(1)\ \ \mathrm{SOD} = 0.34 \times (\%\mathrm{VS}_{0\text{–}2\mathrm{cm}}) + 0.68;\ N = 36,\ R^2 = 0.82$$

SWCA performed a secondary analysis of SOD at depths using the above relationship and measurements of summertime %VS at depths taken over the course of 4 years (2010–2013). The purpose of this analysis was to examine what the resultant SOD would be if surficial bed layers were scoured or removed. For example, if the top 2 cm of sediment were removed from the riverbed, how much would SOD change? Additional studies are required to understand the extent to which SOD at depths below the top 2 cm is influenced by inorganic chemical oxidation in addition to biological decomposition of organic material.

Results for average SOD over the timeframe of study (2010–2013) show two important trends (Table 1). First, estimated SOD rates are relatively similar among depths at each site, though there is significant variation among sites. For example, at 2100 S after the Surplus Canal and 300 N, potential rates are consistent throughout the depth profile, but at 2500 S and 1300 S after conduit, potential rates tend to increase throughout the depth profile. These results would tend to imply that a removal of top sediments, through scour or dredging, would not necessarily reduce SOD rates in a significant way. In fact, at some sites (e.g., 1300 S and Burnham Dam), removal of the top 2 cm of sediment could result in increased SOD rates by up to 30%. It is important to note here that for most sites, sediment core data only extend to 30 cm below the surface, and information about deeper sediments is limited. Also, due to high industrial activity in the past, there is a potential to uncover contaminated sediments that have been buried by years of deposition.

Second, in contrast to the initial findings of Hogsett and Goel (2009), there does appear to be a positive relationship between SOD and stormwater discharges. Namely, at sites downstream of the major tributary discharges (1300 S after conduit, 900 S after conduit, 300 N, and Burnham Dam), SOD rates increase markedly compared to measurements just upstream (see Table 1). This is likely due to several factors, but the simplest being that tributary creeks and stormwater/wastewater discharge are loading organic matter that settles into the sediments of the lower Jordan River. This was a primary finding of the Jordan River TMDL, which estimates that stormwater contributed approximately 53% of fine particulate organic matter (FPOM) loads to reaches 2 and 3(UDEQ 2013). The drop-off in SOD rates after 1300 S may be an indication that the organic loads from the storm conduit are mainly coarse debris, and thus are quickly deposited on the riverbed as opposed to being carried downstream. This is supported by TMDL findings where it was necessary to prescribe up to 3.5 g m^{-2} d^{-1} of additional SOD in a model to account for coarse organic loads (UDEQ 2013).

Table 1. Estimated Summertime Sediment Oxygen Demand at Varying Depths along the Length of the Lower Jordan River

Depth (cm)	2500 S before Surplus	2100 S after Surplus	1700 S	1300 S after Conduit	900 S before Conduit	900 S after Conduit	700 S	300 N	Burnham Dam
2	1.2	1.0	1.3	3.6	1.1	2.5	1.7	1.9	2.5
5	1.4	0.8	1.3	4.7	–	–	1.7	1.9	3.5
10	1.8	0.8	1.0	3.4	1.0	1.7	1.8	2.0	2.9
15	1.5	–	–	6.7	–	–	2.2	1.8	2.5
20	2.1	0.8	0.8	3.3	1.0	1.4	1.4	1.5	2.3
30	2.7	1.0	1.0	4.1	2.0	2.1	–	1.9	1.8

Note: Numbers indicate average SOD [g m^{-2} d^{-1}]. SOD is averaged from calculations based on %VS data (Equation 1) measured at varying depths from 2010 to 2013. Blank spaces indicate a lack of data. Error bars are not shown for clarity, but the depth-averaged coefficients of variation are 0.05, 0.05, 0.21, 0.36, 0.13, 0.04, 0.18, 0.22, and 0.19 for sites from left to right (in direction of flow).

Data from the follow-up study also show that there is a significant gradient in the quantity and fractionation of VS along the lower Jordan River, which has important implications for SOD rates (Hogsett et al. 2013). For instance, %VS increased with distance downstream of the Surplus Canal diversion, whereas the coarse fraction of %VS (%VS_{CPOM}, percentage of %VS that is greater than 1 millimeter) decreased. In other words, reach 1 had a much greater percentage of labile (bioavailable) organic matter than reaches 2 and 3. This corroborates the finding that SOD rates are greater in reach 1 than in reaches 2 and 3 because labile organic matter is positively correlated with oxygen consuming processes (Wetzel 2001). Additionally, it was found that the cumulative quantity of organic matter found in reach 1 (top 10 cm) accounted for over 60% of all the organic matter in the lower Jordan River (reaches 1 through 3). In other words, the combined mass of sediment organic matter in reaches 2 and 3 is less than 50% of the mass of sediment organic matter in reach 1 alone.

In summary, it is difficult to make any robust conclusions about the behavior of SOD in the lower Jordan based on currently available data. However, some generalizations are apparent:

1) SOD increases along the length of the lower Jordan and is likely the result of increased organic matter deposition and decomposition.
2) SOD rates are likely similar or greater at increasing depths when compared to the top 2 cm (see Table 1).
3) Tributaries appear to be significant sources of oxygen demanding substances, and consequently have effects on local SOD rates.
4) Most of the organic matter in the lower Jordan is found in reach 1 and most of this organic matter is < 1 millimeter, and thus is assumed to be more bioavailable than SOD in reaches 2 and 3.

1.3. Relationships among River Processes and Flow

For the data considered in the following sections, samples were generally taken monthly, and duplicate samples were taken on the order of two to three times per year for quality assurance and quality control. It is worth noting that in the following analysis, there is a discord in the timing of measurements between flow and water chemistry. Water chemistry data are generally taken as daytime instantaneous values, whereas flow data are daily averaged values except where noted. Considering the low variability of flow in the Lower Jordan, average daily flows are generally representative of flows taken at the time of sampling.

1.3.1. Dissolved Oxygen

DO is an important parameter for assessing aquatic ecosystem health and function. As such, it is important to understand the controls on DO, and the interactions among those controls. The multitude of influences and factors that affect DO often make it difficult to identify any one particular dominant process (Figure 3), but a reasonably sufficient job can be done with adequate data. This report focuses on assessing the impact of flow on DO and on DO-influencing processes. In the lower Jordan River, DO regulations are defined by two criteria: 1) chronic (30-day average) DO concentration > 5.5 milligrams per liter (mg/L), and 2) acute (instantaneous) DO concentration > 4 mg/L for May–July and > 4.5 mg/L for August–April.

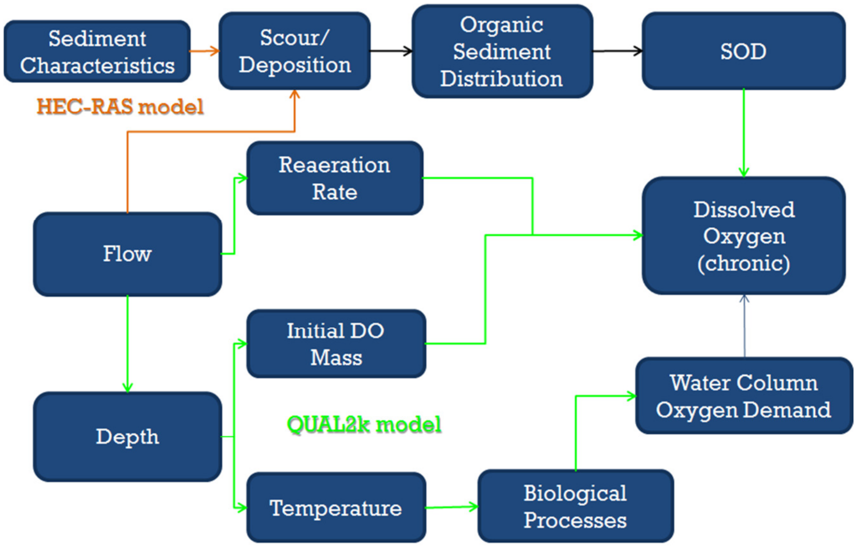
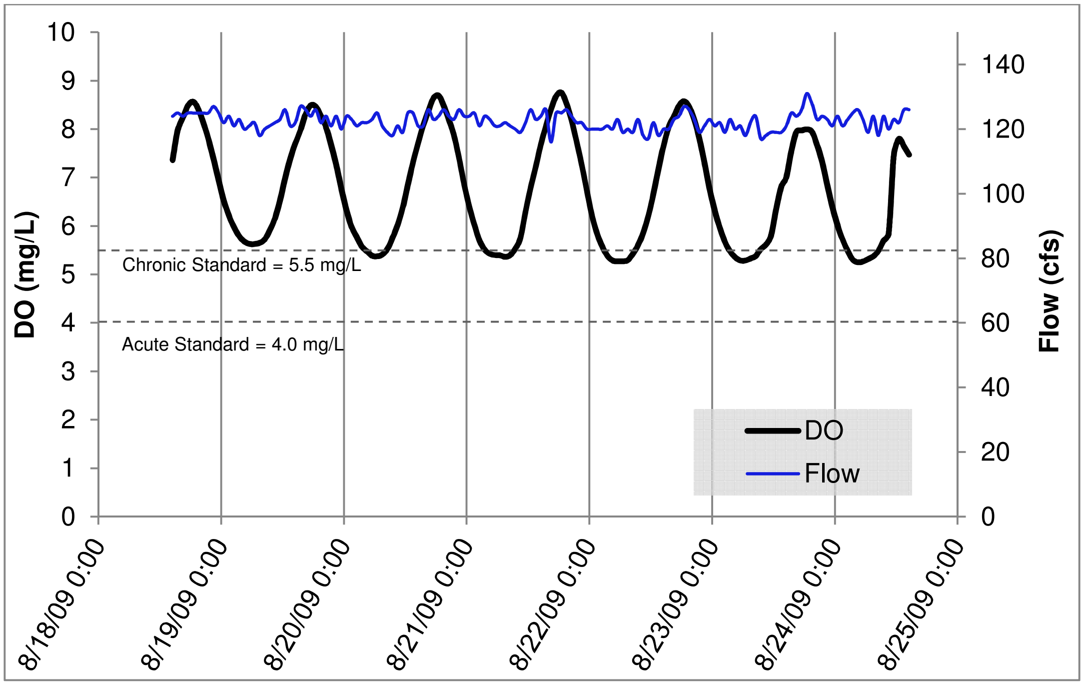


