DESIGN OF A WATER QUALITY INFORMATION SYSTEM FOR SOURCE WATER ASSESSMENT: A DENVER WATER CASE STUDY, DENVER, COLORADO

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Colorado Water
Resources Research Institute

Completion Report No. 197

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ABSTRACT

DESIGN OF AWATER QUALITY IINFORMATION SYSTEM FOR SOURCE WATER ASSESSMENT: A DENVER WATER CASE STUDY

The questions water quality information systems are being called upon to answer are changing as the management of water quality shifts from a historically point source control framework to investigation of non point sources of pollution. A specific example is that of large Public Water Systems (PWS), providers of drinking water to the public within larger municipalities, who have managed the quality of the source water, from which they draw their supplies, primarily at the intake to the treatment system. In the case of contamination, the potential of finding a new source of supply is rare for large PWSs and thus new emphasis is placed on protection of current supplies to diminish the risk of contamination. This idea of moving farther up into the watershed for water quality management of drinking water supplies is presented by the U.S. Environmental Protection Agency (USEPA) in the Source Water Assessment and Protection (SWAP) program. This thesis proposes a process by which a large PWS can incorporate existing knowledge concerning water quality monitoring into a practical application for production of usable, defensible information used in the management of water quality.

The source water quality monitoring system for Denver Water, a large PWS serving the City and County of Denver, Colorado and surrounding areas, is reviewed within this work. The review is presented as an updated water quality monitoring design for Denver Water's entire source area. The emphasis of the design is placed on the need to connect the information needs of management, in this case Denver Water, with the feasible products of water quality monitoring.

Analysis was conducted to determine reasonable sampling frequencies for estimation of mean concentrations, trends, and pollutant loads for physical and chemical water quality parameters identified. Additionally, 48 sampling sites were selected for the source area of approximately 2.5 million acres. In the end, Denver Water is presented a functional monitoring system which enables information production to meet needs for management of the vast area from where they draw drinking water.

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CHAPTER 1.0 INTRODUCTION

The 1996 amendments to the Safe Drinking Water Act (SDWA) introduced information based programs targeted towards the quality of source water. Specifically, the consumer confidence reporting (CCR) and source water assessment program (SWAP) both contained mandates to produce information on the source area from which purveyors obtain their water for consumption. This step to identify the condition of drinking water further up in the watersheds is logical from a quality standpoint as problems or potential problems can be identified before they are typically encountered just prior to treatment. While the benefit of these programs is evident, there are problems encountered by the agencies ultimately responsible for producing the information required to drive their implementation. The problem facing one such agency, the organizations providing water for public consumption, is incorporating the additional informational needs of the programs into their current water quality monitoring information systems. In particular, with regards to the SWAP, the guidance document produced by the U.S. Environmental Protection Agency (USEPA) implies the creation of a source water protection program (SWPP) through the process of completing the SWAP. The SWPP is explicitly defined as having source water quality monitoring as a component. The public water systems (PWS), those organizations providing water for public consumption, affected by a SWPP would need an effective method for combining the information needs of the SWPP with the legal and operational needs they currently address. The method for doing this is not provided by the USEPA guidance document for the SWAP. This thesis, through the use of a case study, exhibits how a large PWS can effectively implement a water quality information system to meet the regulatory requirements of programs presented in the SDWA amendments of 1996 while also providing information for legal and operational needs.

1.1 SCOPE

The results of a water quality information system design completed for Denver Water are presented in this thesis. Due to time constraints the design is not all encompassing, but emphasis was placed on developing the solid framework needed for a successful water quality information system. In particular, this document includes the formulation and documentation of Denver Water's information goals, the data analysis procedures prescribed to Denver Water, and a monitoring network design specific to the Denver Water source area water quality. An additional goal of this work was to create a document to serve as a reference for other large water purveyors facing the same growing information demands Denver Water is experiencing. This thesis is considered to be such a reference by providing a practical approach to handling the effective gathering and production of information as shown in the Denver Water design.

1.2 BACKGROUND

The Denver Water Department, or Denver Water as it is known today, was formed in 1918 and from that time began planning and developing a water supply system to meet the needs of the citizens of Denver and the surrounding areas. Presently, Denver Water serves the City and County of Denver and about 40% of those who live in the suburbs. The present purpose of Denver Water is best summarized in its mission statement:

> "Denver Water will provide our customers with high quality water and excellent service through responsible and creative stewardship of the assets we manage. We will do this with a productive and diverse work force. We will actively participate in and be a responsible member of the water community."

The supply of water is presently obtained from an accumulated drainage area of 4,000 square miles (2.5 million acres) and a network of thirteen reservoirs. This vast amount of land covers eight counties of Colorado and is located on both sides of the Continental Divide. This source watershed region can be characterized as mostly mountainous, and almost all the water comes from snowmelt/runoff. A general depiction of Denver Water's watershed area is shown in Figure 1.1.

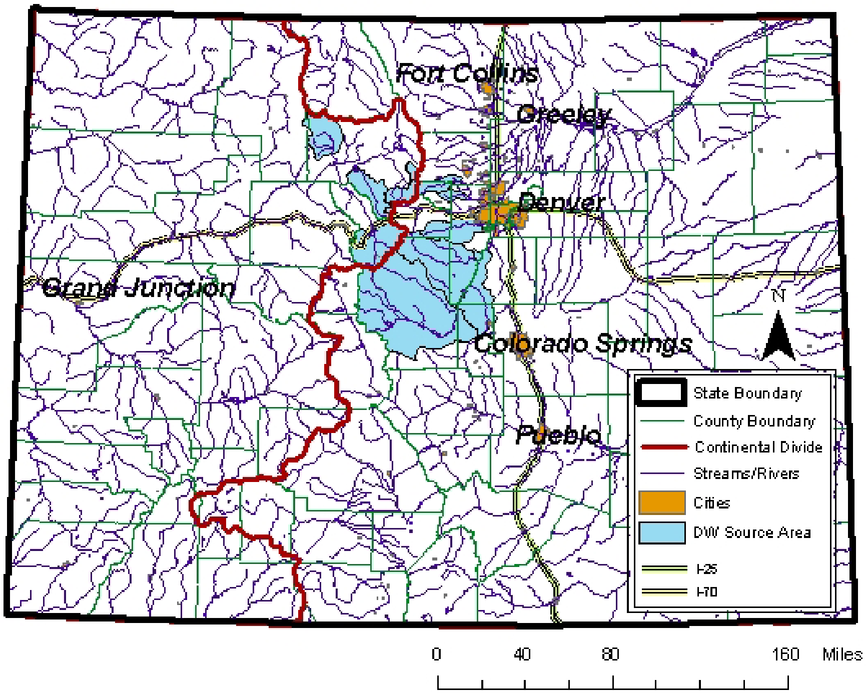


Figure 1.1: Location of the Denver Water source watershed area within the state of Colorado. Data sources : Denver Water: collection systems; CDPHE: continental divide and cities; USEPA: roads; GIS Data Depot: state boundary, county boundary, and hydrography.

Although the water quality is known to be good in the source watersheds, Denver Water has identified the need to better track status and trends in the quality of its source water. A water quality monitoring system has been developed to provide the detailed information Denver Water requires to better carry out the mission statement of providing high quality water through responsible and creative stewardship of the assets managed.

1.3 APPROACH

A complete monitoring system, based on the flow of information, is described by Ward et al. (1990) and summarized in Figure 1.2. The monitoring system serves as the means to describe water quality conditions in the environment and provide information needed to support responsible decision-making. As shown, the system can be viewed as consisting of two parts: (1) data generation, and (2) information generation.

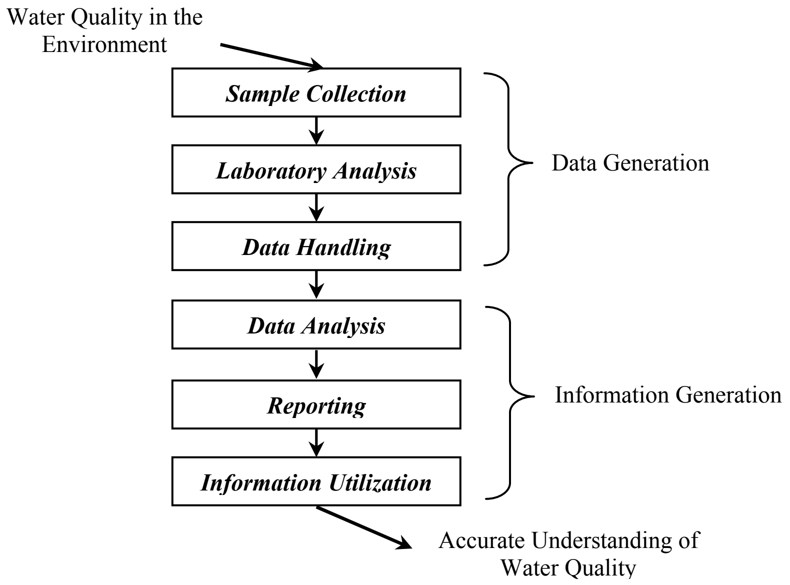


Figure 1.2: The definition of a complete water quality monitoring system by Ward et al. (1990).

Historically, emphasis has been placed on data generation with the production of information addressed on an "as needed" basis. While this information strategy met the needs of Denver Water in the past, there is a desire to be more proactive in supplying water quality information for the future.

