# USING FULL FACTORIAL ANALYSIS TO ENHANCE WATER QUALITY MONITORING PROGRAMS

William S. Gonwa, P.E., Ph.D., Harris L. Byers, Brandon J. Koltz
Symbiont
6737 West Washington Street, Suite 3440
West Allis, Wisconsin 53214

## ABSTRACT

Statisticians use a group of techniques collectively called “Design of Experiments” when designing a sampling program. A formal experimental design can multiply the information gained from a sampling program many times over an informal design. Full Factorial Regression Analysis is one such technique particularly useful for designing stream or river sampling programs.

Full Factorial Regression Analysis collects all sampling data in n-orthogonal dimensions at two or more levels in each dimension. For example, upriver and downriver from a potential contaminant source could form one of the dimensions, collected at two levels. Wet weather and dry weather could form another dimension, also at two levels. Collecting data in orthogonal patterns allows sample to be used in multiple paired comparisons and maximizes the ability to determine the causes of data variability. In addition, Full Factorial Regression Analysis permits assessment of factor interaction.

This paper provides a background on the Full Factorial Regression Analysis technique used to design a water quality sampling program and analyze the data. It discusses the use of regression analysis to process data and overcome the problem of missing samples. Lastly, it highlights two sampling programs designed and analyzed with Full Factorial Analysis. The two programs, one conducted on the Mississippi River by the City of Rock Island, Illinois and the other conducted on the Illinois River by the City of Peoria, Illinois were designed to document the effects of combined sewer overflows on water quality in receiving waters with multiple pollution sources.

## KEYWORDS

Full factorial analysis, design of experiments, water quality sampling, statistical analysis, Mississippi River, Illinois River, City of Rock Island, City of Peoria, combined sewer overflows

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## INTRODUCTION TO FULL FACTORIAL REGRESSION ANALYSIS

Limitations exist on the use of common parametric statistical methods to analyze water quality data collected to characterize river water quality. Often, the collection of a large number of samples needed to characterize average conditions is impractical due to cost and schedule limitations. If samples are collected over a long period of time, there are uncontrollable factors such as changes in river flow rate, temperature, and multiple potential sources may be expressed in the data. The elevated variance caused by the uncontrollable factors makes it difficult to draw conclusions with regards to changes in water quality with any acceptable degree of statistical confidence.

Several statistical models have been developed for situations where conclusions must be drawn from datasets with relatively small sample sizes subject to numerous factors. One that has proven useful in river water quality studies is called full factorial analysis (FFA) modeling. FFA models can be used to estimate the magnitude of change in water quality due to change in an effect (influencing factor). Furthermore, the FFA models can determine if the change is statistically significant. An effect is any independent variable of interest in the water quality study that may influence water quality. An example of an effect is sample **depth** (ex. shallow or deep). Another example of an effect that may influence water quality is **location** with respect to the shoreline (ex. near shore, center of channel, or far shore). An additional benefit of FFA modeling is that it can quantify the interactions between effects. Interactions are cross-products that occur when the magnitude of change in water quality from one effect depends on the level of another effect.

Often, missing samples or slight departures from orthogonality occur during a sampling program, no matter how rigorously the sampling program is planned. When this occurs or if an uneven number of replicate samples are collected, the analysis becomes unbalanced.

Regression analysis provides a useful tool for assessing the magnitude of effects. When regression analysis is applied to a FFA model, it is called full factorial regression analysis (FFRA). Many off-the-shelf statistical packages provide this capability. For any situation that exceeds a two-level, completely balanced design, the data analyst is advised to use FFRA.

Monitoring data analyzed with FFRA models must be collected in orthogonal patterns. In its simplest form, a two-level FFRA model can be envisioned as a n-dimensional box. Each dimension of the box represents an effect. Samples are collected at every vertex of the box; therefore, the number of samples required for an analysis equals $2^n$.

Samples may also be collected at intermediate points along one or more edges of the box. In the example of the depth effect mentioned above, there were two levels (shallow and deep). In the example of location with respect to shoreline, there were three levels (near shore, center of channel, and far shore). For a FFRA model with two effects, one with

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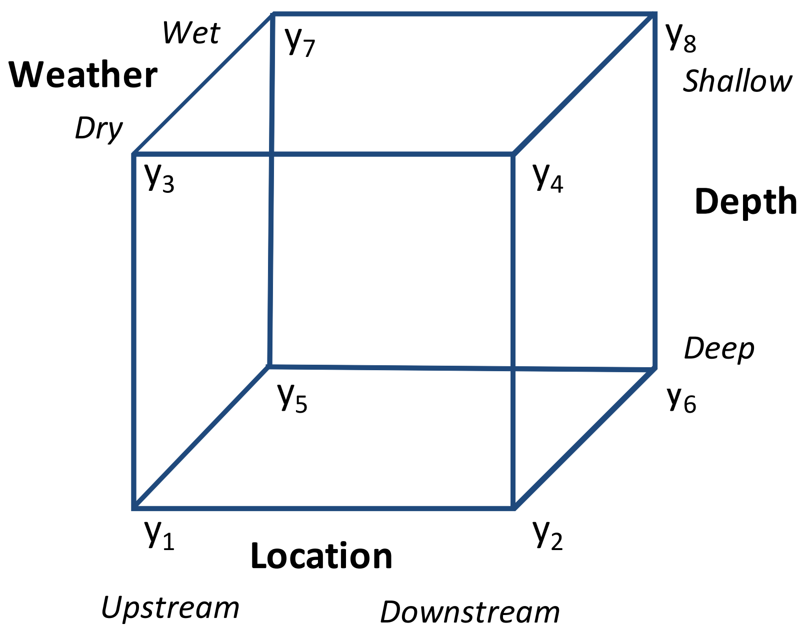
two levels and the other with three levels, the two-dimensional box has 2 x 3 = 6 locations where samples must be collected.