Figure 3. Simplified influence diagram for controls on dissolved oxygen in lower Jordan River and tools used in this project.

Generally, flow will have a non-linear effect on DO in streams and rivers. For example, turbulent flows that result from high discharge events may directly increase reaeration rates, but may also mobilize local sediments thereby increasing water column oxygen demand. In the lower Jordan River, however, these events are currently very rare. The main sources and sinks for DO in the lower Jordan River can be simplified, respectively, to 1) photosynthesis, reaeration, and oxygen introduced from the upstream reach, and 2) respiration associated with biological oxidation and all first-order reactions that consume oxygen (e.g., nitrification and methane oxidation). The question then becomes, how does flow impact these sources and sinks of DO?

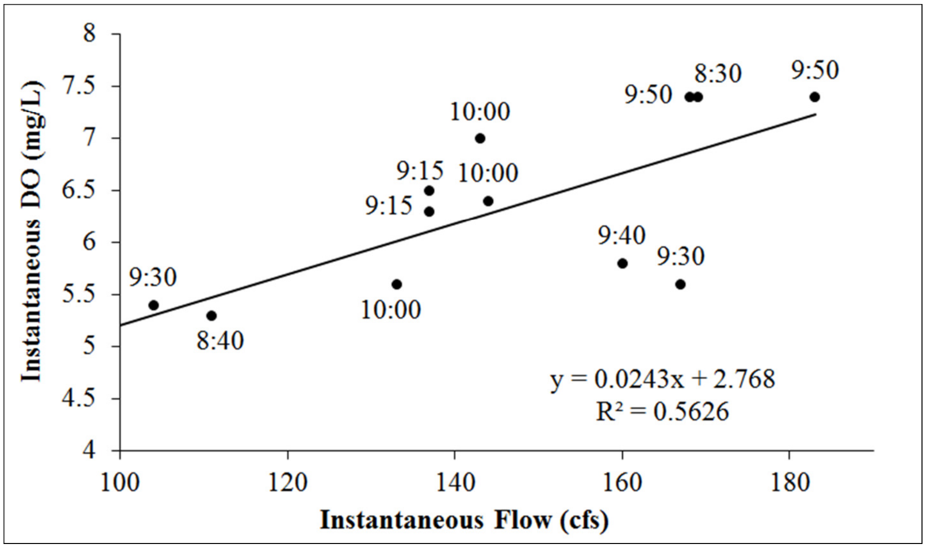
A first glance at available DO and average daily flow data indicates a complete lack of correlation between the two parameters ($R^2 = 0.0006$). However, because flow and DO vary at both seasonal and daily timescales (Figure 4), it is more informative to compare them at a precise season and time than to look at average daily values across all seasons.



Note: Data from 8/18/2009 to 8/24/2009 at 1700 S (DO data from University of Utah). For this timeframe, flow is able to explain 25% of the variation in DO.

Figure 4. Daily fluctuations in dissolved oxygen and flow.

When DO and flow are compared as instantaneous values and only during the late summer months of August and September (when most DO violations occur), a more robust signal appears. Theoretically, this signal should be most evident when photosynthetic controls on DO are lowest (night and early morning), and indeed this appears to be the case in the lower Jordan River. By only examining data that occur prior to photosynthetic maxima, it becomes clear that flow exerts a strong influence on DO (Figure 5). This signal becomes much less pronounced when later times of the day are considered. Again, this trend is only valid for the timeframe considered (late summer), and seasonal variations are almost guaranteed.



Note: Data from August and September, 1988–2013. Plot is for times from 8:00 to 10:00; a clear positive trend is visible.

Figure 5. Instantaneous flow vs. instantaneous dissolved oxygen at 1700 S.

1.3.2. Reaeration Rates

Reaeration rates (K_{20}; K = reaeration rate and K_{20} = reaeration rate corrected to 20 degrees Celsius) per day are a measure of the propensity for oxygen to diffuse into the water column. Negative rates indicate that the water column is supersaturated with oxygen with respect to the atmosphere and thus oxygen is diffusing out of the water. Positive rates indicate that oxygen is diffusing into the water to replace oxygen consumed by respiration and first-order reactions. Reaeration is a function of the biological, physical, and hydraulic properties of a river, but it is generally modeled as a function of flow velocity (v) and depth (d) where flow velocity has a positive relationship with reaeration ($K \propto v^{\sim 0.8}$) and depth has a stronger inverse relationship with reaeration ($K \propto d^{\sim -1.5}$). Because flow affects both velocity and water depth, it can be expected that changes in flow will induce a significant change on reaeration rates. Wind velocity also has an impact on reaeration rates, although it is rarely included in mechanistic models.

Reaeration rates for the lower Jordan River were measured over the course of 3 days in the middle of September 2009 (Hogsett and Goel 2009; Table 2). Hogsett and Goel (2009) point out that the potential for surface reaeration in reaches 1 and 2 is significantly lower than in reach 3 and the rest of the upper Jordan. They attribute this to increased depths, slower flows, and a more uniform bottom in reaches 1 and 2 when compared to the rest of the river. A relationship between flow and reaeration rates for the lower Jordan River has not yet been completed, but can be estimated with empirical equations (e.g., Churchill, O'Connor & Dobbins, and Owens) and known channel geometry.

Table 2. Reaeration Rates in the Lower Jordan River, Taken from Goel and Hogsett (2009)

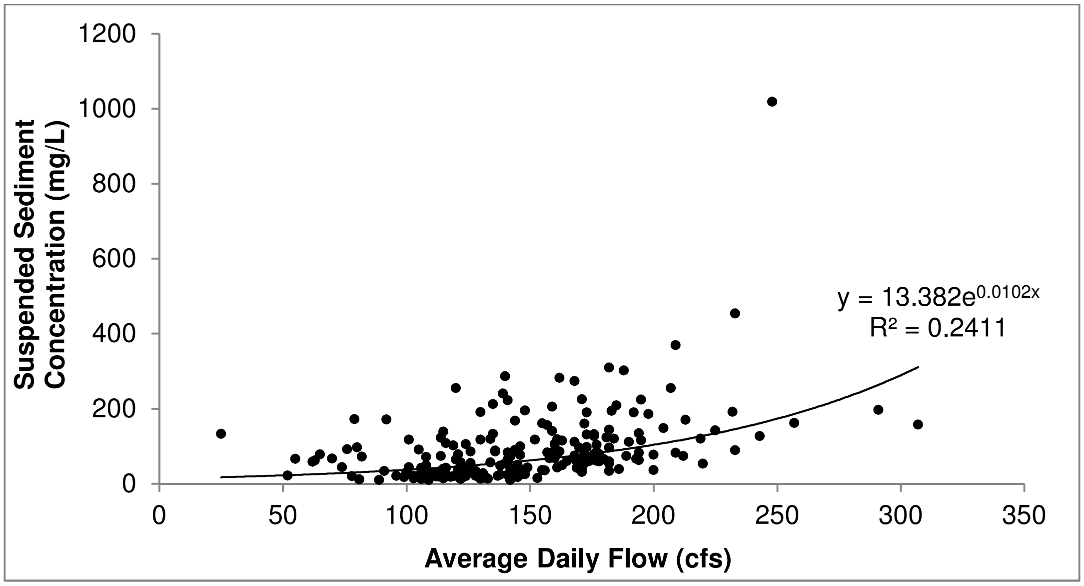
Reach Number	K_{20} [d^{-1}]	Average Depth (m)	Dates Sampled	Times Sampled
1	0.6	1.0	September 11–12, 2009	19:55–00:30
2	0.6	1.0	September 11–12, 2009	19:55–00:30
3	4.2	0.8	September 13, 2009	13:00–14:30

Note: Reaches 1 and 2 were combined into one measurement in this study.