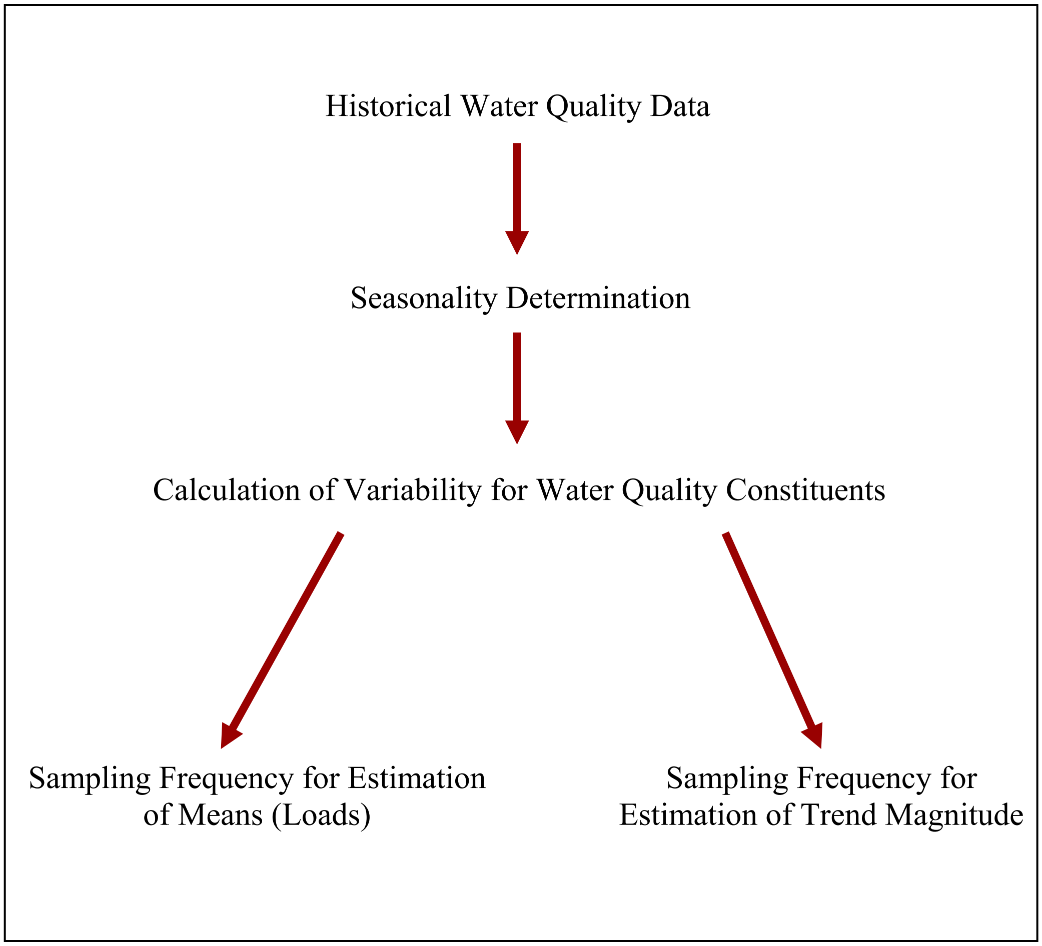
To be more supportive of management decision-making, monitoring systems should be designed with an information product in mind rather than analyzing data as information needs arise. Such a design framework encompassing all components of a water quality monitoring system has evolved from experience of various professionals working in the field (Ward et al., 1990). The framework is listed below:

1) Define the surface water information needs of water utility management.
2) Define information that can be produced by monitoring.
3) Design monitoring network.
4) Document data collection procedures.
5) Document information generating and reporting procedures.

Within the context of this thesis, focus is placed on steps one through three above. First, the important connection between information needs and monitoring provides for the strong foundation supporting the information system operation. Then the monitoring system is designed to produce the required information for management decision-making.

The information needs of management are a composite of many topics including operational, planning, legal, public relations, and regulatory. The documented needs were drawn directly from discussions with Denver Water staff in addition to referencing applicable regulatory mandates, both state and federal. Identifying the level of information that monitoring could produce was an important step in developing an accurate account of what the information system would output. This step involved comparing monitoring capabilities with the identified information needs. The information needs found to be supplied through monitoring were documented for reference. In defining the ability of monitoring to produce information, the data methods to be used were selected. Identifying beforehand how the data will be analyzed allows for full knowledge of what information is to be produced and limits interpretation of the results. The design of the monitoring network entails determining the mechanics of the monitoring to be completed. Specifically, selecting monitoring sites, monitoring frequencies, and water quality parameters to monitor are included in the network design. The process for choosing monitoring sites and constituents to monitor was qualitative and involved subjective decisions based on known conditions. This was completed based upon general consensus of the design team. Estimating monitoring frequency was completed in a more quantitative manner by incorporating statistical analysis of historical water quality data. As discussed later, the desired products from monitoring consist of estimates of central tendency, trends, and mass loads for water quality constituents within the Denver Water source watersheds. A monitoring frequency was estimated for each product, and the final results were compared to arrive at a single frequency for the whole monitoring system. Through the analysis process used to estimate monitoring frequency,the historical water quality data available for the study area was were partitioned into seasons, and variability was determined for each of these seasons. The variability of the water quality data was the input for equations used to estimate monitoring frequency. A general concept of the process used to estimate the information system monitoring frequency is shown in Figure 1.3.

Figure 1.3: Conceptual framework utilized in developing estimates for monitoring frequency of the Denver Water watersheds information system.



CHAPTER 2.0 MANAGEMENT NEEDS OF INFORMATION

A key step in the design of a water quality monitoring system is identification of the information desired. Collection of data with no formulated goal tends to create the "Data-rich, but Information-poor Syndrome" described by Ward et al. (1986). In the case of Denver Water, information needs were identified through informal discussions and a meeting with management. Additionally, some direction with respect to information needs was gained from referencing implications contained in laws.

Safe Drinking Water Act

Because Denver Water is a public water system (PWS, as defined by 1401(4)(A) in PL 104-182), it is regulated on a day-to-day basis by the SDWA. The 1996 amendments to the SDWA (PL 104-182) recognize that effective drinking water protection must be founded on government accountability and public understanding and support (USEPA 1997). As a result, PL 104-182 required two programs, the Consumer Confidence Reporting (CCR) and the Source Water Assessment Program (SWAP), designed to involve and inform the public. More specifically, these mandates contain implications, in addition to several requirements, for information pertaining to the quality of the source area from which a PWS draws raw water. The section of the 1996 amendments to the SDWA (PL 104-182) describing the CCR (1414(c)(4)(B)(ii)) reads: "[The reports shall contain] Information on the source of the water purveyed." As this is a requirement for each PWS, the issue of needed information arises. What is needed to fulfill the requirements of the law? Could this information serve a purpose to a PWS in addition to providing material for a CCR? Perhaps management could use this information in decision making related to operations.

Similarly, 1453(a)(2)(B) of the 1996 amendments to the SDWA (PL 104-182) describes an information driven program focused on the source of a drinking water supply.

> "Identify for contaminants regulated under this title for which monitoring is required under this title (or any unregulated contaminants selected by the state, in its discretion, which the state, for purposes of this subsection, has determined may present a threat to public health), to the extent practical, the origins within each delineated area of such contaminants to determine the susceptibility of the public water systems in the delineated area to such contaminants."

Again, an implicit need for information is highlighted, but this mandate differs from the CCR as state governments are ultimately responsible for implementation rather than individual PWSs. Legally, the PWS is exempt from involvement with this program, but reasoning detailed in the United States Environmental Protections Agency (USEPA) SWAP guidance suggests benefits for a PWS who partakes in the program. The statement from the SDWA amendments of 1996 (PL 104-182) describing the SWAP (1453(a)(1)) as "for the protection and benefit of the public water systems" was identified in the USEPA guidance (1997) as Congress' intent for the SWAP to be the initial phase of a source water protection (SWP) program. This SWP program is defined in the USEPA guidance as consisting of the following components:

- Delineating the source water protection area.
- Inventorying the significant potential sources of contamination.
- Understanding the susceptibility of the source waters of the PWS to contamination.
- Forming a team.
- Monitoring source water quality.
- Implementing management measures for sources of contamination.
- Contingency planning.

Therefore, the SWAPs are not considered to be a complete process in and of themselves, but rather the start of a continued SWP program of which source water quality monitoring is a critical part. The PWS is left to determine what type of monitoring is needed and how the resulting information relates to management decision-making.

Water Rights Considerations

Denver Water must acquire water supplies under Colorado's water law system, based on the prior appropriation doctrine. The complexities of this legal system will not be addressed in this report; however, examples are provided to illustrate the need for water quality informationWater Quality Information Goals

Denver Water intends to use the legal implications of the SDWA programs to formulate information needs of a source water quality monitoring system. The desired product of such a system is information that enables management to make decisions or become informed on source water issues. These issues are used in the formulation of information goals that guide development of the monitoring system. These goals include:

1) Evaluating source water quality and its impact on water treatment
2) Measuring nutrient loading
3) Evaluating the impact of development within watersheds
4) Satisfying due diligence relating to water law in Colorado
5) Evaluating water quality explaining irrigation/exchange impacts
6) Satisfying terms of the Colorado River Agreement

2.01 Source water quality: How it affects water treatment

It is recognized that both ground and surface waters are vulnerable to gradual degradation from natural sources and human activities and to acute contamination caused by incidents such as hazardous material spills or natural phenomena (e.g. Buffalo Creek flood). An expressed interest of Denver Water is to associate any degradation of the water quality with a possible need for change in water treatment. For a system avoiding filtration under the Surface Water Treatment Rule (SWTR, 40 CFR Part 141) the cost of degrading water quality is significant as major treatment works must be funded when degraded water quality levels are reached. Denver Water does not yet find itself in this situation, but is interested in identifying a relationship between the quality of the source water and the associated cost of treatment as does the SWTR. A benefit of such information is the ability to place importance on programs addressing sites where pollution is known to cause degradation (identification of these sites is yet another information need), if it is, in fact, cost effective. Also, with this information, further study could be conducted in optimization of costs associated with treating water, as described by the United States Forest Service (USFS, 2000).