Each orthogonal dimension represents an effect that varies independently of all other effects. The FFRA model should not have effects that are obviously interrelated. An example of two interrelated effects is time and distance when tracking a plume resulting from of an instantaneous introduction of dye introduced into a river. Since time increases as the current moves the plume of dye downstream, the two independent variables cannot be considered orthogonal because they are interrelated.

The FFRA model derives its strength in analyzing water quality data through its ability to utilize each sample in multiple paired comparisons. Take, for example, a three-dimensional box with two level in each dimension, as illustrated in Figure 1. The first dimension is **Depth** and describes where the sample was collected in the water column (shallow or deep). The second dimension is **Weather** which represents whether or not local storm water runoff and combined sewer overflow (CSO) discharge was occurring when samples were collected (wet or dry). The third dimension is **Location** and denotes if samples were collected upstream or downstream of storm water and CSO outfalls (up or down). The value, $y_i$, at each vertex of the box represents a water quality sample collected under a specific set of effects. For example, $y_8$ denotes a shallow water quality sample collected during wet weather, downstream of the outfalls. Likewise, $y_1$ denotes a deep water quality sample collected during dry weather, upstream of the outfalls.

**Figure 1 – $2^3$ Full Factorial Regression Analysis Model**




The average effect caused by a change in location, depth and weather are given by the following formulas:

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$$\text{Average Location Effect} = \frac{(y_2 - y_1) + (y_4 - y_3) + (y_6 - y_5) + (y_8 - y_7)}{4}$$

$$\text{Average Weather Effect} = \frac{(y_5 - y_1) + (y_6 - y_2) + (y_7 - y_3) + (y_8 - y_4)}{4}$$

$$\text{Average Depth Effect} = \frac{(y_3 - y_1) + (y_4 - y_2) + (y_7 - y_5) + (y_8 - y_6)}{4}$$

As these equations show, eight samples result in a total of 12 paired comparisons with each effect quantified as an average of four paired comparisons. Collected in a haphazard manner, collecting the same amount of information would require 24 samples. The systematic multiplication of the information provided by full factorial analysis gives the method its power and its advantage in analyzing water quality data sets like the two case studies presented in this manuscript.

In addition to quantifying the main effects, FFRA allows assessment of interactions between effects. For example, one might wonder if a location effect is stronger or weaker, depending upon depth. The interaction effect is quantified by subtracting the average location effect at deep depth from the average location effect at shallow depth. By convention, the difference is divided by two to obtain the depth x location interaction effect

$$\text{Shallow Depth Location Effect} = \frac{(y_4 - y_3) + (y_8 - y_7)}{2}$$

$$\text{Deep Depth Location Effect} = \frac{(y_2 - y_1) + (y_6 - y_5)}{2}$$

$$\text{Depth x Location Interaction Effect} = \frac{(y_4 - y_3) + (y_8 - y_7) - (y_2 - y_1) - (y_6 - y_5)}{4}$$

Similarly the Depth x Weather and Location x Weather interaction effects can be calculated.

For more information on full factorial analysis or FFRA, the reader is encouraged to consult texts such as *Statistics for Environmental Engineers* by Berthouex and Brown (2002), a particularly useful reference for the authors in preparing this description.

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## SAMPLING PROGRAM DESIGN

Designing a sampling program where the data will be analyzed with FFRA requires careful planning to ensure that your sampling program expenditures are well spent. Several of the key steps in designing a sampling program are outlined below.

### Determine the Questions You Wish to Answer

What questions do you need to answer with your sampling program? Do you want to know if CSOs degrade water quality? Do you want to know if water quality impacts are confined to the shoreline or if they spread horizontally across the entire river channel? Well posed questions provide the clarity and guidance an investigator needs to determine the appropriate effects to test, design an adequate sampling protocol, and develop an appropriate list of constituents for analysis. A well defined set of questions will narrow the focus of the project to a defined set of goals and thereby restrict the number of tangential analyses, which will thereby save money.

### Identify Effects and Levels

Each effect, whether categorical or continuous, should relate to questions you seek to answer. Only investigate effects that directly relate to specific programmatic questions and have the potential to be significant based on prior studies.

Categorical levels should be clearly distinct and have a clear meaning when presenting the data. Examples of effects with two levels include **Location** (upstream and downstream of a potential pollution source), **Season** (during recreation season and outside of recreations season), and **Position** (within a swimming area and outside the swimming area). An example of an effect with three levels is **Channel Position** (near shore, main channel, and far shore). Avoid levels with indistinct physical meanings as much as possible.