1.3.3. Suspended Sediment

For many systems, sediment loads are positively correlated with river and stream discharge (Rosgen 2010). Sediment transport comprises a suspended load in the water column and a bedload that is transported along the riverbed; both of these modes of transport are directly influenced by flow velocities. The suspended load is easier to measure than the bedload and is calculated using suspended sediment concentrations (SSC) or total suspended solids concentrations (TSS). It has been shown that SSC is a better measure of suspended load than TSS (USGS 2000), and as such, it is used to develop the sediment rating curve for this study.

A sediment rating curve is used to estimate SSC when a continuous record of SSC is lacking. The correlation coefficients of previously created curves suggest that the relationship between flow and SSC is relatively imprecise, with errors that span several orders of magnitude apart from measured data (Walling 1977). Results from the lower Jordan River suggest that average daily flow is able to explain approximately 24% of the variation in SSC when modeled as an exponential relationship (Figure 6). There is a large amount of variability about the best fit line, but the overall trend is an exponential increase in SSC with flow. Other factors potentially affecting SSC include sediment grain size, sediment cohesiveness, bedslope, and stream power.



Note: SSC data were taken monthly from October 1974 to September 2003 (NWIS). Best fit line slightly improved when only winter samples were considered (R^2 = 0.33) and slightly worsened when only summer samples were included (R^2 = 0.12).

Figure 6. Sediment rating curve for 1700 S.

1.4. Critical Shear Stress

As water flows through a channel, a shear stress is imparted to a riverbed along the direction of flow. Critical shear stress is the shear stress required to overcome particle resistance to motion and mobilize sediments. Therefore, if the observed shear stress exceeds the critical shear stress, sediment will be mobilized. Although extensive literature exists on the subject of critical shear stresses for coarse sediments, data regarding fine-grained cohesive soils are more limited. Additionally, the available literature indicates that the properties of cohesive soils are very site specific. The *HEC-RAS River Analysis System Hydraulic Reference Manual* provides useful commentary on differences between modeling coarse-grained and fine-grained sediments (U.S. Army Corps of Engineers [USACE] 2010). Within the HEC-RAS model, sedimentation can be modeled using a “standard” transport model or by using the Krone and Partheniades approach. The standard transport model is applicable to coarse materials, whereas the Krone and Partheniades approach is preferred for fine-grained cohesive materials. The implementation of the Krone and Partheniades approach in HEC-RAS is based on the work of Krone (1962) and Partheniades (1962). To use the Krone and Partheniades option in the HEC-RAS model, the following parameters must be specified: shear threshold, erosion rate, mass wasting threshold, and mass wasting rate. The following excerpt from the hydraulic reference manual discusses key differences in the mechanics of fine- and coarse-grained particle mobilization (USACE 2010).

> Cohesive particles are small enough that their behavior is usually dominated by surface forces rather than gravity. A fundamental concept of Krone deposition being the probability that the flock will “stick” to the bed (as opposed to sand and gravel that “sink” to the bed). Similarly, in Partheniades erosion, the issue is whether the bed shear is sufficient to overcome the electrochemical forces holding the grains together (rather than determining whether the bed shear is adequate to physically lift a grain particle of a given volume and weight off the bed). (USACE 2010:13–19)

And later:

> The key to success for the Partheniades method is estimating the process thresholds and the erosion rates. These parameters are strongly site specific and even vary significantly with location and depth

> at a given site. Therefore, the variables can either be developed computationally, by calibrating them to some other measured parameter, or experimentally with a SEDFLUME apparatus. (USACE 2010:13–23)

Whereas with coarse materials, it is the size and weight of a particle that determine its resistance to movement, with fine-grained sediments, inter-particle forces play a dominant role (U.S. Bureau of Reclamation 2006). As particle size decreases, the relative importance of inter-particle forces increases as compared to gravitational forces. However, there is no clear boundary between cohesive and non-cohesive sediment. In general, sediments with a grain size smaller than 2 micrometers (µm) (clay) are considered cohesive, and sediments with a grain size larger than 60 µm are non-cohesive. Silt spans the intermediate area. In engineering practice, silt and clay are often grouped together and considered cohesive. However, the cohesive properties of a silt-clay mixture are predominantly a result of the clay fraction. The accuracy of a model for predicting the erosion of cohesive materials is entirely dependent on the parameters specified.

The preceding discussion gives some background reasons for the variability in the critical shear stress values of fine-grained sediments. A summary of typical critical shear stress values found in the literature for cohesive materials is provided in Table 3. The values in Table 3 provide a basis of comparison to the modeled shear forces listed below (see Section 2.2.2). If the modeled shear stresses are larger than the values shown in Table 3, it could be expected that cohesive materials in the bed of the river could be mobilized.

Table 3. Summary of Critical Shear Stresses Associated with Cohesive Materials

Type of Sediment	Critical Shear Stress (lb/ft^2)	Citation
Riverbank	0.42	Julian & Torres 2006
Streambeds and banks	0.12	Papanicolaou 2000
General, not site specific	0.63	USACE 2010

lb/ft^2 = pounds per square foot.

Based on the data in Table 3, it can be seen that critical shear stress values for cohesive soils are quite variable. The peak value shown in the table, 0.63 pound per square foot (lb/ft^2), was obtained from the *HEC-RAS River Analysis System Hydraulic Reference Manual* (USACE 2010). The reference manual provides several curves of critical shear stress force versus voids ratio, but cautions that the curves should only be used as a starting point for calibration. The value of 0.63 lb/ft^2 corresponds to a very compact clay, and the overall range given by the curve is 0.03–0.63 lb/ft^2.

Based on the literature findings, the critical shear stresses for FPOM are comparatively low. One reference (Cushing et al. 1993) gives a critical shear stress of 0.05 Newton per square meter for FPOM, which corresponds to a shear stress of approximately 0.001 lb/ft^2, well below the values of critical shear stress given for cohesive sediments in Table 3. No literature was found giving values of critical shear stress for coarse particulate organic matter (CPOM). However, if it is assumed that CPOM has a similar density to FPOM and if the approach used by Cushing et al. (1993) is duplicated for CPOM, a value of 0.5 Newton per square meter (0.01 lb/ft^2) can be estimated for CPOM. It is expected that the critical shear stress for CPOM will be highly variable and dependent on the source of the organic matter and the physical and biological processes that have affected the organic matter.

1.5. Data Gaps

The literature findings regarding critical shear stress have two primary shortcomings; these contribute to uncertainty in predicting erosion in the lower Jordan River. The first is that there are insufficient literature data available to adequately define the threshold for sediment movement (critical shear stress) in the lower Jordan River. Second, available literature indicates that shear stress–related parameters vary widely between different locations. Moreover, the available literature sources often do not give a complete description of the sediments for which critical shear thresholds are published. To address these deficiencies, site-specific shear stress data need to be measured.

The reaeration rates available for the lower Jordan River are based on field measurements collected over 3 days in September 2009. However, reaeration rates are unlikely to be static and probably vary over time and with flow. A more dynamic range of reaeration rates, based on an empirical relationship between reaeration rates and flow, for the Jordan River would improve the sensitivity analysis by reducing uncertainty associated with this variable. Jordan River and Farmington Bay Water Quality Council (JR/FBWQC) and DWQ has been collecting continuous DO data in reach 1 with three in-situ sondes for the past 6 months (personal communication between Erica Gaddis, SWCA, and Nick von Stackelberg, DWQ, September 21, 2013), and it is likely that such a relationship could be developed with these data.

2. MODELING

Two models were used to explore two pathways by which changing flow in the lower Jordan River could influence chronic DO levels: QUAL2kw (Q2k) and HEC-RAS. HEC-RAS is a one-dimensional steady-state hydraulic model developed by the USACE. Using river profile and cross-sectional data, the model predicts water depth throughout a reach and stream power to mobilize and carry sediments.

Q2k is a one-dimensional river and stream water quality model and is one of the most widely used tools to predict in-stream water quality (Pelletier and Chapra 2008). It assumes a well-mixed channel and steady state hydraulics, but models heat and water quality variables on a diel time scale (varies sinusoidally over the course of a day). Input data necessary for Q2k include headwater boundary conditions, point source or abstraction conditions, and in-stream chemical, biological, and physical parameters (Table 4).