2.02 Nutrient loading

The nutrients that are of the utmost concern for Denver Water's source area are nitrogen and phosphorous. Both are essential elements for the growth of algae and other aquatic organisms. Elevated nutrient levels in lakes/reservoirs contribute to the eutrophication process which is represented by increased productivity (growth of algae and other aquatic organisms). The increased production of algae and associated organic matter can negatively alter conditions in a lake/reservoir. Impacts include increased turbidity, raised levels of total organic carbon (TOC) which can lead to disinfection by-product formation, taste and odor problems, and depleted dissolved oxygen (DO) levels. These impacts can be both toxic and cause considerable secondary effects including difficulty in the treatment of water. The problem of excess nutrients in water bodies was recently recognized by the USEPA, resulting in proposed water quality nutrient criteria for specific areas of the country (66 FR 1671). These criteria are numerical values for both causative (e.g. nitrogen and phosphorous) and response (e.g. chlorophyll a) variables associated with the prevention and assessment of eutrophic conditions.

Denver Water operates a network of thirteen reservoirs for the storage, exchange, and treatment of water. The dynamics of nutrients entering, exiting, and residing in these reservoirs presents a potential source of contamination to raw water supply about which Denver Water desires to be informed. It is recognized that relatively simple control measures within drainage basins can be implemented to minimize nutrient loadings, and these actions are often much more economical than treating degraded water supplies (NRC 2000). The question of knowing whether control measures are needed, and ultimately successful, begs for information on water quality.

2.03 Development within watersheds

Increased population growth and development has brought people to locations within Denver Water's watersheds historically unaffected by humans. Figure 2.1 shows the population increase of counties from the geographic area that Denver Water utilizes as a source of supply. Overall, the population increase in the last 10 years within these counties is relatively high. More specifically, the three counties with the highest population increases in Figure 2.1 are among the counties with the highest population increases in Colorado (CDLA 2000). This flux of people is typically accompanied by a change in land use of the occupied area. Given land uses are known to impact water quality. For example, water sources located in forests are more than likely to be affected by logging, erosion, and timber management impacts on water quality (USFS 2000). A focus of Denver Water, considering the potential effects of rural growth, is identifying land use changes involving the increase of small waste management systems (e.g. septic tanks), increased infrastructure (e.g. roads, utilities), and commercial/industrial applications growth within the watersheds used as a source of drinking water. All of which create a potential source of contamination to water quality.

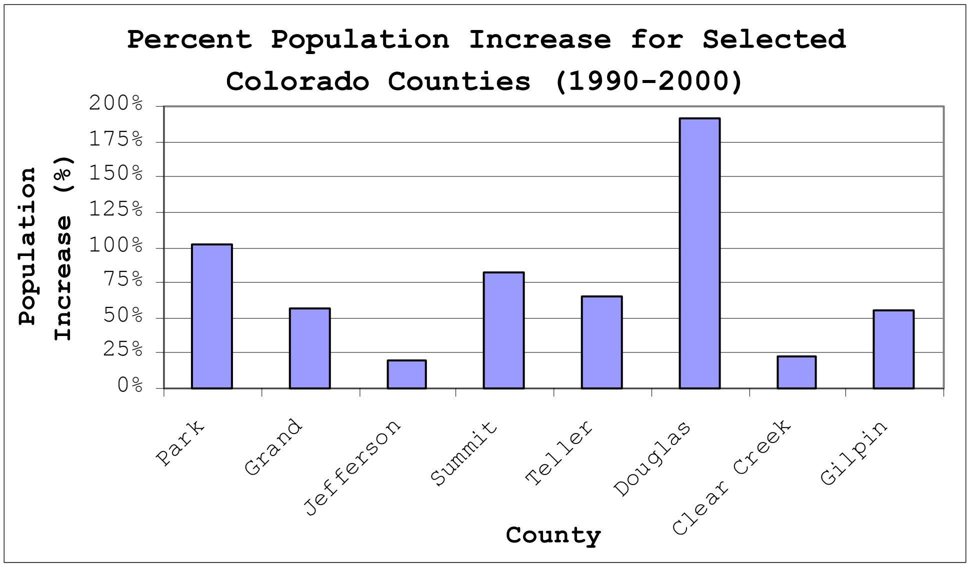


Figure 2.1: 1990-2000 population data for counties within Denver Water's source area (Colorado Department of Local Affairs 2000).

2.04 Reasonable diligence

With the existence of large-scale water supply projects in development, Denver Water may not be able to put appropriated water to beneficial use immediately. Therefore, assurance of the appropriation priority before initiation of such a project is provided by the doctrine of conditional rights under Colorado water law. This doctrine allows an appropriator to obtain a decree that relates back to an earlier time than the time when the acts required for appropriation would actually have been completed (Corbridge Jr., 1999). The holder of a conditional decree is required by law to exhibit reasonable diligence in applying the appropriation or to have the decree made absolute. This reasonable diligence is defined in the 1969 Water Right Determination and Administration Act (Id. 37-92-301(4)(b) and (c)):

> (b) The measure of reasonable diligence is the steady application of effort to complete the appropriation in a reasonably expedient and efficient manner under all the facts and circumstances. When a project or

> integrated system is comprised of several features, work on one feature of the project or system shall be considered in finding that reasonable diligence has been shown in the development of water rights for all features of the entire project or system.
>
> (c) Subject to the provisions of paragraph (b) of this subsection (4), neither current economic conditions beyond the control of the applicant which adversely affect the feasibility of perfecting a conditional water right nor the fact that one or more governmental permits or approvals have not been obtained shall be considered sufficient to deny a diligence applications, so long as other facts and circumstances which show diligence are present.

Such diligence is shown at select sites throughout Denver Water's source area by monitoring the quality of the water. While the monitoring fulfills the need of showing diligence it also provides data to be used in the production of information needed and meeting other monitoring goals.

2.05 Irrigation/exchange impacts

Denver Water is currently involved in litigation with the City of Thornton, Colorado, involving water rights on the South Platte River. This case is of particular interest because the influence of water quality is being used to argue the impacts of exchanging water rights. Historically, acknowledgement has been given to the connection between water quality and water quantity, but until recently the management of the two aspects of water have been treated separately by law. The court case is making this important connection in the legal realm. Denver Water is concerned that future opposition to water rights might take on a similar form, and therefore wants to produce information on the quality of water it exchanges and the subsequent impacts on irrigation for downstream users.

2.06 Colorado River Agreement

This need for monitoring is a direct result of legal mandates outlined in the findings of fact, conclusions of law, judgment and decree in the United States District Court for the District of Colorado concerning the Combined Consolidated Civil Case Nos. 2782, 5016, and 5017 and District Court, Water Division 5, State of Colorado Case No. 91CW252 also referred to as the "Colorado River Agreement." Denver Water, at times, is required to release water from its Dillon Reservoir facility to fill the downstream Green Mountain Reservoir that holds senior water rights. Denver Water arranged an augmentation-substitution plan where water would be released from Wolford Mountain Reservoir in place of Dillon Reservoir water. A similar appropriative rights exchange Wolford Mountain Reservoir water to be replaced with Dillon Reservoir water also exists. Users located downstream of both Green Mountain Reservoir and Wolford Mountain Reservoir opposed this action as stated in Paragraph 19 of the judgment.

> "The total dissolved solids ("TDS") of the water to be released from Wolford Mountain Reservoir for the substitution is expected to be greater than the TDS of the portion of the water which would have been released from Green Mountain Reservoir in the absence of the substitution. Certain of the Opposers have raised issues regarding the source of the substitution water during the irrigation period."

As a result, a stipulation was entered into by Denver Water and the "Opposers" which is described in Paragraph 19.1 of the judgment.

> "The River District [co-applicant with Denver Water] shall gather and provide on a periodic basis to such Opposers water quality data available regarding Wolford Mountain Reservoir and its releases. On a monthly basis, temperature, conductivity, and dissolved oxygen data will be provided. On an annual basis, total dissolved solids, major constituent ions, pH, temperature, dissolved oxygen, and other information as normally published by the United States Geological Survey (USGS) will be provided."

Similarly, the City of Grand Junction and Clifton Water District objected the action and subsequently entered into a similar stipulation described above.

Denver Water has the need for scientifically defensible information on the water quality leaving Wolford Mountain Reservoir. This information gives insight into the effects, if any, of the water as it is used downstream for irrigation. Also, this knowledge of the water quality allows for identification of degradation from other sources than Wolford Mountain Reservoir to be made. The only information need identified is that prescribed by the judgment.

Summary of Information Goals

A summary of the information goals identified for the Denver Water watershed monitoring program and the information needs developed through examination of the goals is presented in Table 2.1.

Table 2.1: Water quality information goals and associated needs identified for Denver Water.

	INFORMATION GOAL	INFORMATION NEED
#1	Source Water Quality: How it Affects Water Treatment	- Define the existence of a relationship between the quality of source water and cost associated with treatment. - Characterize the quality of source water over time.
#2	Nutrient Loading	- Identify the impacts of nutrients entering/exiting reservoirs over time. - Identify the effects of nutrient transport within rivers/streams. - Determine reservoirs to be either a source or sink of nutrients.
#3	Development within Watersheds	- Associate a change in land use (as a result of development) with water quality levels. - For a given land use, identify a “baseline” water quality level.
#4	Due Diligence	- Produce adequate information to show reasonable diligence according to Colorado Water Law
#5	Irrigation/Exchange	- Create a list of background water quality levels for known “agricultural” variables - Track the change in water quality over time that could potentially contribute to the hindrance of irrigated agriculture.
#6	Colorado River Agreement	- Produce data on the water quality variables mandated by the U.S. District Court findings.

CHAPTER 3.0 THE ABILITY OF MONITORING TO PRODUCE INFORMATION NEEDS

After defining what information is needed for each water quality goal, the ability of monitoring to produce the information must be carefully evaluated. The success of a monitoring system design requires matching the information needs of management with the information that can be produced by the monitoring system. The following factors limit, or hinder, the ability of monitoring to produce the desired information. Also discussed is the general form that information from a water quality monitoring system can take on. Finally, data analysis methods are recommended for the production of information that meets the needs described previously for Denver Water.