FFRA can also use continuous variables. Water temperature is one example of a continuous variable. When defining the levels of a continuous variable, at a minimum select levels at the extreme of the range of variation of the effect. Optionally, add intermediate points to create three or more levels.

### Plan to Quantify Variance

If the natural variability of a water quality constituent within a waterway is characterized, the statistical significance of observed changes can be evaluated. Quantifying variance requires collecting replicate samples under nominally equivalent conditions. Performing two sampling rounds for each effect and level at different times is one of the most rigorous methods of characterizing the variance. This approach virtually doubles the cost of sampling and analysis. A less costly approach involves taking a series of replicate samples at one or two locations in the study area, with all samples taken under nominally

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equivalent conditions. For example, samples could be collected at one location at 4-hour intervals over a 24 hour period during dry weather, steady-state conditions.

Collecting replicate samples to characterize natural variability should not be confused with collecting field duplicates in the same location at the same time to test the accuracy of the laboratory procedures. Those are separate and necessary samples.

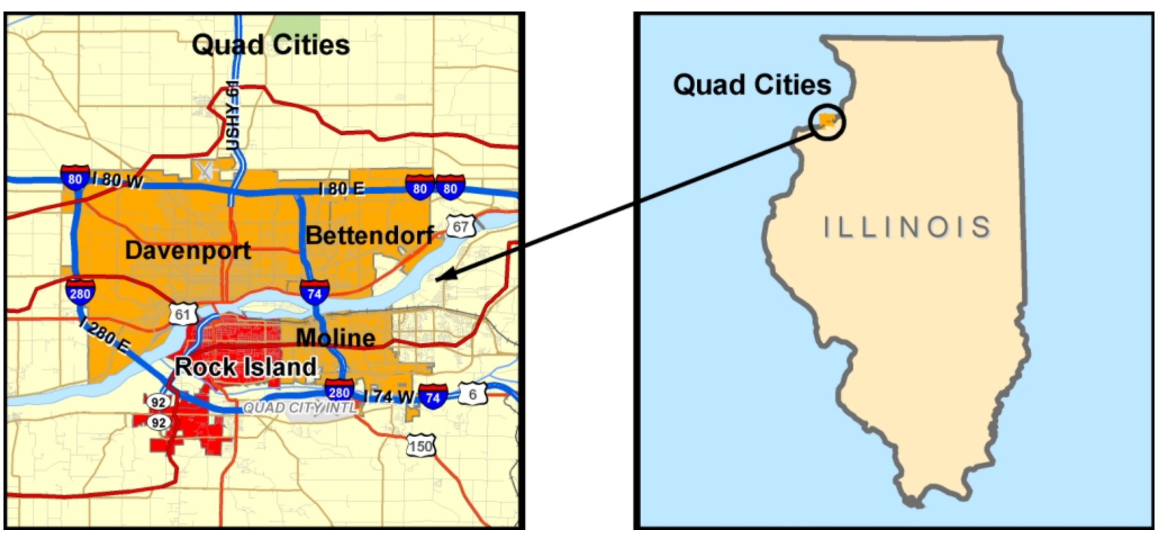
### Plan to Collect Samples in a Random Order

The principles of good sampling design require randomized sample collection. With studies in rivers, it is very tempting to always collect samples in the same order (upstream to downstream or vice versa) to save time. Avoid the temptation to do this as it could introduce systematic error into the sampling program. Some statistical packages have features to assist you in creating a randomized design for your experiment.

## CASE STUDY – MISSISSIPPI RIVER AT THE CITY OF ROCK ISLAND

The case study of the Mississippi River at the City of Rock Island, Illinois was first reported in Koltz et al. (2006). Rock Island is located in western Illinois at the confluence of the Rock River with the Mississippi River. Rock Island is one of ten contiguous communities comprising the "Quad Cities," a metropolitan area of about 350,000 people. This is the largest metropolitan area on the Mississippi River between the Minneapolis/St. Paul, Minnesota area and St. Louis, Missouri. Rock Island is the most downstream community of this metropolitan area on the Illinois side of the river with a population of approximately 45,500 people. The location of Rock Island is illustrated on Figure 2.

**Figure 2 – Location Map**




(Koltz et al., 2006)

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Rock Island is served by combined sewers, partially separated sewers, and separate sanitary and storm sewers. As part of its CSO Long Term Control Plan (LTCP) efforts, the City was required to document existing water quality and assess CSO impacts to the receiving waters. Accurate definition of CSO impacts to the receiving waters was found to be difficult, given the difference between river flow and CSO discharge volume, the fact that available monitoring data was not specific to wet weather impacts, and sample locations were not established to evaluate CSO impacts. A monitoring program was designed by Symbiont to fill data gaps with respect to CSO discharge under different river flow conditions.

The City of Rock Island discharges CSOs in two general locations along the Mississippi River as illustrated in Figure 3. One location is in the downtown area where four permitted outfalls discharge. The City's LTCP intends to eliminate these outfalls. The other location is farther downstream at the Mill Street Wastewater Treatment Plant, but still upstream of the mouth of the Rock River. At this location, one outfall to the river discharges a combination of fully treated wastewater treatment plant effluent, CSO discharge, and storm sewer discharge. The City of Rock Island intends to add CSO storage and treatment at this location.