Table 4. Input Data Requirements for QUAL2kw Model

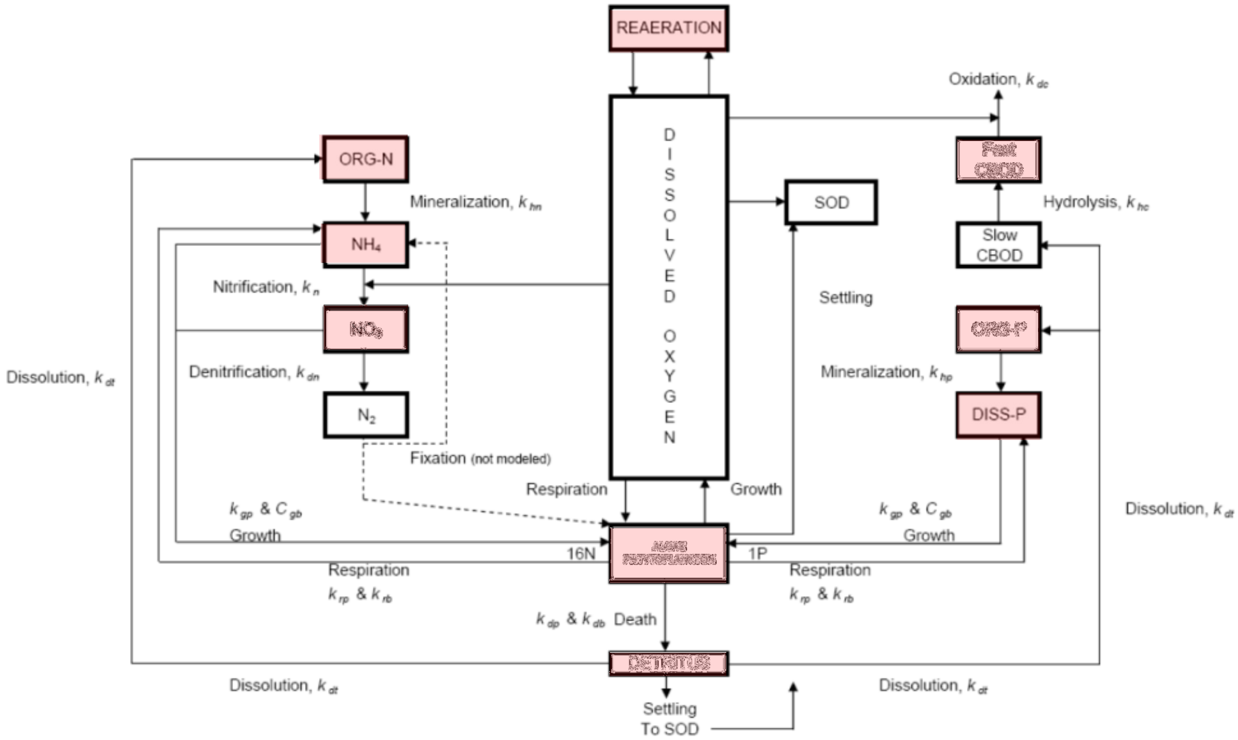
Model Component	Description
Geometric	Stream length, reach segmentation
Meteorological	Cloud cover, air temperature, dew point, solar radiation, wind speed
Hydrologic	Headwater and tributary inflows and diversions
Hydraulic	Bottom roughness, bottom width, side and bottom channel slope
Water Quality	Inflow and upstream boundary conditions, concentrations, and calibration data
Effluent	Flow rates and concentrations
Reaction Rates	Reaeration, oxidation, reaction and settling rate coefficients, nutrient half-saturation coefficients, temperature correction factors
Other	Simulation time, computation time step

Source: Adapted from EPA (1997).

2.1. QUAL2kw Sensitivity Analysis

A final calibrated and validated Q2k model for the Jordan River was used to test the sensitivity of the model output to changing flows (calibrated for August 2009). The data used for inputs and calibration for Q2k come from multi-day synoptic surveys during summer critical conditions where physical, chemical, biological, and meteorological data were collected (UDEQ 2013). Additional point source discharge information was obtained voluntarily from publicly owned treatment works along the Jordan River.

DO is both an input and output variable within Q2k in that it is prescribed for headwater and tributary sources, but is also calculated based on its interactions with other model parameters (Figure 7). Flow does not explicitly affect DO in Q2k, but it does affect DO source and sink processes (e.g., reaeration, particulate settling, photosynthesis, and first-order consumption processes). To account for model uncertainty, the acute standard of 4.5 mg/L was increased by a margin of safety of 1 mg/L to a model DO target of 5.5 mg/L (UDEQ 2013).



Note: Adapted from Stantec Consulting, Inc. (2009). Sources include algal/phytoplankton photosynthesis and reaeration, and sinks include SOD, biochemical oxygen demand, respiration, and nitrification. Factors directly influenced by changes in depth and volume (associated with change in flow) are highlighted in red.

Figure 7. Influence diagram for dissolved oxygen in QUAL2kw.

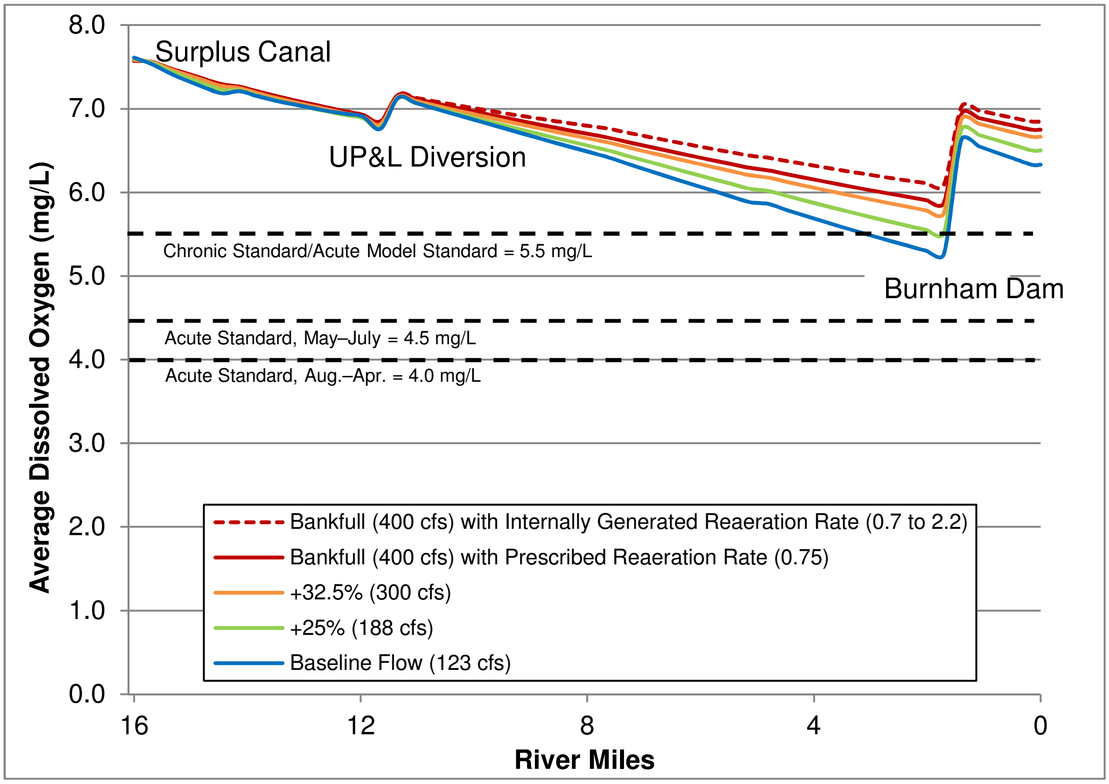
The only parameters that SWCA adjusted within the model were the quantity of flow diverted to the Surplus Canal and modeled reaeration rates from the North Temple Conduit to the Burnham Dam (initially prescribed at 0.75 d^{-1}).

2.1.1. Sensitivity Scenarios

Q2k allows the user to either prescribe reaeration rates for a reach or allow the model to generate them internally based on velocity and depth. The Q2k model developed for the Jordan River TMDL, and used in this analysis, uses a prescribed reaeration rate based on field data collected in September 2013. The prescribed reaeration rate (0.75 d^{-1}) is substantially lower than the reaeration rates generated internally by Q2k (1-2.25 d^{-1}). The first sensitivity scenarios were developed keeping the prescribed reaeration rate constant, to evaluate other flow-based effects on DO. A second round of sensitivity scenarios were run at varying flows allowing the model to calculate reaeration rate internally. SWCA determined that it was worthwhile to consider alternative rates because DO is highly sensitive to them and because the prescribed reaeration rate was determined from a one-time reaeration measurement made in September 2009 (Hogsett and Goel 2009). When reaeration rates were not prescribed, the model calculated them using the O'Connor & Dobbins equation for all lower reaches. The model was run for a 6 day simulation.