3.1 DATA RECORD ATTRIBUTES

Water quality data records have attributes that must be understood and accounted for when attempting to extract management information. For example, parametric statistical methods assume normally distributed data. Data often do not adhere to these assumptions, which creates difficulties in specifying analysis methods for the monitoring system. In an effort to limit the potential flaws described, attributes of the data record can be handled through the design and operation of the monitoring system. These attributes can be grouped into two major categories: (1) those that are a function of the monitoring system failing to obtain high quality data, and (2) those that are a function of the statistical behavior of the variables themselves (Ward 1999). These are listed below and briefly described thereafter. Recommendations for approaches to be used by Denver Water in handling these attributes are placed in a table at the end of this section.

Data Limitations

- Multiple observations
- Outliers
- Changing sampling frequencies
- Missing values
- Censoring

Statistical Limitations

- Non-normality
- Seasonality
- Serial correlation

3.11 Multiple Observations

Multiple observations occur when more analytical results are recorded than the sampling frequency dictates for a given time period. This is generally a result of collecting replicate samples for QA/QC purposes. Problems include one time period (with multiple observations) being given more weight during data analysis. There are two differing suggestions in handling this situation: (1) average the multiple observations into one value (Adkins, 1993), and (2) only one observation should be stored per time period, ideally storing QA/QC data in a separate record (Ward, 1999).

3.12 Outliers

Outliers are values much higher or lower than the majority of the data. Possible causes include measurement or recording error, an observation from a population not similar to that of most of the data, or a rare event from a single population that is quite skewed (Helsel and Hirsch, 1992). Common practice is to include the last two types of outliers in the data record as they are true observations. It is recommended that an outlier should be discarded only if evidence proves it is the result of a monitoring system malfunction (Ward, 1999).

3.13 Changing Sampling Frequencies

Adkins (1993) identifies four possible factors responsible for changing sampling frequencies: (1) increased funding, (2) changing regulatory requirements, (3) modified management priorities resulting from the discovery of new contaminants, and (4) loss of funding. Ward (1999) added that the absence of a formal monitoring system design encourages change in sampling frequency as the above situations arise. Bias can be introduced to the analysis if there are more data contained in certain segments of the data record (similar to impacts of multiple observations). A quick fix is to collapse the data thus producing a record of equally spaced samples, but this has negative impacts regarding the homogenous variance assumption of many data analysis methods.

3.14 Missing Values

Missing values can either be random or systematic (Adkins, 1993). Random missing values are a result of equipment failure, misplaced samples or test results, inclement weather, illness, or government shutdown. Hydrologic extremes (e.g. seasonal flow patterns) and changing sampling frequencies are indicative of systematic missing values. Missing values may create serious problems for some statistical methods. However, non-parametric methods are adequate with the presence of missing values as shown by Lettenmaier et al. (1991). Methods do exist to replace missing values, but are not recommended as they introduce bias.

3.15 Censoring

Censoring is the replacement of numerical lab measurements with qualitative explanations such as “ND”, “<T”, “less than LOD”, or “V” (Adkins, 1993). Censoring of data is a result of lack of confidence in the numerical result and/or a fear that the uncertain numerical results may be misused or misinterpreted (Ward 1999). Adkins (1993) also discusses the present problems with detection limits and the confusion therein. The best practice is to not accept censored data from laboratories. Rather the measured concentration should be reported along with a statement of uncertainty. Many nonparametric methods, though, will perform well in the presence of a moderate number of non detects.

3.16 Non-normality

Water quality data are normally right skewed and violate the assumption of normality (Adkins, 1993). Lettenmaier et al. (1991) also point out that water quality data tend to be poorly behaved statistically by not following convenient probability distributions such as the well known normal or lognormal distributions. Most parametric methods used to analyze water quality data assume a normal distribution of the data. If data do not adequately fit a normal distribution, then the power of statistical tests (and therefore effectiveness of information) are reduced and confidence levels may be affected as well. Handling of this attribute is commonly addressed by using non-parametric analysis techniques which do not assume a statistical distribution. Parametric methods should be used only when it is certain the data are normally distributed.

3.17 Seasonality

Seasonality is the characteristic of water quality data reflecting a known cycle occurring in the data (Ward, 1999). This cycle increases the variability of water quality data, thus enlarging the width of confidence intervals used in estimation and decreases the power of hypothesis tests. There are two methods by which seasonality is commonly approached if present in a data record: (1) transform the data to remove the quantitative seasonal cycle, and (2) use data analysis methods that account for seasonality in the data record.

3.18 Serial Correlation

When data are analyzed statistically a redundancy of information can result if samples are taken too close together relative to the time period of interest. This is referred to as serial correlation. Water quality is most likely to exhibit positive serial correlation, which means high values have the tendency to follow high values and low values to follow low values. Loftis et al. (1991) conclude that the question of whether a given series of equally spaced observations is independent or serially correlated is scale dependent in many situations. They further state that serial correlation works to reduce rather than increase the variance of error in estimating specific interval (annual, for example) means from a given number of equally spaced observations that span the interval of interest. It is also pointed out that the distinction between serial correlation and trend in a time series is scale dependent. Adkins (1993) suggests describing serial correlation by a lag 1 Markov model. Another approach is to disregard serial correlation under appropriate circumstances based on an accurate definition of scale as addressed by Loftis et al. (1991).

3.19 Data Attribute Recommendations

A description of recommended handling procedures for the data record attributes by Denver Water are found in Table 3.1.

Table 3.1: Data record attribute handling procedures for Denver Water's monitoring program.

DATA ATTRIBUTE	***DENVER WATER ACTION***
Multiple observations	▪ Only one observation is to be stored per time period in the data record. ▪ QA/QC data should be stored separately and should not be included in data analysis.
Outliers	▪ All outliers shall be included in the data record for analysis unless evidence supports the outlier to be a result of monitoring system malfunction, then it should be discarded.
Changing sampling frequencies	▪ A data record suffering from a change in sampling frequencies should be collapsed to a standard frequency with the understanding of resulting impacts on chosen statistical analysis procedures.
Missing values	▪ Missing values should be addressed in data analysis by using methods (mainly non-parametric) that accommodate missing values. ▪ If the problem is widespread, the data record should be collapsed to accommodate statistical analysis. Implications of collapsing the record should be identified in this scenario as assumptions for certain statistical tests may be violated.
Censoring	▪ Censored data will not be accepted from the laboratory. o The measured concentration should be reported along with a statement of uncertainty. ▪ If censored data must be reported, then the standard procedure will be to replace the detection limit with 0.5*detection limit for data analysis.
Non-normality	▪ Non-parametric methods will be used to address non-normality in the data record. ▪ Parametric methods will only be used when it is certain the data were sampled from a normal distribution.
Seasonality	▪ Methods accounting for seasonality will be used in certain analysis methods (e.g. trend detection) ▪ Conducting analysis within defined seasons will be used in the remaining situations (e.g. mean estimation)
Serial correlation	▪ Serial correlation will be ignored as the scale of interest (as defined) will be confined to the period of record for the data undergoing analysis.

A benefit of a well-designed and documented monitoring system is the absence of impacts from the data record attributes described here on the information produced. Effective monitoring program operating procedures will minimize data limitations while proper selection of data analysis methods will minimize the statistical impact of those data limitations that remain.

3.2 INFORMATION TYPES

Before defining data analysis methods, it is advantageous to discuss the type of information that can be produced as a result of a monitoring effort. For the purpose of the Denver Water watershed monitoring program design, the information to be produced can be classified as: narrative, numerical, geographical, graphical, and statistical.

3.21 Narrative

Narrative information is useful in communicating with the lay public. Generalities are commonly conveyed through narrative methods, but care must be taken so that misinterpretation does not occur as the wording chosen can often give certain unwanted impressions. Denver Water uses such information in the creation of its yearly Consumer Confidence Report. It is possible to foresee such information used in future reports to the public (e.g. SWAP), but current information objectives do not define such a need.

3.22 Numerical

The production of raw data as an end is indicative of the information produced by past monitoring systems and a practice that Denver Water is trying to avoid with the implementation of a information-goal driven monitoring program. However, it is recognized that some situations include the need for raw data as a final product. It must be understood that analysis of raw data collected without information objectives in mind may produce results unwanted and incomparable because methods were not specified *a* *priori*. Denver Water is mandated to collect data for reasonable diligence determination and irrigation issues (see Colorado River Agreement) which require no data analysis. This information will be presented as raw data.

3.23 Geographical

The production of geographical information is a necessity for the connection of water quality to a spatial context. For example, to track the changing water quality with land use an effective medium for comparing the two data types is needed. This is accomplished through incorporating the data into a geographical context for the production of information. A key tool in implementing this is geographical information system (GIS) technology. GIS is reliable and widely accessible and is thus a valid format for creating information associated with monitoring goals. In addition to present needs, this information appears to have vast potential for future applications. Its value in mapping spatial locations of sources of contaminants, pollution problem areas, and the display of other data of interest is a key component to effective watershed protection.

3.24 Graphical

Graphical displays are probably the most useful approach all around for conveying information to a wide variety of audiences, both technical and non-technical (Ward et al., 1990). The ability to display spatial and temporal changes in water quality with an ease of implementation is a benefit that should be recognized and utilized. Box and whisker plots are an asset as they present a large amount of statistical information (e.g. distribution, central tendency, and outliers) in a format that is simple to construct.

Likewise, time series plots enable visual affirmation of change over time in water quality data sets. The strength of graphical methods should be seen as a complement to non-graphical statistical analysis.