Key questions this investigation sought to answer about water quality in the Mississippi River using FFRA modeling were:

- Does water quality significantly degrade or change from upstream to downstream of a CSO discharge location, the wastewater treatment plant discharge, and the Rock River?
- Are there significant differences in water quality between the Illinois shore, the main navigation channel, and the Iowa shore?
- Does river stage/flow rate make any difference when assessing water quality?
- How do water quality impacts differ between wet weather (when City of Rock Island CSO and storm sewer discharges occur) and dry weather?

A monitoring program with 12 sampling locations was developed to answer these questions. Figure 3 presents a schematic of the sampling locations. Sampling rounds took place during high stage – wet weather, high stage – dry weather, low stage – wet weather, and low stage – dry weather. Samples were analyzed for enteric bacteria , total suspended solids, biochemical oxygen demand, and a number of other parameters.

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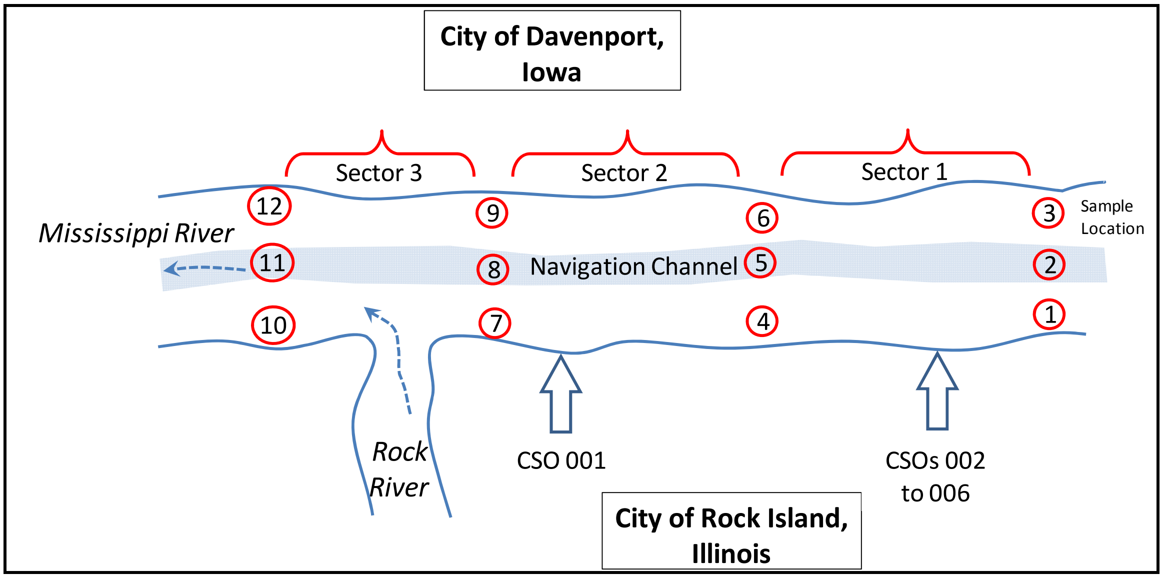
**Figure 3 – City of Rock Island Sampling Schematic**




A 5-factor (3x2x2x3x2) FFRA model was created to analyze the surface water quality data taken on the Mississippi River for each constituent. In the 5-factor model, it is assumed that any particular water quality sample receives influence from a combination of each of the five factors listed below:

1. **River Sector** (1, 2, or 3)
2. **Impact Source** (upstream or downstream of a potential pollution source)
3. **CSO Occurrence** at CSO 001 and CSO 005 (Yes–Occurring; No–Not occurring)
4. **Transect** (left, center, or right side of Mississippi River channel – facing downstream)
5. **River Stage** of the Mississippi River (high or low)

Figure 4 illustrates the set-up of the FFRA model. The FFRA model has 72 sampling points. In actuality, there were only 48 sampling points. Sampling locations 4 through 9 each were used twice, once as being upstream of a pollution source and once as being downstream of the source. Alternately, river sector and impact source could have been combined into one 4 level categorical effect to create a 4x2x3x2 FFRA model.