2.1.2. Results

Results from the sensitivity analysis indicate that increasing flows into the lower Jordan River should result in measurably higher DO levels (Figure 8). An increase in flow by 25% (from 123 to 188 cfs) into the Jordan River from the Surplus Canal was the minimum flow required to bring average DO concentrations over the model target of 5.5 mg/L (with implicit margin of safety). Internally calculated reaeration rates were 50-300% higher than the prescribed reaeration rate of 0.75 d^{-1}. Runs in which internally generated reaeration rates were used had significantly higher DO at all modeled flows when compared to model runs using prescribed reaeration rates. The respective drop and spike in DO at the Utah Power and Light (UP&L) diversion and Burnham Dam are artifacts of differences in the bottom algal coverage at those structures. An abrupt decrease in algal coverage at UP&L lowers local oxygen levels and an abrupt increase in algal coverage at Burnham Dam raises local oxygen levels.



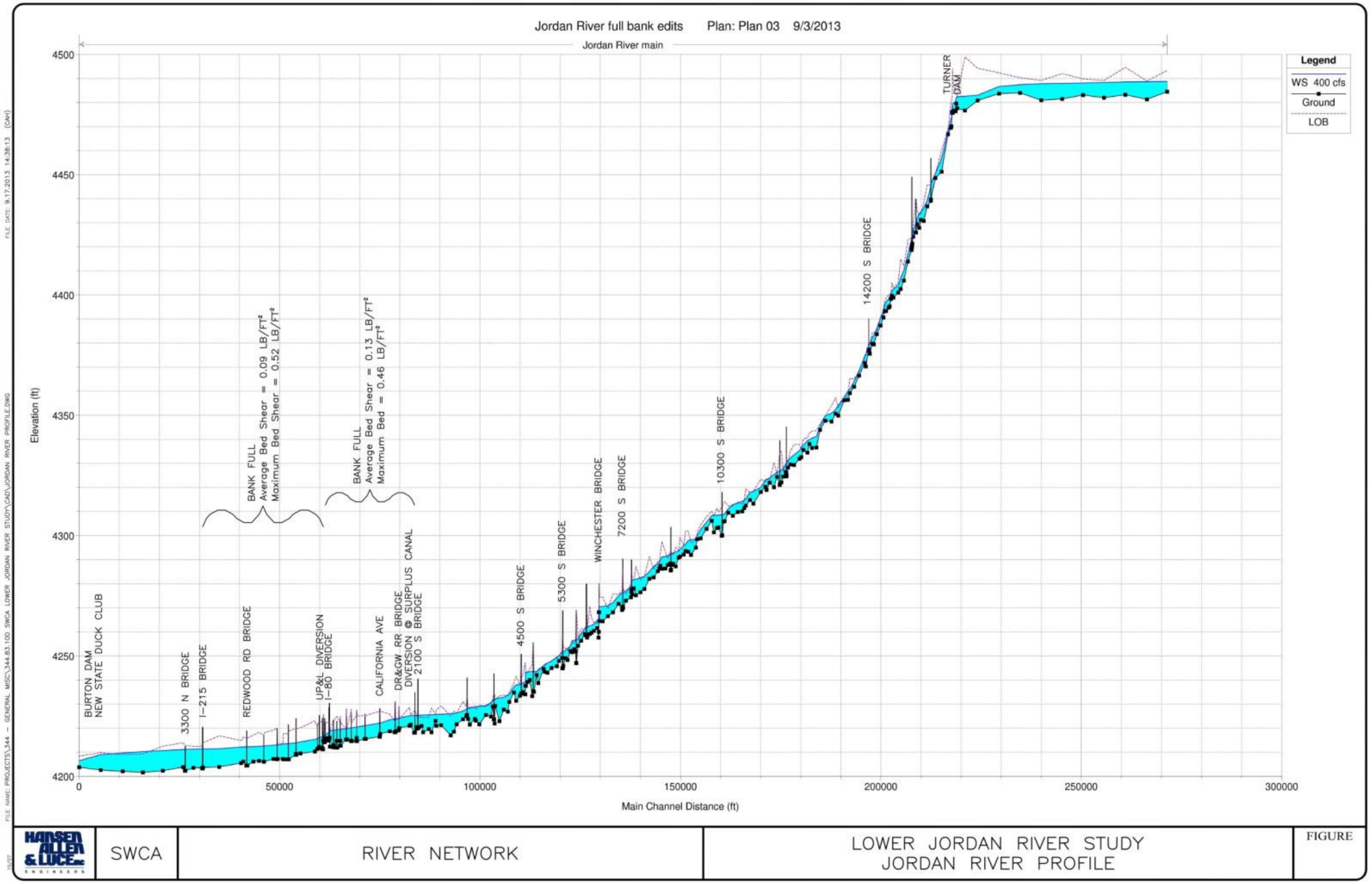
Note: Flow rates in parentheses are the flows just downstream of the Surplus Canal. Percentages show increased flow percent above model baseline. The model baseline flow of 123 cfs violates the chronic DO standard of 5.5 mg/L. By increasing flows to the lower Jordan by 25%, chronic violation is prevented. Internally generated reaeration rate runs are only shown at bankfull flow for clarity, but at every flow, DO levels were higher than using prescribed rates.

Figure 8. Sensitivity of model to changing flow conditions.

2.2. HEC-RAS

2.2.1. Model Description

The HEC-RAS model provided by Salt Lake County includes cross-sections beginning at the outlet of Utah Lake and extending north to Burton Dam. A profile view of the HEC-RAS model has been included on Figure 9. In all, there are 429 cross sections entered into the model, which extend just over 51 river miles. However, if only the cross sections downstream of the 2100 S bridge are considered, the number of cross sections, including bridges, is reduced to 145. The corresponding length of the lower Jordan River from 2100 S to the Burton Dam is approximately 16 miles. Several cross sections that are associated with notable locations have been labeled on Figure 9. Within the HEC-RAS model, each cross section includes data describing the shape of the channel at that location, the Manning's n for that reach, and the location of the left and right bank of the channel. As shown by Figure 9, reach lengths vary widely within the HEC-RAS model. Within the lower Jordan River, the shorter reaches generally have lengths within the range of approximately 50–100 ft. Conversely, the longest reach has a length of 5,500 ft and is upstream of Burton Dam. In addition to showing the labeled cross sections, the profile view also illustrates how channel slope changes at different locations along the Jordan River. Just below Turner Dam, the channel is the steepest. The slope progressively becomes less steep moving downstream.



Note: Lower Jordan River begins at 2100 South.

Figure 9. Jordan River profile from Utah Lake to Burton Dam.

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2.2.2. Results

The HEC-RAS model was run with flow rates of 200 cfs, 400 cfs, 700 cfs, and 900 cfs, and the resulting water surface elevations were compared against the elevation of the left and right bank at each cross section. Based on this comparison with bank elevations, the 400 cfs flow scenario was selected as the best approximation for bankfull flow. The 200 cfs flow scenario was modeled to determine the potential for sediment resuspension at the minimum flow rate previously determined to raise DO levels above the model target (188 cfs; see Section 2.1.2). Using the output from the flow scenarios, the bed shear stress (τ_b) was computed for each cross section according to the following:

$$\tau_b = \gamma d S$$

where: γ = the unit weight of water [lbs ft^{-3}]
d = the depth of flow [ft]
S = the friction slope [ft ft^{-1}]

For the purpose of summarizing the shear stress results, the lower Jordan River was subdivided into three segments (these are not the same as previously defined river reaches). The first segment begins at the 2100 S bridge and extends down to the UP&L diversion. The next segment starts at the UP&L diversion and extends down to the Interstate 215 (I-215) bridge. The final segment extends from the I-215 bridge to the Burton Dam. Shear stress results are summarized in Table 5.

Table 5. Summary of Bed Shear Stress

Segment	Average Shear (lb/ft^2)			Minimum Shear (lb/ft^2)			Maximum Shear (lb/ft^2)		
	200 cfs	400 cfs Bankfull	700 cfs Flood Stage	200 cfs	400 cfs Bankfull	700 cfs Flood Stage	200 cfs	400 cfs Bankfull	700 cfs Flood Stage
2100 S to UP&L diversion	0.09	0.13†	0.16†	0.01	0.02	0.03	0.46†	0.46*	0.56*
UP&L diversion to I-215 bridge	0.08	0.09	0.11	0.004	0.01	0.02	0.52*	0.52*	0.25†
I-215 bridge to Burton Dam	0.03	0.04	0.05	0.004	0.01	0.02	0.06	0.06	0.09

*High potential to move sediment based on literature values.

†Low to moderate potential to move sediment based on literature value.

Maximum shear stresses are predicted for relatively short river segments that are generally just downstream from in-channel control structures (e.g., UP&L diversion). It should also be noted that HEC-RAS calculates shear stress in a way that results in a single value representing each river cross section. In reality, there is a range of local shear values within a given reach; the model computed values represent the central tendency of this range.