3.25 Statistical

Statistical methods permit quantitative statements to be made about natural processes that involve error and uncertainty (Ward et al., 1990). As Denver Water plans to collect samples from the population of water in its watersheds and infer the behavior of this entire population, the need for statistical information is clear. Denver Water will use statistical methods in estimating (e.g. central tendencies) and testing (e.g. trend detection) in the production of water quality information.

A synopsis of the monitoring goals resulting from the data analysis methods prescribed is found in Table 3.2. The connection between the previously stated information goals and the monitoring goals provides a solid basis for the monitoring system design. As a result, products of the monitoring system have detailed measurements by which information is to be gauged. Also, misinterpretation of data and subjective analysis is limited by the development of these connections.

Table 3.2: Associated monitoring goal for previously defined information need (and goal) for Denver Water's monitoring program.

	INFORMATION GOAL	INFORMATION NEED	MONITORING GOAL
#1	Source Water Quality: How it Affects Water Treatment	- Define the existence of a relationship between the quality of source water and cost associated with treatment. - Characterize the quality of source water over time.	- Detection of statistically significant upward/downward trends over a 5-year period at a confidence level of 90% and 80% power. - Estimation of the associated trend magnitudes.
#2	Nutrient Loading	- Identify the impacts of nutrients entering/exiting reservoirs over time. - Identify the effects of nutrient transport within rivers/streams. - Determine reservoirs to be either a source or sink of nutrients.	- Detection of statistically significant upward/downward trends over a 5-year period at a confidence level of 90% and 80% power. - Estimation of the associated trend magnitudes. - Estimation of nutrient mass loadings
#3	Development within Watersheds	- Associate a change in land use (as a result of development) with water quality levels. - For a given land use, identify a "baseline" water quality level.	- Estimating the central tendency of water quality with 90% confidence intervals. - Detection of statistically significant upward/downward trends over a 5-year period at a confidence level of 90% and 80% power. - Estimation of the associated trend magnitudes.
#4	Due Diligence	- Produce adequate information to show reasonable diligence according to Colorado Water Law	- Formulation of laboratory analysis results into a numerical information context.
#5	Irrigation/Exchange	- Create a list of background water quality levels for known "agricultural" variables	- Estimating the central tendency of water quality with 90% confidence intervals. -

	INFORMATION GOAL	**INFORMATION NEED**	**MONITORING GOAL**
		- Track the change in water quality over time that could potentially contribute to the hindrance of irrigated agriculture.	- Detection of statistically significant upward/downward trends over a 5-year period at a confidence level of 90% and 80% power. - Estimation of the associated trend magnitudes.
#6	Colorado River Agreement	- Produce data on the water quality variables mandated by the U.S. District Court findings.	- Formulation of laboratory analysis results into a numerical information context.

3.3 DATA ANALYSIS METHODS

A description of methodologies for narrative and numerical information types described above is not included in this section as there is no analysis the data must go through prior to being reported. For the remainder of information types, this discussion on analysis methodology is not intended to be the ultimate resource but rather to provide a synopsis of the chosen technique. References to literature and appendices containing step-by-step procedures for analysis are included for further detail.

3.31 Geographical methods

As mentioned previously, the incorporation of a GIS format for this information is recommended. Details of developing a GIS are beyond the scope of this description, but certain characteristics are important to note. A sound geographic database should be constructed which includes all major waterways, lakes/reservoirs, and watershed boundaries. This allows the placement of data relevant to Denver Water's watersheds for visual comparison. Additional data could be added as resources permit. Suggestions include the aforementioned land use data, permitted discharge locations, impaired stream segments, and best management practice (BMP) locations among many possibilities. Also, water quality data could be stored within the GIS for presentation. The GIS is a powerful tool that should be incorporated into any water quality monitoring system. The USEPA has acknowledged this with the introduction of their Better Assessment Science Integrating Point and Nonpoint Sources (BASINS, USEPA 1998) model for watershed and water quality based assessment. A widespread format for developing GIS tools are software products offered by Environmental Systems Research Institute (ESRI) including ArcInfo and ArcView. An example of what has been discussed with respect to creating geographical information system is shown in Figure 3.1. To display water quality data in conjunction with a GIS layer of land use has the potential to effectively increase the information utilization by management. In addition to facilitating the reporting of data, GIS has the potential to impact the analysis also. For example, water quality data could be tested for differences between land use designations in an attempt to highlight pollution concerns related to land use.

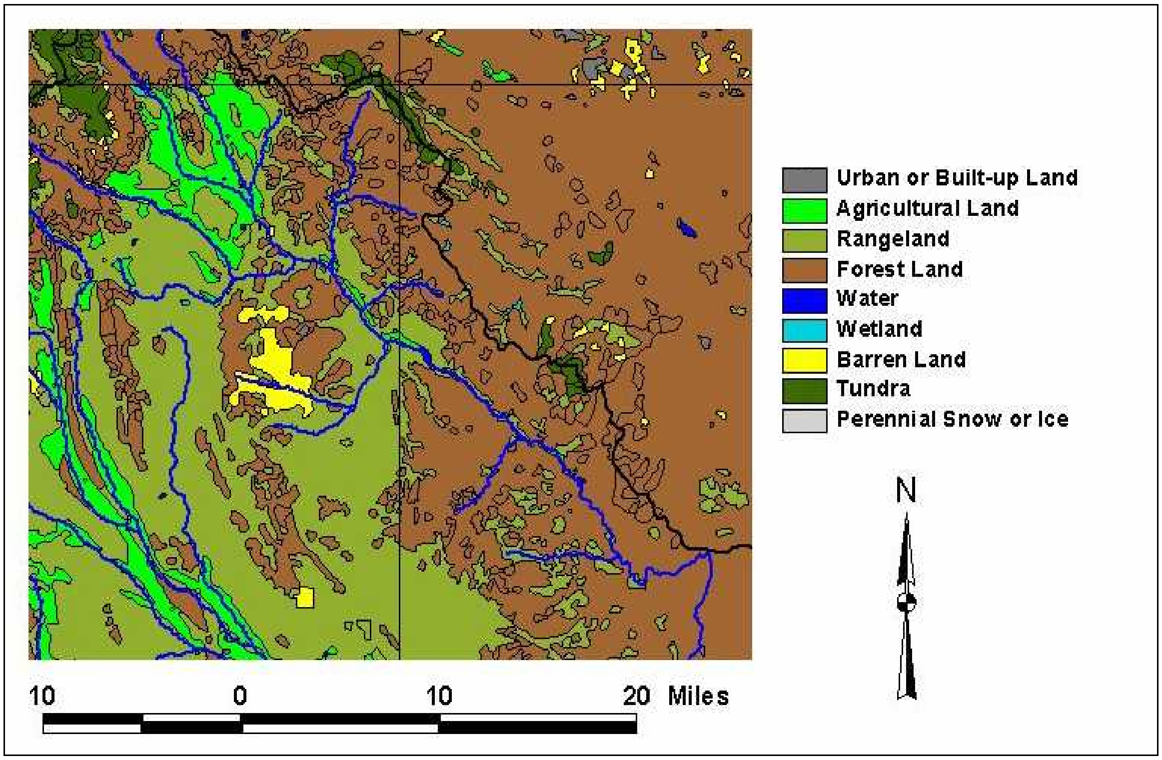


Figure 3.1: GIS example of land use classification displayed spatially using ESRI ArcView 3.2.

3.32 Graphical methods

As described previously, time series and box and whisker plots are recommended for use by Denver Water in their analysis of water quality data. The methodologies for both are provided here.

Time series plots

Time series plots are completed by plotting the concentration of the variable of interest versus time. Time series plots provide a visual indication of seasonal patterns and changes over time. Changes over space may be portrayed by placing time series for multiple stations on the same graph. Most modern statistical software programs (e.g.

Minitab™) have the ability to construct a time series plot. An example plot created using Minitab™ is shown below in Figure 3.2.

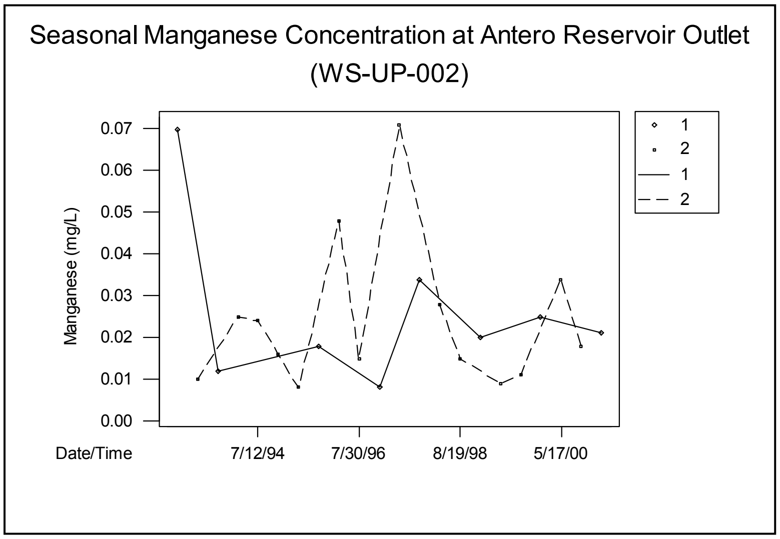


Figure 3.2: Time series plot example created in Minitab™ comparing manganese data for a Denver Water source watershed monitoring station during different seasons.

<u>Box and whisker plots</u>

Box and whisker plots are constructed per the description given by Helsel and Hirsch (1992). Box and whisker plots provide visual summaries of the distribution of a data and will be used in the Denver Water watershed monitoring program to supplement statistical analysis for trend detection and estimation of central tendency. A known strength of box and whisker plots is in the comparison of more than one data set, and this will be incorporated into data analysis for Information Goals #1 - #3. A simplified example of a box and whisker plot showing the comparison of data for a water quality variable in different seasons, a potential use in central tendency (mean, median) estimation, is presented in Figure 3.3. This particular example was constructed in the

Minitab™ statistical software package. For a stepwise procedure on construction of box and whisker plots see Appendix A.