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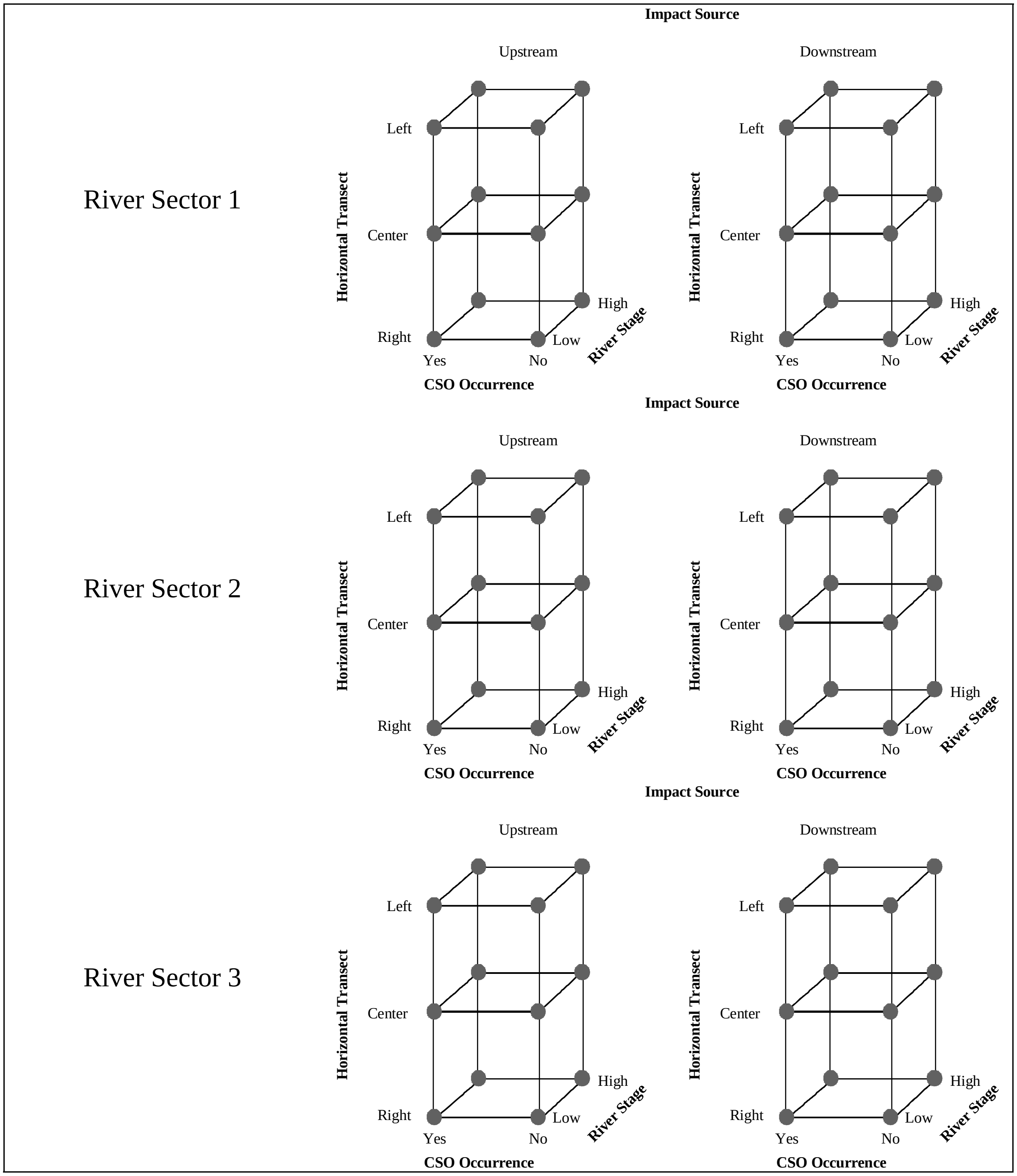
**Figure 4 – 5-Factor City of Rock Island FFRA Model**




Koltz et al., 2006

Koltz et al. (2006) described the findings of the FFRA modeling, which are summarized here. The full factorial regression analysis indicated that increases in *E. coli*, nitrite-nitrogen, nitrate-nitrogen, total suspended solids and total volatile solids occurred from upstream to downstream while CSOs were occurring. Concurrently, FFRA analysis of the data indicated that concentrations of chloride, ammonia, total Kjeldahl nitrogen and

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total dissolved solids decreased from upstream to downstream while CSOs were occurring. This suggests that both storm water runoff and CSO discharge affect water quality observed downstream under these conditions.

The investigation sought to describe mixing and determine the potential for lateral movement of CSO impacted water across the Mississippi River. The FFRA of the data noted water quality differences between the Iowa near shore sample locations, the navigational channel locations, and the Illinois near shore samples. Water quality was found to be better in the navigational channel compared to flow along either shore. The near shore flows were found to differ from each other as well. For instance total suspended solids, volatile suspended solids, nitrate-nitrogen and fecal coliform concentrations were found to be greater along the Iowa shore. *E. coli*, total phosphorus, total Kjeldahl nitrogen, nitrite, ammonia and chloride had greater concentrations along the Illinois shore. This finding, coupled with subsequent dye studies to define mixing along the south shore downstream from Outfall 001, confirmed that CSO inputs from Rock Island are limited to a relatively small area downstream from the outfall and parallel to the shoreline. Flow in the navigational channel serves as a significant barrier to lateral pollutant transport.

Based on the FFRA model it can be concluded that bacteria discharged with CSO from Rock Island are unlikely to migrate to the Iowa side of the river in the metro area. Of equal importance, non-disinfected effluent discharged across the river from the Davenport, Iowa treatment plant is unlikely to affect bacteria levels on the Illinois side of the river at Rock Island. The most important result of these findings is that CSO control measures may only affect water quality in a limited portion of the river.

Another critical finding from FFRA modeling was that geometric mean concentration of enteric bacteria as measured by fecal coliform did not vary with river stage when a CSO was occuring. Furthermore, fecal coliform concentrations during wet weather events were greater when a CSO was not occuring. CSO control in and of itself may therefore not completely ensure conformance to water quality standards for fecal coliform.

## CASE STUDY – ILLINOIS RIVER AT PEORIA, ILLINOIS

The Peoria-Pekin metropolitan area has an estimated population of 351,000. Of this total, approximately 113,000 live within the City of Peoria. Figure 5 shows the location of Peoria. Most of the communities in the metropolitan area front the Illinois River.