Model simulations reveal that average shear stress values for segments downstream of the UP&L diversion (see Table 5) are less than the lowest cohesive critical shear stress reported in the literature (0.12 (lb/ft^2; see Table 3). Furthermore, the upper segment (2100 S to UP&L diversion) has an average shear stress at bankfull flow just slightly higher than the lowest cohesive shear stress reported on Table 3.

These results indicate that bankfull shear stresses in the lower Jordan River are on average too small to move cohesive bed deposits.

On the other hand, modeled shear stress values are greater than estimated critical values for FPOM and CPOM (0.001 lb/ft^{2}and 0.01 lb/ft^2, respectively). Hence, it is expected that shear stresses produced at both bankfull flow (400 cfs) and at 200 cfs should be sufficient to mobilize FPOM and CPOM.

3. CONCLUSIONS

3.1. Conclusions

3.1.1. Potential Effect of Flow on Dissolved Oxygen

The Phase 1 analysis described in this report provides a body of evidence that indicates that flow has a strong potential to affect DO concentrations in the lower Jordan River. While increased flows decreased modeled reaeration rates, they also decreased oxygen-consuming processes by a greater amount and delivered a larger mass of oxygen (by delivering a larger volume of water) to the lower Jordan River that buffered constant SOD rates. The net result of these modeled effects is improved DO concentrations in the lower Jordan River. The effect of reduced oxygen-consuming processes due to increased flows is also supported by the morning-time relationship between flow and DO (see Figure 5). Given these findings, it is reasonable to assume that increased flows should induce greater oxygen concentrations in the lower Jordan River during late summer.

3.1.2. Scour Potential

Based on the modeling results and the findings of the literature review, it appears that bankfull flow average shear stresses for the lower Jordan River downstream of the UP&L diversion are generally too small to mobilize cohesive bed deposits. The upper segment of the lower Jordan River from the 2100 S bridge to the UP&L diversion has a higher bed slope and higher average shear stress than lower segments, and depending on the actual bed materials' properties, riverbed sediments could be mobilized. Uncertainty in the estimation of the Jordan River bed cohesive properties and critical shear stress characteristics are too large to confidently predict effects of bankfull flow shear stresses on the riverbed scour. Although critical shear stress is site specific and varies widely, the overall range presented by the literature is similar in magnitude to the shear values predicted by the HEC-RAS model. In addition, the estimated critical shear stresses for FPOM and CPOM are sufficiently low that FPOM and CPOM (not attached to a cohesive bed) are likely to be mobilized under most flow conditions.

3.1.3. Risk in Exposing Deeper Sediments

Even if the scour potential were determined to be significant, there is some risk in exposing deeper sediments in the lower Jordan River. Estimated SOD rates for lower sediments are generally the same or higher than SOD rates in surficial sediments (see Table 1), though this finding is based on a regression equation developed specifically for surficial sediments and could be validated through empirical study. In addition, there is a potential for excavating relic hazardous chemicals generated historically during times of greater industrial activity.

4. RECOMMENDATIONS FOR NEXT STEPS

The recommended next steps are organized into three sections based on three distinct threads or linkages between flow and DO. The first section focuses on linkages between base flow and violations of chronic

DO standards. These recommendations will be pursued by River Network and SWCA in Phase 2 of this project. The second section focuses on acute (event-based) linkages between flow and DO and the third focuses on the relationship among flow, sediment, and DO. Recommendations related to the latter two threads are potential avenues of pursuit and possible research questions that other groups could follow-up on. The findings of all three threads could be integrated as a later phase of work, as they all inform potential management of the lower Jordan River to improve water quality and habitat.

4.1. Linkages between Flow and Chronic Dissolved Oxygen Violations

The results from Phase 1 indicate that management of base flows as low as approximately 190 cfs could resolve the chronic DO violations during the late summer. Work elements in Phase 2 aim to confirm this finding by evaluating continuous oxygen data collected by the Jordan River/Farmington Bay Water Quality Council (JR/FBWQC) and DWQ in 2013, to evaluate in more detail whether the assigned reaeration rates are representative of conditions throughout the summer and across different years, to update the Q2k model to explore the relationship between flow and DO during different parts of the summer season, and to test the model outputs with a managed flow experiment in summer 2014. The following recommendations would be performed primarily by SWCA and HAL in consultation with River Network and other partners. The primary purpose of these recommendations is to provide sufficient evidence for Salt Lake City and the Jordan River Commissioner to increase base flows in the lower Jordan River during the summer season to improve DO concentrations.

4.1.1. Additional Data Analysis

An update of the current analysis of TSS, flow, and DO data will allow us to improve the certainty of our Phase 1 results and provide a more detailed understanding of the mechanisms through which flow affects DO in the lower Jordan River. This work is made possible by the continuous DO sondes currently installed in the lower Jordan River by JR/FBWQC with funding from DWQ.

4.1.1.1. LINKAGE BEWTEEN DISSOLVED OXYGEN AND FLOW USING 2013 DATA SET

The linkage between DO and flow would be greatly improved with the inclusion of continuous monitoring data of both variables for 2013. JR/FBWQC and DWQ have been monitoring DO continuously in several different locations in the lower Jordan River since March 2013. We recommend using this data set to update the statistical analysis (see Section 1.3.1) between DO and flow (using the continuous USGS gage data). This will provide a much stronger evaluation of the temporal (both seasonal and daily) and spatial correlations between flow and DO.

4.1.1.2. IDENTIFY COVARIATES BETWEEN FLOW AND DISSOLVED OXYGEN

In Phase 1, we identified a positive linear relationship between flow and DO. Although this relationship was significant, it could be improved and clarified with an analysis of covariates that also impact DO, such as temperature, atmospheric pressure, and concentrations of redox reaction products and reactants. Much of these data are already currently available, and the continuous sonde data referenced above should be used to explore the relative importance of covariates at different times of day and seasons.

4.1.2. QUAL2k Model Update and Expansion

The Q2k model used for the Phase 1 analysis and the TMDL is only valid for the critical late-summer period (August 2009, specifically). An update of Q2k using new data from JR/FBWQC's 2013 DO monitoring study and the recommendations listed below would improve the accuracy of the model for other periods throughout the year and could be used to verify critical period predictions for years outside of the 2009 calibration year.

4.1.2.1. EVALUATE REAERATION RATES FOR LOWER JORDAN RIVER

Measured reaeration rates are only available for 1 day in late summer, at a flow of 125 cfs. Although these rates provide reasonable inputs for the Q2k model, they are significantly lower than the predicted reaeration rates generated by the model, which are internally calculated based on stream velocity and depth. Because reaeration is a sensitive parameter in the Q2k model, the large variability between predicted model values versus measured values points to the need for a more accurate assessment of reaeration as it relates to flow. Therefore, an empirical relationship between reaeration rates and flow would be highly valuable for predicting effects of varying flow scenarios on DO levels in the lower Jordan River. A continuous record of DO data from JR/FBWQC that is available for most of 2013 could be used to create such a relationship, assuming that other factors affecting DO are known or less sensitive.

4.1.2.2. EVALUATE DIVERSION STRUCTURE DISSOLVED OXYGEN AND BOUNDARY CONDITION

During the Phase 1 study, a question was raised regarding the concentration of DO below the diversion structure as water enters the lower Jordan River. Although we think that the water just downstream of the diversion is well aerated due to the presence of a riffle, water column DO profiles measured just upstream and just downstream of the diversion structure would be helpful to confirm this assumption. Such measurements would also provide an understanding of how DO changes through the diversion structure and also help to set the boundary DO conditions for the Q2k model. This would be a relatively simple task that would require bimonthly DO profile measurements at the diversion structure over the course of 10 months.

4.1.2.3. QUAL2K MODEL EXPANSION

Currently, the Q2k model is developed for the critical condition determined in the Jordan River TMDL to be August 2009. The model is calibrated to data collected during that month, and all of the scenarios presented as part of Phase 1 reflect that condition. An update of the model to current (2013) conditions and expansion to other seasons would provide greater model validation and also has the potential to provide insight on the linkages between DO and flow during other periods, including late spring, early summer, and fall. We recommend that additional Q2k models be developed for a week during each of these other seasons using the rate constants and other calibrated parameters from the existing model. An expansion of the model would allow us to run various flow scenarios for different seasons, using 2013 as a typical year.

4.1.3. Conduct Flow Experiments

Following additional data analysis and model scenario runs, we recommend a series of experiments over a range of flows in the lower Jordan River. This would provide an empirical demonstration of the recommendations that are derived from the modeling and data analysis and vastly improve the confidence of our recommendations regarding increasing the base flow in the lower Jordan River during the summer season.