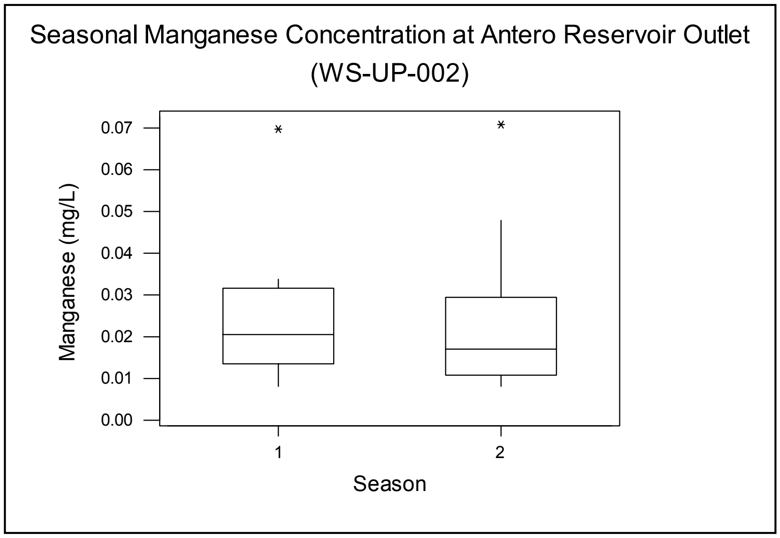


Figure 3.3: Box and whisker plot example created in Minitab™ comparing manganese data for a Denver Water source watershed monitoring station during different seasons.

3.33 Statistical methods

The statistical methods used in Denver Water's watershed monitoring program can be subdivided into 3 general categories: summary, trend detection, and load estimation. The description of each follows. Each statistical method discussed below can easily be incorporated into a statistical computer program (e.g. WQStat Plus™ or Minitab™) for ease of calculation and improved presentation of results.

Summary statistics

Summary statistics are defined here to include maximum and minimum value determination, interquartile range, sample median, sample mean, and sample variance.

These indicators depict the center of the distribution along with its spread of the measures. A methodology for estimating these terms is contained within Appendix A.

Trend detection

A hindrance associated with commonly used parametric methods for detecting trends is the violation of the normality assumption. To account for this situation, nonparametric trend detection techniques are recommended, in particular, the seasonal Kendall slope estimator to determine trend magnitude in conjunction with the seasonal Kendall trend test to identify the significance of the trend (Gilbert, 1987). The seasonal Kendall trend test poses the null hypothesis (H_O) that no trend exists versus the alternative hypothesis (H_A) that an upward or downward trend exists. The only assumption in this test is that the trend is monotonic and observations are independent. As stated, this method is nonparametric and thus deals with the ranks and signs of the data, but not with the data values implicitly, so data normality is of no concern. These methods also account for seasonal components of variability that may be present in the data. This eliminates the possibility of the seasonal cycles present in the data being mistaken for trends of the water quality. The specific methodology for this analysis is found in Appendix B.

Load estimation

A common method for calculating river loads is to use a rating curve to relate intermittent constituent concentration data to daily discharge data. This relationship is combined with a continuous record of discharge data to produce estimates of mass loads.

Normally the rating curve is a least squares regression with, at a minimum, discharge as the explanatory variable and load as the predicted variable. Each regression variable is typically log transformed for a better least squares line fit. Ferguson (1986) showed that retransformation of the logs introduces bias into the estimation. To address this problem a nonparametric retransformation method (Duan 1983) will be used in the regression based load estimation.

This regression based approach with the nonparametric retransformation correction has been shown to estimate the load as well as the minimum variance unbiased estimator when regression residuals are normally distributed. It is presumed that the absence of an assumption pertaining to the distribution of the regression residuals enables the nonparametric method to minimize error in load estimation better than comparable parametric methods when the residuals are non-normal. This method was chosen as the non-normality of regression residuals is likely to occur often. A detailed methodology describing the estimation of river loads using the regression based nonparametric method is located in Appendix C.

CHAPTER 4.0 MONITORING NETWORK DESIGN

The water quality monitoring network design includes 3 phases: water quality variable selection, sampling site selection, and sampling frequency determination. This has been completed for the Denver Water watershed monitoring program as described in the following section. Additionally, an associated cost of monitoring was calculated for the program, and the results are located in Appendix D.

4.1 WATER QUALITY VARIABLES

The water quality variables to be sampled for the watershed monitoring program are listed in Table 4.1. The selection of the variables was a function of their importance to information goals identified previously. Reasoning for inclusion of each parameter is also listed in Table 4.1. The variables recommended for the monitoring program include mainly physical and chemical, with some microbiological, constituents.

Table 4.1: Water quality variables to be sampled by the Denver Water watershed monitoring program.

	Variable	***Descriptor***	***Reason for Monitoring***
1	Alkalinity, Total as CaCO3 (mg/L)	General	Drinking water standard[3]; Indicator of carbonate species concentrations; Acid neutralizing capacity (ANC) of water (buffering effect on pH).
2	Bromide (mg/L)	Ion	Total anion component.
3	Cadmium, Dissolved (mg/L)	Metal	Water quality standard[4,5]; Indicator of pollution from mining activity (at elevated levels).

	Variable	***Descriptor***	***Reason for Monitoring***
4	Cadmium, Total (mg/L)	Metal	Drinking water standard[1,3]; Indicator of pollution from mining activity (at elevated levels).
5	Calcium (mg/L)	Major Ion	Drinking water standard[3]; Hardness indicator (imparts hardness to water); Typically in form of carbonate species..
6	Chloride (mg/L)	Major Ion	Drinking water standard[2]; Water quality standard[4,5]; Indicator (at high concentrations) of industrial and sewage effluents; High levels render water unpalatable.
7	Coliform, Total (/100 mL)	Microorganism	Drinking water standard[1,3]; Indicator of potentially harmful bacteria.
8	Escherichia coli (/100 mL)	Microorganism	Indicates presence of wastewater or fecal contamination.
9	Fluoride (mg/L)	Ion	Drinking water standard[1,3]; Water quality standard[4,5]; Found in wastewater due to use in industrial applications; Also occurs naturally.
10	Hardness, Total as CaCO3 (mg/L)	General	Treatment implications; Hard water causes scaling in water heaters/boilers, and soft water is considered corrosive.
11	Iron, Dissolved (mg/L)	Metal	Water quality standard[4,5]; Affects treatment (can cause taste and discoloration).
12	Iron, Total (mg/L)	Metal	Drinking water standard[2]; Water quality standard[4,5]; Affects treatment (can cause taste and discoloration)
13	Lead, Dissolved (mg/L)	Metal	Drinking water standard[1,3]; Water quality standard[4,5]; Indicator of pollution from mining activity (at elevated levels).
14	Magnesium (mg/L)	Major Ion	Hardness indicator (imparts hardness to water).
15	Manganese, Dissolved (mg/L)	Metal	Water quality standard[4,5]; Undesirable impurity (aesthetic – taste and odor) in water supplies resulting from oxidation.
16	Manganese, Total (mg/L)	Metal	Drinking water standard[2]; Water quality standard[4,5]; Undesirable impurity (aesthetic – taste and odor) in water supplies resulting from oxidation.
17	Molybdenum, Dissolved (mg/L)	Metal	Indicator of pollution from mining activity (at elevated levels).
18	Molybdenum, Total (mg/L)	Metal	Indicator of pollution from mining activity (at elevated levels).
19	Nitrogen, Ammonia (mg/L)	Nutrients	Water quality standard[4,5]; Aquatic life protection; Indicator of organic pollution by sewage or industrial effluent, agricultural wastes, and fertilizers.
20	Nitrogen, Nitrate (mg/L)	Nutrients	Drinking water standard[1,3]; Water quality standard[4,5]; Potential health risk (esp. infants);

	Variable	***Descriptor***	***Reason for Monitoring***
			Helps the assessment of the character and degree of oxidation in surface waters.
21	Nitrogen, Nitrite (mg/L)	Nutrients	Drinking water standard[1,3]; Water quality standard[4,5]; Indicator of microbiological quality of water (increased levels associated with unsatisfactory quality).
22	Nitrogen, Total Kjeldahl (mg/L)	Nutrients	Determination of total organic nitrogen; Increased levels of organic nitrogen indicate pollution of water bodies.
23	Oxygen, Dissolved (mg/L)	General	Water quality standard[4,5]; Essential for aquatic life; Indicator of organic pollution, destruction of organic substances, and the level of self-purification in natural water (oxygen is involved in, or influences, all chemical/biological processes within water bodies).
24	Organic Carbon, Total (mg/L)	Nutrients	Indicator of pollution; Arises from living material and waste materials and effluents; Disinfection by-products precursor.
25	pH (SU)	General	Drinking water standard[2,3]; Water quality standard[4,5]; Important variable in water quality assessment as many biological and chemical processes involved in water bodies are pH dependent.
26	Phosphate (ortho), dissolved (mg/L as P)	Nutrients	High concentrations indicate pollution; Indicator of nutrient status (algal growth).
27	Phosphorus, Total (mg/L)	Nutrients	Indicator of nutrient status (algal growth)
28	Potassium (mg/L)	Major Ion	Indicator of pollution from run-off and discharges.
29	Sodium (mg/L)	Major Ion	Drinking water standard[3]; Increased levels in surface waters may arise from sewage and industrial effluents (and road salts); Also can impact irrigation effectiveness.
30	Specific Conductance (æS)	General	Drinking water standard[3]; Provides relationship to concentrations of total dissolved solids in water and major ions.
31	Stream Flow (cfs)	Hydrological	Necessary for flow dependent analysis and load estimation (amount of suspended and dissolved matter in a water body depends on discharge).
32	Sulfate	Major Ion	Drinking water standard[2]; Water quality standard[4,5]; Treatment implications (taste and odor); Indicates industrial effluents and mine drainage at elevated levels.
33	Suspended Solids, Total (mg/L)	General	Amount of particulate matter in a water sample—implications for water treatment, stream habitat, and reservoir life.