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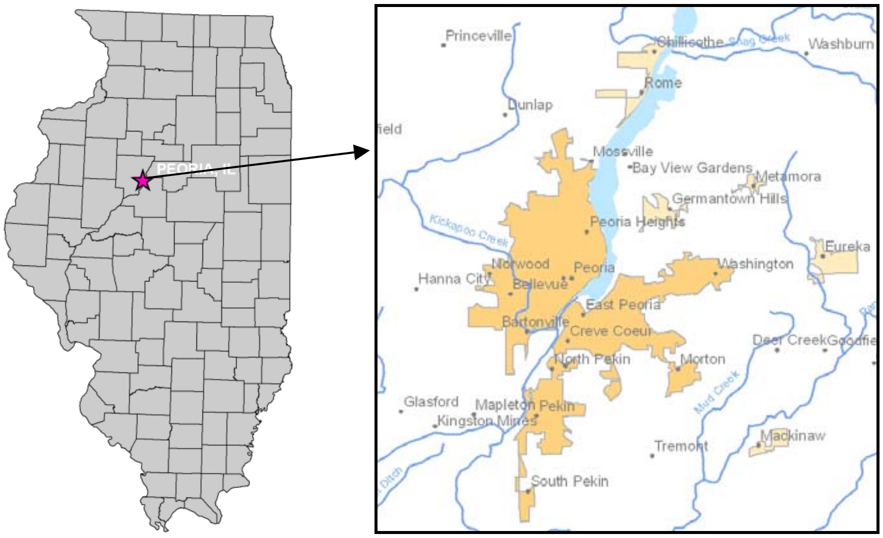
**Figure 5 – Peoria, Illinois**




The City of Peoria is served by combined sewers, partially separated sewers, and separate sanitary and storm sewers. The City of Peoria discharges CSO at 16 permitted outfalls along the Illinois River. Discharge through three of these outfalls pass through swirl concentrators designed to remove trash and floating debris. The remaining outfalls receive no treatment. Most of the CSO discharge to the Illinois River occurs northeast and southwest of the downtown area. Partial separation efforts conducted in the 1980s have nearly eliminated overflows from the downtown CSOs. The Greater Peoria Sanitary District wastewater treatment plant and its discharge are located at the downstream limit of the City of Peoria's combined sewer service area. This treatment plant receives flow from the City of Peoria and several other surrounding communities.

The water level in the Illinois River is maintained at a depth sufficient for commercial navigation with locks and dams, supplemented by dredging. The area potentially impacted by City of Peoria CSOs extends from the south end of Peoria Lake downstream to the Peoria Lock and Dam as presented in Figure 6.

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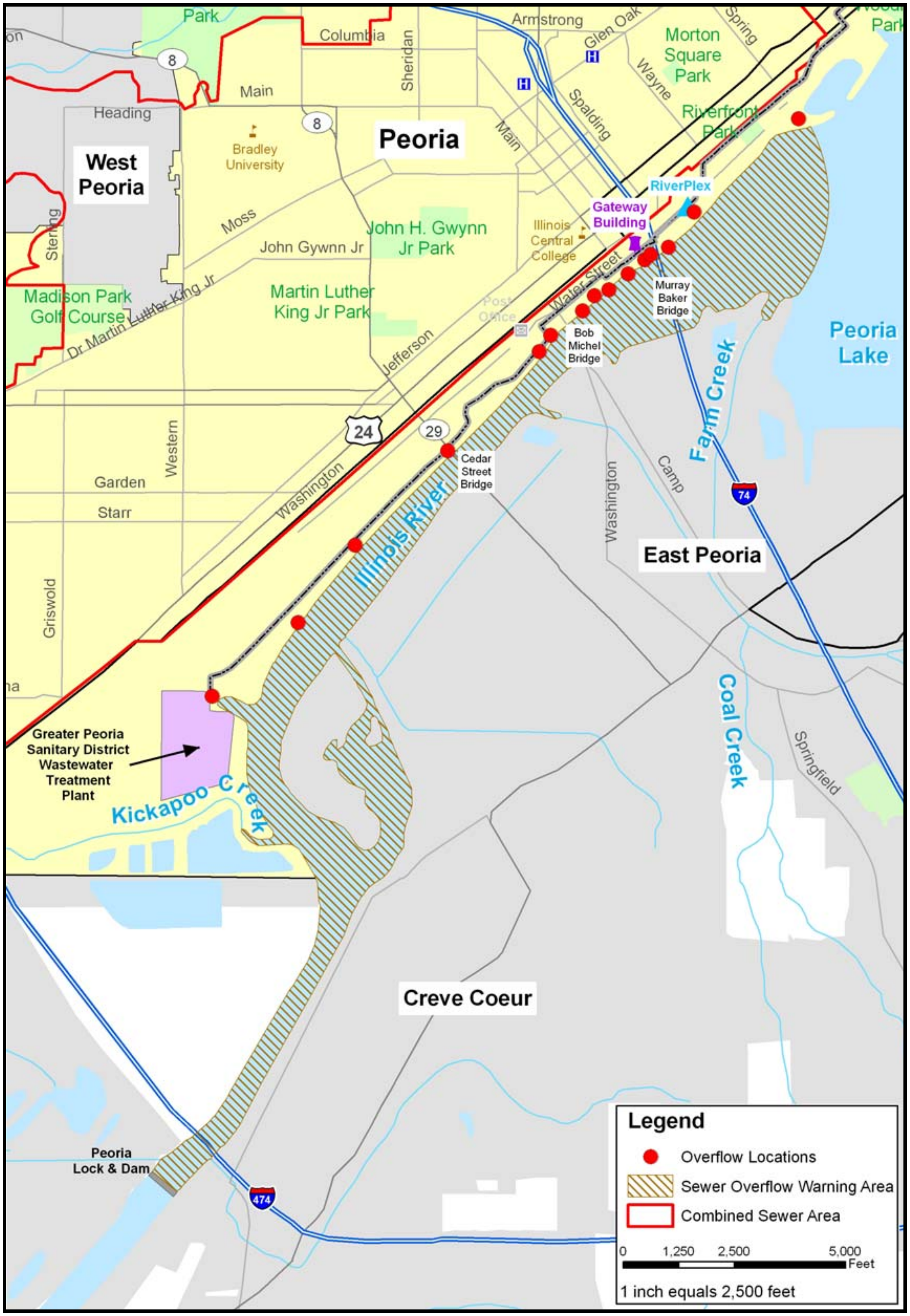
## Figure 6 –CSO Warning Areas in Peoria, Illinois