We recommend that four to six separate flow experiments be conducted in summer 2014, each with duration of 1 week. Flows would be increased to at least the recommended flow derived from the seasonally specific output of the Q2k modeling. The selected weeks should represent a variety of hydrologic and climatic conditions, including both early summer and late summer and if possible both dry periods and storm events (flow raised prior to a storm would still be kept low enough to prevent the possibility of flooding). The following parameters, at a minimum, should be measured during the experiments at Q2k model nodes in the lower Jordan River: continuous sonde data (DO, pH, conductivity, and temperature), turbidity, SSC, CPOM, FPOM, biochemical oxygen demand, stream velocity, and depth. In addition, cross-sectional data could be taken before and after the experiment to evaluate the degree to which sediment moved in relation to flow (see Section 4.3.1). The design of the experiments would be finalized in consultation with stakeholders and a technical advisory team (TAT) to be formed to inform and oversee technical aspects of the work.

Completion of this work element would also require consideration of other risks and benefits that could occur as a result of increasing base flow. For example, there are two restoration projects in progress on the lower Jordan River. Although increasing base flow would likely provide additional water to newly planted riparian plants, it would be important to confirm with Salt Lake City and other sponsors of restoration activities that increased flows would not damage newly constructed banks or other structural features. This work element will include exploration of other habitat and aquatic life benefits that could result from increased flows and/or timing that moves towards mimicking a more natural flow regime. Increased flows could provide benefits to in-stream microhabitat structure, downstream wetland hydrology, and Great Salt Lake health. It would also be important to check with researchers conducting monitoring on the lower Jordan River that the flow experiment would not disrupt their studies. Finally, the experiments would require close coordination with Salt Lake City, Salt Lake County, and the Jordan River Commissioner to ensure that there are no concerns regarding flood protection, in-stream structures, or water rights before the experiment moved forward.

4.2. Acute Linkages between Flow and Dissolved Oxygen

Historically, peak flows in the lower Jordan River were likely responsible for transporting large quantities of sediment and organic matter from the riverbed to the surrounding floodplains and wetlands that surround Great Salt Lake. Although peak flows are less frequent and of smaller magnitude than they were historically (due to the influence of diversion structures), their effect on in-stream processes is still significant. This is evidenced by sharp drops in DO during storm events in the lower Jordan River. Thus exploration of the effects of flow on acute violations of DO is an important thread of exploration related to flow management, though quite different than the baseflow and chronic DO exceedances explored in the previous section. While this is an interesting avenue of inquiry, it will not be the focus of Phase 2 of the River Network project. However, we understand that there are several researchers currently engaged in these questions, including the Jordan River/Farmington Bay Water Quality Council, Salt Lake City, and several academics partnering with the UDEQ. It will be important to continue collaboration with these parties through Phase 2 of the project to ensure good information and data sharing and to build on all findings relating dissolved oxygen to flow management.

4.2.1. Analyze Causes of Acute Dissolved Oxygen Violations during Past Storm Events

The effect of peak flows due to storm events on river water chemistry is difficult to predict with currently available data and models. High discharge events mobilize sediments and organic loads from the riverbed and from tributaries in a way that is not currently modeled by HEC-RAS or Q2k. However, DO can plummet to nearly zero during storm events in some parts of the Jordan River, as evidenced by data collected by Salt Lake City during a large storm on July 4, 2013 (See Figure 10, Source JRFBWQ Council).

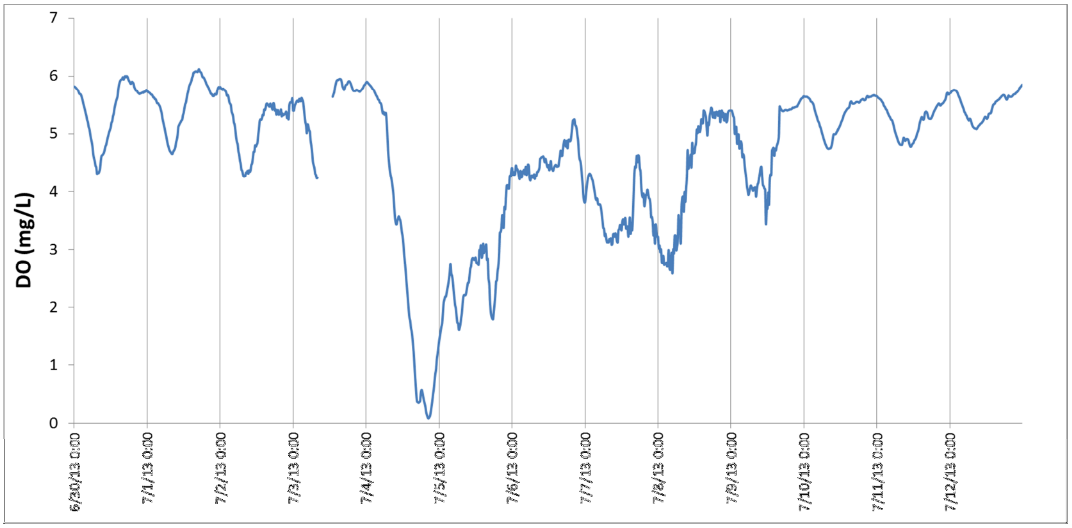

Figure 10. DO signal at 300 N from 6/30/13-7/12/13.

Using the previously mentioned 2013 JR/FBWQC monitoring data, periods of acute DO violations could be identified and correlated with specific storm events in which they occurred. This analysis would include examination of potential explanatory variables and covariates such as turbidity, length of time between storms, storm magnitude, base flow prior to storm, and diurnal DO patterns prior to and following a storm (to indicate influence of respiration and photosynthesis). Together with experimental research ongoing in the lower Jordan River regarding biochemical processes affecting DO in the sediment and water column, the proposed analysis could explain the most likely causes and mechanisms of acute DO violations. For example, if there is a linear relationship between the magnitude of the storm event and the magnitude of DO drop, it would be reasonable to assume that acute DO violations are a result of some oxygen-demanding load that scales linearly with flow. On the other hand, if there is a certain storm magnitude at which DO drops become non-linearly related to flow, there may be another mechanism at work (e.g., gas escape from sediments due to bed fluidization). This initial examination of the causes of acute DO violations will help to inform future decisions for monitoring DO during storm events. If length of time between storms proves to be positively correlated with the magnitude of the DO violation, we would have evidence that the release of trapped gases built up between storm events is an important mechanism.

4.2.2. Review Storm Events Monitoring Plan for Lower Jordan River

A storm event monitoring plan will help clarify some of the uncertainty surrounding acute DO excursions and may help inform flow-based planning decisions. We recognize that Salt Lake City has a monitoring plan for storm events that is currently guiding sampling along the lower Jordan River. This work element involves reviewing this monitoring plan and recommending additional elements that could be used to better characterize the linkages between storm flows and DO in the lower Jordan River.

4.2.3. Perform Sediment Fluidization/Mobilization Experiment

To test the hypothesis that acute DO violations are a result of reduced gases (e.g., methane) being released from fluidized sediments (i.e., soil liquefaction), a few simple analyses could be performed. First, it would be informative to understand the pore pressures and the characteristics of the streambed sediments.

Liquefaction occurs when an external load is applied in such a fashion that the pore pressures in the sediment exceed the contact stresses of the sediment particles, causing the sediment to behave like a liquid. Therefore, if these two parameters are known, it may be possible to calculate the necessary load that produces liquefaction under constant vibration and shear conditions. This experiment would require sampling of both pore pressures and sediment at several key locations along the lower Jordan River (i.e., upstream, at, and downstream of major storm conduits). Alternatively, sediment cores could be taken into the laboratory so that they can be subject to increasing loads (i.e., water depths) until liquefaction occurs. If these loads correspond to actual loads observed in the lower Jordan River, then it is likely that gas release due to liquefaction is a significant driver of acute DO excursions. There remains significant uncertainty about the methods that could be employed for such an experiment, their validity, and their costs.

In a simple test, sediment could also be manually mobilized upstream of a DO sensor to test the immediate effects of sediment mobilization on DO levels. This test would elucidate the timing and effect of sediment mobilization on DO levels. If the behavior of DO in the experiment is similar to that during storm events, this experiment would provide evidence for sediment mobilization and subsequent gas release as the driving mechanism for acute DO violations.

4.3. Linkage between Sediment Dynamics and Dissolved Oxygen

The findings form Phase 1 indicate that sediment is unlikely to be mobilized at bankfull flows due to relatively low shear stresses associated with high flows. Further, preliminary analysis suggests that scouring organic sediments may not result in improved DO conditions because the oxygen demand of underlying sediments may be as high as or higher than surficial sediments. However, there were significant uncertainties with this analysis primarily due to the lack of site-specific sediment characteristics. Although this line of work will not be directly pursued as part of Phase 2 of the SWCA contract with River Network, the following recommendations could inform work funded by others that may have additional interest in the findings. The work elements in this section would resolve that uncertainty and explore the potential to improve the management of stream sediments through targeted dredging. We understand that Dr. Goel at the University of Utah is pursuing several research questions that relate to these recommendations in collaboration with DWQ. We recommend that this research be coordinated such that findings can be integrated with other work elements (e.g. additional modeling) relating flow and water quality in the lower Jordan River.