	Variable	*Descriptor*	*Reason for Monitoring*
34	Temperature (C)	General	Drinking water standard[3]; Water quality standard[4,5]; Affects chemical, physical, and biological processes – therefore the concentration of many variables.
35	Turbidity (NTU)	General	Drinking water standard[1,3]; Indicator of biological activity in the water column.
36	Uranium (mg/L)	Metal	Water quality standard[4];
37	Zinc, Dissolved (mg/L)	Metal	Water quality standard[4,5]; Indicator of pollution from mining activity (at elevated levels).
38	Zinc, Total (mg/L)	Metal	Drinking water standard[2]; Indicator of pollution from mining activity (at elevated levels).

[1] National Primary Drinking Water Regulations (USEPA 2000)
[2] National Secondary Drinking Water Regulations (USEPA 2000)
[3] Colorado Primary Drinking Water Regulations (CDPHE 1999)
[4] Classification and Numeric Standards for South Platte River Basin. (CDPHE 1999)
[5] Classification and Numeric Standards for Upper Colorado River Basin. (CDPHE 1999)

A list of the water quality variables for the monitoring program, subdivided by sampling “suites” to be used per site, is shown in Table 4.2. These are the groupings by which samples will be analyzed depending on the their location and associated information goal. Note that “WS-TL1” is considered the “basic” parameter set (for future reference).

Table 4.2: Water quality variable analysis suites as defined by the Denver Water watershed monitoring program.

WS-TL1	***WS-TL2***	***WS-TL3***	***WS-TL4***	***WS-TL5***	***WS-TL6***	***WS-TL8***
Coli	Coli	Coli	Coli	Coli	Coli	Coli
Temp	Temp	Temp	Temp	Temp	Temp	Temp
pH	pH	pH	pH	pH	pH	pH
Hardness	Hardness	Hardness	Hardness	Hardness	Hardness	Hardness
Alk, total	Alk, total	Alk, total	Alk, total	Alk, total	Alk, total	Alk, total
Spec Cond	Spec Cond	Spec Cond	Spec Cond	Spec Cond	Spec Cond	Spec Cond
Turbidity	Turbidity	Turbidity	Turbidity	Turbidity	Turbidity	Turbidity
DO (titr)	DO (titr)	DO (titr)	DO (titr)	DO (titr)	DO (titr)	DO (titr)
NH_3	NH_3	NH_3	NH_3	NH_3	NH_3	NH_3
Flow	Flow	Flow	Flow	Flow	Flow	Flow
TOC	TOC	TOC	TOC	TOC	TOC	TOC
TSS	TSS	TSS	TSS	TSS	TSS	TSS
Fe	Fe	Fe	Fe	Fe	Fe	Fe

WS-TL1	***WS-TL2***	***WS-TL3***	***WS-TL4***	***WS-TL5***	***WS-TL6***	***WS-TL8***
Fe, diss.	Fe, diss.	Fe, diss.	Fe, diss.	Fe, diss.	Fe, diss.	Fe, diss.
Mn	Mn	Mn	Mn	Mn	Mn	Mn
Mn, diss	Mn, diss.	Mn, diss.	Mn, diss	Mn, diss	Mn, diss	Mn, diss.
P, total	P, total	P, total	P, total	P, total	P, total	P, total
	F	F	F	Na	Na	Mo
	Cl	Cl	Cl	K	K	Mo, diss.
	NO2	NO2	NO2	Mg	Mg	
	Br	Br	Br	Ca	Ca	
	NO3	NO3	NO3	Zn	Zn	
	Ortho-P	Ortho-P	Ortho-P	Zn, diss.	Zn, diss.	
	SO4	SO4	SO4	Cd	Cd	
	TKN	Mo	Uranium	Cd, diss	Cd, diss	
		Mo, diss.			Mo	
					Mo, diss.	

4.2 SAMPLING LOCATION

To facilitate the discussion of sampling site selection, the organization of Denver Water's watershed monitoring program should be explained. Figure 4.1 depicts the structure of the program. There are five collection systems designated within the watershed monitoring program. Each collection system contains the watershed(s) from which water quality samples are taken. The division of monitoring into smaller geographic regions allows for more effective discussion on sampling site selection by diminishing the vast scale of Denver Water's entire watershed monitoring system. This partitioning of Denver Water's source area is shown visually in Figure 4.2.

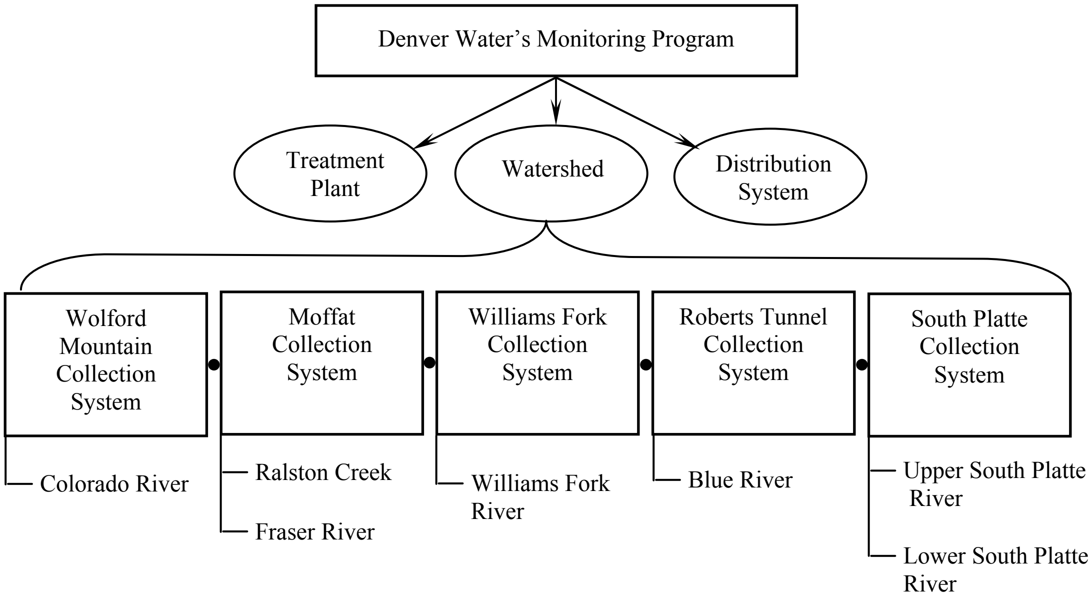


Figure 4.1: Organizational structure for the Denver Water monitoring program.

Sampling site locations were determined based on certain design parameters: a) the site should be close to a stream gauging station so that loads could be calculated and relationships between water quality and flow could be analyzed, b) the site should be accessible, safe, and within a reasonable distance from the laboratory, and c) there should be some significance to the site, in particular, with respect to the information goals that were formulated. The sampling locations for the present monitoring system were used as a basis for selection of new sampling locations. In the end, the network of present sampling locations was deemed adequate for the new system. The present sites met the criteria for selection well and were conveniently established already. This list of sampling locations, organized according to the watersheds from each collection system, is shown in Tables 4.3 – 4.9. For each sampling site, the associated information goal

(Tables 2.1 and 3.2) that mandates monitoring is shown in addition to the current designation Denver Water uses in identifying the site ("DW Designation").

Table 4.3: Proposed sampling locations in the Blue River watershed for the Denver Water watershed monitoring program.

Station ID	***Station Description***	***DW Designation***	***Information Goal***
WS-BL-001	Blue R. Inlet at Dillon Res.	Storage Reservoir	2, 3
WS-BL-002	Snake R. Inlet at Dillon Res.	Storage Reservoir	2, 3
WS-BL-003	Ten Mile Ck. Inlet at Dillon Res.	Storage Reservoir	2, 3
WS-BL-004	Blue R. Outlet at Dillon Res.	Storage Reservoir	2
WS-BL-005	East Portal of Roberts Tunnel	Storage Reservoir	1, 2
WS-BL-006	Straight Ck. 1.3 miles above Dillon diversion structure	Due Dilligence	4
WS-BL-007	Straight Ck. below Dillon diversion structure	Due Dilligence	4
WS-BL-021	Blue River below Green Mountain Reservoir	Colorado R. Agreement	6

Table 4.4: Proposed sampling locations in the Colorado River watershed for the Denver Water watershed monitoring program.