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As part of ongoing CSO LTCP efforts, a team consisting of personnel from MACTEC and Symbiont conducted a water quality study of the Illinois River to evaluate CSO impacts. This study was designed around a planned FFRA analysis of the data to answer the following key questions about water quality impacts to the Illinois River:

- Does water quality degrade in the Illinois River during a CSO event
  - Generally?
  - in the CSO Warning Area?
  - upstream of the CSO Warning Area?
  - as it flows through the City?
- Is water quality during CSO/wet weather worse when the river is at low stage compared to high stage?
- Is the water quality worse along the City of Peoria shoreline during CSO/wet weather compared to the navigation channel or far shore?
- Is water quality worse or better
  - while a CSO is occurring compared to before the event?
  - after the river is flushed compared to during a CSO event?
  - after the river is flushed compared to before a CSO event?
- Does the water quality degrade as it flows through the City during baseflow?
- Is the water quality homogeneous across the river channel during baseflow?
- Is baseflow water quality affected by river stage?

A monitoring program with 20 sampling locations was developed to answer these questions. Figure 7 presents a schematic of the sampling locations. Sampling rounds took place during normal pool – wet weather, above normal pool – wet weather, normal pool – dry weather, above normal pool – dry weather. Samples were analyzed for bacterial contamination, total suspended solids, biochemical oxygen demand, and a number of other parameters.

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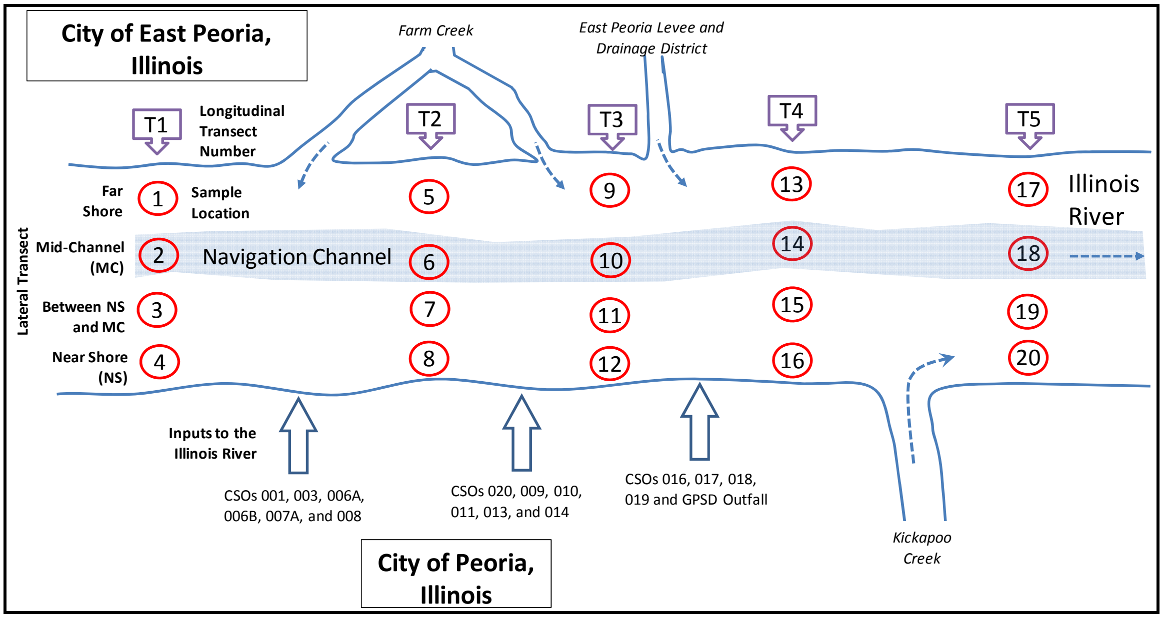
**Figure 7 – City of Peoria Sampling Schematic**




Due to the varying nature of the questions this investigation sought to answer, several FFRA models were developed. The models were partially redundant in nature but were tailored in each case to best address each question. Questions to be answered by each model, FFRA model effects, and effect levels are presented in Table 1.