4.3.1. Characterize Sediment

The scour analysis conducted as part of Phase 1of this study was limited by a broad range of literature-based critical shear stress values, leading to some uncertainty about whether (and to what extent) higher flows to the lower Jordan River would mobilize and transport sediments downstream. This uncertainty would be significantly reduced by developing site-specific, critical shear stress values. These values are dependent on site-specific particle size distributions (PSD) and characterization of the cohesive properties of the sediment bed. There are several methods that could be employed to characterize the sediments. A Sedflume could be used to measure erosion rates, density, and PSD in core samples from selected locations along the Jordan River. If this method were employed, the results from the Phase 1 effort would be used with a field reconnaissance to identify representative locations along the Jordan River.

As an alternative to or supplement to the Sedflume approach to defining the sediment erosion characteristics; cross sections at selection river locations could be measured before and after the flow test experiments (see 4.1.3). The measured changes in the river bed could be used to calibrate a dynamic

HEC-RAS sediment transport model. This would require that the flow tests include flows closer to bankfull (e.g. 400 cfs).

Regardless of the approach selected, sedigraphs (the variation of suspended sediment concentration with time) paired with storm runoff hydrographs would be needed to better understand the effects of storm runoff in tributaries to the lower Jordan River on river sediment mechanics. We understand that there are current ongoing studies by other Jordan River partners which may help in developing representative sedigraph/hydrographs for selected tributaries.

A PSD completely characterizes the relative amount of particles, by diameter or mass, present in a material. Similarly, a water column PSD could be measured at different flow rates to determine the types of material that are transported under baseflow conditions versus during storm events. Both of these measurements would allow for more accurate predictions of sediment and organic matter transport in the lower Jordan River.

It would also be worthwhile to measure soil redox potentials to determine at what depth various reduced compounds are being generated (e.g., methane, H_2S, Fe^{2+}). This work relates to ongoing work being conducted by Dr. Goel's laboratory at the University of Utah. This analysis would help to identify the most important compounds that may contribute to both chronic oxygen demand from SOD and potential acute oxygen demand from mobilized sediments.

4.3.2. Model Sediment Transport

A model of sediment transport would benefit our understanding of the geomorphology of the lower Jordan River. The timing, distribution, and quantity of sediment that is moved through the system have important implications for both water quality and habitat for aquatic species. For instance, if zones of accretion and erosion can be identified, then these sites can be targeted for specific management plans (e.g., dredging, bank stabilization). In order for sediment transport in the lower Jordan River to be modeled accurately, a much more thorough characterization of streambed sediments is required (see section 4.3.1).

Using the sediment characterization completed in Work Element 4.3.1, critical shear stresses could be determined from the measured erosion rates. River bed critical shear stress characteristics would then be compared with the shear stresses predicted with the HEC-RAS model to better identify sediment transport potential at various constant flows. In addition, the measured sediment erosion characteristics could be used with the dynamic option of HEC-RAS to model bed erosion and deposition resulting from selected hydrographs. This would help to target scour and deposition zones and could be used to develop a more targeted dredging plan for the lower Jordan River.

4.3.3. Measure Sediment Oxygen Demand at Depth

In Phase 1, potential SOD rates that would occur if sediment layers at depth were exposed due to scouring or dredging were estimated using a regression equation developed by Hogsett et al. (2013) for surficial sediments. The accuracy of this approach could be validated with actual measurements of SOD at depth. For such measurements to be tractable, sediment cores would need to be collected from the river for analysis in the laboratory.

At the same time, cores could be analyzed for byproducts of industrial activity (e.g., benzene, toluene, ethylbenzene, xylene, and vinyl chloride) to determine the potential of uncovering historic industrial chemicals through scour or dredging. For both of these analyses, it is recommended that core samples go below 30 cm (the current extent of most available core samples) to at least 1 meter.

Another potential avenue of exploration for SOD in the lower Jordan River is an analysis of the relative oxygen demand of FPOM versus CPOM. Currently, it is assumed the FPOM is more bioavailable, and thus exerts a stronger oxygen demand that CPOM; this is vetted by observations of greater FPOM and SOD in reach 1 compared to reaches 2 and 3. However, to our knowledge the primary cause of greater SOD rates in reach 1 has not been verified.

4.3.4. Review Dredging Management

A review of dredging management could be used to streamline potential management options for improving DO in the lower Jordan River. Salt Lake County is responsible to maintain adequate flood capacity of the river, which historically has required dredging and removal of woody debris flows and accumulation in the river. Salt Lake City and Salt Lake County Flood Control have discussed possible ways to improve river flood control management to manage SOD and dissolved oxygen demand to meet TMDL goals, including exploring the potential to identify and manage strategically placed depositional pools to be dredged on a regular basis. An evaluation of this idea using the sediment transport capability in HEC-RAS could be completed. This would be dependent on developing site-specific sediment erosion characteristics (see section 4.3.1) for sediments in the lower Jordan River. Also, it should be recognized that if scour areas were identified and encouraged, there is the potential to uncover toxic substances and create an environment suitable for undesirable bacterial growth. The dynamic HEC-RAS sediment transport model (see 4.3.2) would be used with representative tributary storm runoff sedigraphs and hydrographs to evaluate alternative locations for depositional pools and dredging effects.

4.4. Cost Estimates

Table 6 summarizes estimated costs for completing the recommended tasks. The costs are presented as a range pending finalization of a specific scope of work. Where appropriate cost assumptions, uncertainties, and contingencies are highlighted in the table.

Table 6. Cost Estimate Summary

Work Element	Estimated Cost	Cost Assumptions and Uncertainties	Contingent on….
Linkages between Flow and Chronic DO	**$38,000–$67,000**		
Additional Data Analysis	$3,000–$7,000	SWCA performs all tasks with input from DEQ. DO data available for lower Jordan River in MS Excel format.	N/A
2013 Data Analysis	*$2,000–$4,000*		
Covariate Analysis	*$1,000–$3,000*		
Update QUAL2k Model	$8,000–$16,000	SWCA performs all tasks with input from DEQ.	
Evaluate Reaeration Rates	*$1,000–$3,000*	Method from DEQ to calculate reaeration rate using sonde data will be provided to SWCA.	
Diversion Structure DO Profiles	*$1,000–$3,000*		Permission to access structure.
QUAL2k Model Expansion	*$8,000–$10,000*	Reaeration is the only parameter that requires updating to obtain good model fit with 2013 data.	Review provided by Nick von Stackelberg, UDEQ.

Table 6. Cost Estimate Summary

Work Element	Estimated Cost	Cost Assumptions and Uncertainties	Contingent on….
Flow Experiments	$19,000–$35,000		Approval from necessary regulatory entities (Salt Lake City, Salt Lake County, Jordan River Commissioner, etc.).
Experimental Design	*$4,000–$7,000*	SWCA coordinate experimental design with partners.	
Experimentation	*$6,000–$13,000*	SWCA would assist with sampling and monitoring; equipment provided by DEQ; laboratory costs not included.	
Data Analysis	*$5,000–$9,000*	SWCA compile and analyze all data.	
Reporting	*$4,000–$6,000*		
Linkages Between Storm Flow and Acute DO	$6,000–$12,000+		
Analyze Past Storm Events	$4,000–$7,000	Supplemental work by SWCA	Ongoing work conducted by SLC, USU, and others.
Review Storm Event Monitoring Plan	$2,000–$5,000	Supplemental work by SWCA	Ongoing work conducted by SLC, USU, and others.
Sediment Mobilization Experiment	Cost unknown.	Methods require additional research before costing.	
Sediment Scour and Transport Linkages to Dissolved Oxygen			
Characterize sediment			
Field reconnaissance	$5,000		
Collect and process SedFlume cores	$30,000–$60,000	20 locations; 5 measurements per core	
Survey cross-sections	$10,000 for first cross-section $6,000 for each subsequent cross-section		Cross-section approach continent on flow experiments (work element 4.1.3)
Define design sedigraphs and PSD	Cost unknown	Need to coordinate with SLC and SLCo to define design storm hydrographs and obtain available storm sediment data.	
Model Sediment Transport			Sediment characterization (work element 4.3.1)
Compare measured critical shear stresses with HEC-RAS predicted shear	$3,000	Use existing steady state HEC-RAS model	
Use HEC-RAS to predict storm bed erosion and deposition	$20,000 - $25,000	Dynamic HEC-RAS model development and calibration.	
Measure SOD at Depth	Cost unknown	Work likely conducted by U of U.	

Table 6. Cost Estimate Summary

Work Element	**Estimated Cost**	**Cost Assumptions and Uncertainties**	**Contingent on….**
Review Dredging Management	$8,000–$12,000		Sediment transport model (work element 4.3.2) Sediment characterization (work element 4.3.1) Coordination with Salt Lake County and Salt Lake City

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