**Table 1 – Description of Illinois River FFRA Model Effects and Effect Levels**

| Question | Model Effects | Effect Levels |
|---|---|---|
| Does water quality in the Illinois River generally degrade during a CSO event?<br><br>Is water quality during CSO/wet weather worse when the river is at low stage compared to high stage? | Longitudinal Transect Number | T1, T2, T3, T4, T5 |
| | Lateral Transect | Near Shore, Between Near Shore and Mid Channel, Mid Channel, Far Shore |
| | Weather | Wet Weather, Dry Weather |
| | River Stage | Normal Pool, Above Normal Pool |
| Does water quality degrade in the CSO Warning Area during a CSO event? | Weather | Wet Weather, Dry Weather |
| | Lateral Transect | Near Shore, Between Near Shore and Mid Channel, Mid Channel, Far Shore |
| | River Stage | Normal Pool, Above Normal Pool |

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**Table 1 cont. – Description of Illinois River FFRA Model Effects and Effect Levels**

| Question | Model Effects | Effect Levels |
|---|---|---|
| Does water quality degrade upstream of the CSO Warning Area during a CSO event? | Weather | Wet Weather, Dry Weather |
| | Lateral Transect | Near Shore, Between Near Shore and Mid Channel, Mid Channel, Far Shore |
| | River Stage | Normal Pool, Above Normal Pool |
| Does water quality degrade in the Illinois River during a CSO event as it flows through the City of Peoria?<br><br>Is the water quality worse along the City of Peoria shoreline during CSO/wet weather compared to the navigation channel or far shore?<br><br>Is water quality worse or better<br>• while a CSO is occurring compared to before the event?<br>• after the river is flushed compared to during a CSO event?<br>• after the river is flushed compared to before a CSO event? | Time | Pre-CSO, During CSO, River Flushed |
| | General Longitudinal Location | Upstream, CSO Warning Area |
| | River Stage | Normal Pool, Above Normal Pool |
| | General Lateral Position | Near Shore, River |
| Does the water quality degrade as it flows through the City during baseflow?<br><br>Is the water quality homogeneous across the river channel during baseflow?<br><br>Is baseflow water quality affected by river stage? | Longitudinal Transect Number | T1, T2, T3, T4, T5 |
| | Lateral Transect | Near Shore, Between Near Shore and Mid Channel, Mid Channel, Far Shore |
| | River Stage | Normal Pool, Above Normal Pool |

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Being able to accurately describe natural variation in a river system is paramount in conducting water quality investigations. In the Rock Island study discussed in this manuscript, natural variability of water quality constituents was not evaluated; thus the FFRA model used the model variance in the regression, which made the regression slightly less powerful because the model variance estimate includes both natural sample variability and model error. In the Peoria water quality study, natural variance in water quality parameters was evaluated through replicate sampling to strengthen the validity of the models. Natural variability was calculated using two strategies. The first strategy calculated the natural variability in water quality during CSO events and involved replicate sampling of the Illinois River while CSOs were actively discharging. The second strategy calculated the natural variability in water quality during baseflow conditions and involved sampling water quality parameters every 4 hours for 24 hours at the upstream and downstream limits of the study area.

The FFRA modeling of the sampling results succeeded in answering the posed questions. Key findings about the Illinois River during this study are:

- Water quality degrades in the Illinois River during a CSO event, in both the downstream areas impacted by Peoria CSOs and the upstream area not impacted by Peoria CSOs.
- During dry and wet weather, water quality was worse in the CSO Warning Area (Transects 2 to 5) as compared to upstream (Transect 1).
- Water quality was worse during a CSO event when the Illinois River was at low stage compared to high stage.
- Enteric bacteria concentrations were greater in the sampling locations closest to the Peoria shoreline (as compared to the rest of the Illinois River) during both dry and wet weather.
- Upstream sources appeared to continue to contribute elevated bacteria concentrations to the river for at least 24 hours following a storm event.
- Enteric bacteria concentrations indicate significant impacts to the Illinois River during baseflow (low river stage) during wet and dry weather.

By calculating the natural variation in constituent concentrations, it was noted that the high natural variability of the fecal coliform concentrations in replicate samples tends to obscure trends and patterns; therefore, fecal coliform may not be as useful an indicator of water quality trends as *E. coli*, which exhibited substantially less natural variability.

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## LESSONS LEARNED

Based on the two case studies presented in this manuscript, the authors have been able to document several lessons learned in applying FFRA models to conduct water quality assessments:

- In general, FFRA modeling can be used successfully to characterize water quality impacts in a river system, as long as careful planning takes place prior to sample collection.
- Before embarking on a project, develop specific questions to be answered with the data collected in the study. Doing so limits the amount of tangential analyses that are costly and may not add to the overall objectives of the study.
- Develop a protocol to characterize natural variability in water quality parameters to strengthen the reliability of FFRA conclusions.
- Some questions cannot be answered by a single FFRA model; therefore, as necessary, tailor each model to answer a specific question.

## ACKNOWLEDGEMENTS

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