Station ID	***Station Description***	***DW Designation***	***Information Goal***
WS-CO-001	Muddy Ck. upstream of Wolford Mountain Reservoir	Colorado R. Agreement	6
WS-CO-002	Colorado R. @ Gore Trail trailhead	Colorado R. Agreement	6
WS-CO-003	Colorado R. north of Parshall	Colorado R. Agreement	6
WS-CO-004	Colorado R. below Williams Fork R.	Colorado R. Agreement	6

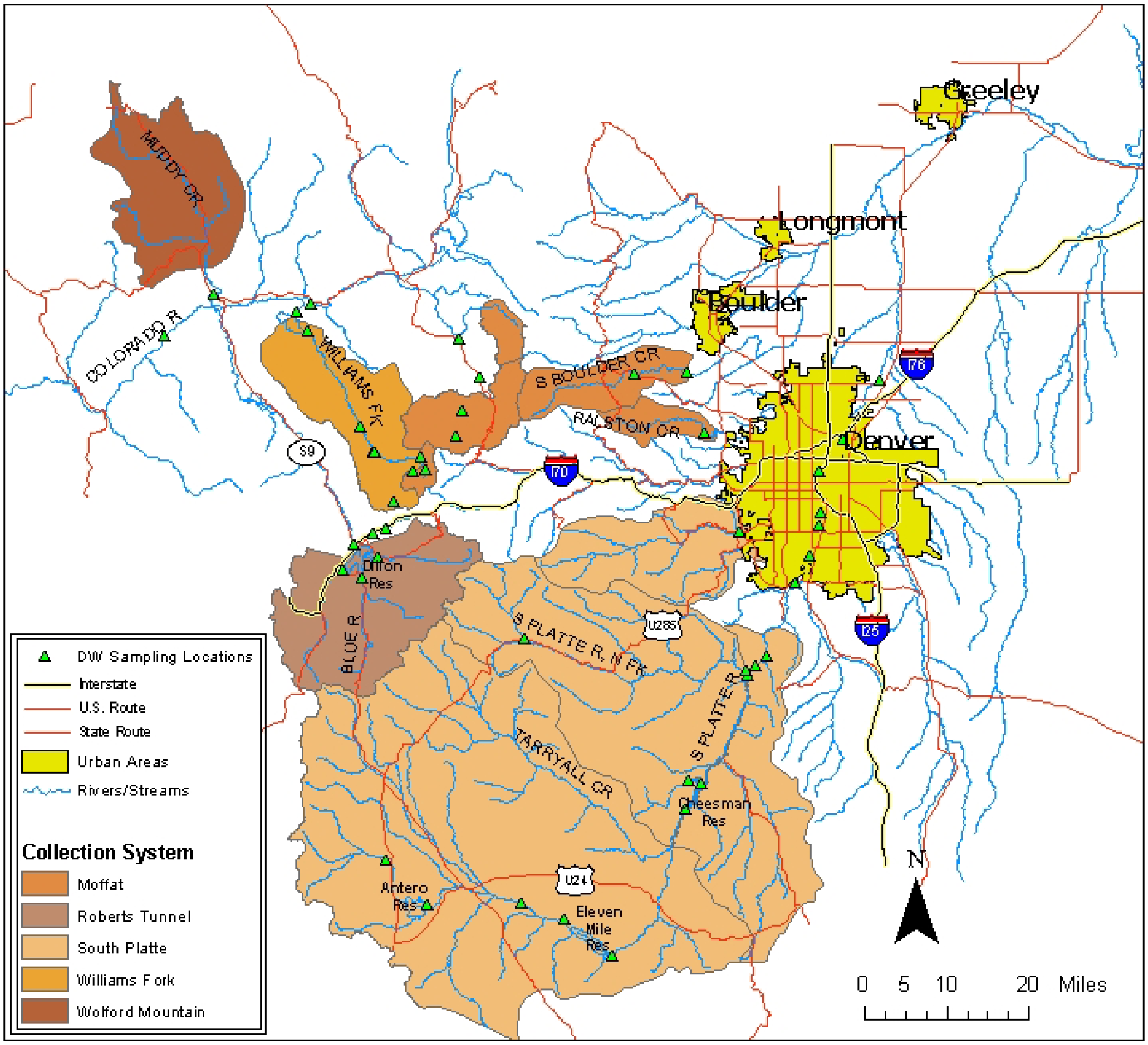


Figure 4.2: Proposed sampling sites for the Denver Water watershed monitoring program, 2001. Data sources: Denver Water: sampling sites and collection system; USEPA (BASINS model): roads, cities, and hydrography.

Table 4.5: Proposed sampling locations in the Fraser River watershed for the Denver Water watershed monitoring program.

Station ID	***Station Description***	***DW Designation***	***Information Goal***
WS-FR-001	Vasquez Ck. above Vasquez Tunnel	Due Dilligence	4
WS-FR-002	Vasquez Ck. at diversion structure	Due Dilligence	4
WS-FR-003	Fraser R. below confluence w/ Vasquez Ck.	Due Dilligence	4
WS-FR-004	Fraser R. at Tabernash	Due Dilligence	4

Table 4.6: Proposed sampling locations in the Williams Fork watershed for the Denver Water watershed monitoring program.

Station ID	***Station Description***	***DW Designation***	***Information Goal***
WS-WF-001	Williams Fork R. above Williams Fork res.	Due Dilligence	4
WS-WF-002	Williams Fork R. below Kinney Ck, below Leal	Due Dilligence	4
WS-WF-003	S. Fork of Williams Fork R. @ S. Fork campground/gauging station	Due Dilligence	4
WS-WF-004	Williams Fork R. above bridge @ Sugarloaf campground	Due Dilligence	4
WS-WF-005	Steelman Ck @ diversion dam	Due Dilligence	4
WS-WF-006	McQueary Ck. above diversion dam	Due Dilligence	4
WS-WF-007	Upper S. Fork of Williams Fork R.	Due Dilligence	4
WS-WF-008	Bobtail Ck. at gauging station	Due Dilligence	4
WS-WF-009	Williams Fork R. below Williams Fork Res.	Colorado R. Agreement	6

Table 4.7: Proposed sampling locations in the Lower South Platte River watershed for the Denver Water watershed monitoring program.

Station ID	***Station Description***	***DW Designation***	***Information Goal***
WS-LP-001	Strontia Springs Res. effluent	Terminal Reservoir	1, 2, 3
WS-LP-002	Chatfield Res. effluent	Exchange/Irrigation	5
WS-LP-003	S. Platte R. below Dutch Ck. (Littleton)	Exchange/Irrigation	5
WS-LP-004	S. Platte R. N. of Dartmouth (Englewood)	Exchange/Irrigation	5
WS-LP-005	S. Platte R. S. of Florida (Denver)	Exchange/Irrigation	5
WS-LP-006	S. Platte R. below confluence w/ Cherry Ck. (Denver)	Exchange/Irrigation	5
WS-LP-007	S. Platte R. below confluence w/ Sand Ck. (Commerce City)	Exchange/Irrigation	5
WS-LP-008	S. Platte R. @ Henderson	Exchange/Irrigation	5
WS-LP-009	Bear Ck. above Harriman headgate (Morrison)	Storage Reservoir	2, 3

Table 4.8: Proposed sampling locations in the Upper South Platte River watershed for the Denver Water watershed monitoring program.

Station ID	***Station Description***	***DW Designation***	***Information Goal***
WS-UP-001	S. Platte above Antero Res. at (US 285)	Storage Reservoir	2
WS-UP-002	S. Platte @ Antero Res. outlet	Storage Reservoir	2
WS-UP-003	Gauging station above Eleven Mile Res.	Storage Reservoir	2
WS-UP-004	Eleven Mile Res. outlet	Storage Reservoir	2

WS-UP-005	Cheesman Res. outlet	Storage Reservoir	2
WS-UP-006	S. Platte R. upstream of confluence w/ N. Fork	Watershed Assess.	2, 3
WS-UP-007	S. Platte R. at gauging station above Cheesman Res.	Storage Reservoir	2
WS-UP-008	S. Platte R. below confluence of N. Fork and S. Platte	Terminal Reservoir	2
WS-UP-009	S. Platte R. upstream of Spinney Mtn. Res.	Storage Reservoir	2
WS-UP-010	Goose Ck. above gauging station	Storage Reservoir	2
WS-UP-011	N. Fork of S. Platte above confluence with S. Platte R.	Watershed Assess.	2, 3

Table 4.9: Proposed sampling locations in the Ralston Creek watershed for the Denver Water watershed monitoring program.

Station ID	***Station Description***	***DW Designation***	***Information Goal***
WS-RL-001	S. Boulder Ck. @ Pine Cliff	Storage Reservoir	2, 3
WS-RL-002	S. Boulder Ck. @ S. Boulder canal diversion	Terminal Reservoir	1, 2
WS-RL-003	Ralston Ck. @ Long Lake headgate	Terminal Reservoir	1, 2, 3

4.2.1 Distribution of Sampling Sites

The sampling locations recommended for the monitoring system design are categorized by their current designation as defined by Denver Water. Note reservoir monitoring is included under the "Other" designation within this chart. Reservoir sampling constitutes the largest segment of water quality monitoring in the source area.

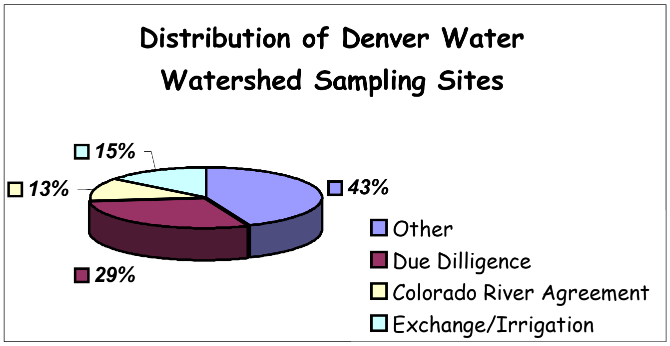


Figure 4.3: Distribution of Denver Water sampling sites by purpose of sampling for the proposed monitoring program.

4.3 SAMPLING FREQUENCY

For sampling frequency calculations, the historical data analysis was required to gain an understanding of the statistical nature of the water quality population to be sampled. This historical analysis gave insight into the variability of the water quality and allowed for determination of seasonality present in the data. The water quality data were taken from the United States Geological Survey's (USGS) Earth Info Quality of Water software (1996), which has since become available on the NWISWeb (USGS 2001) system offered by the USGS. The period of record for the data was from 1950 to 1997 and was arranged according to 8-digit USGS hydrologic unit codes (HUC). Again, use of the HUCs allowed for analysis of the Denver Water watersheds on a smaller scale than the entire system. The Denver Water collection system boundary was overlain with the series of USGS HUCs used in the historical data analysis to present the compatibility between the two. Stations falling within close proximity of both the Denver Water watersheds boundary and the USGS HUCs were used for analysis. The boundaries are shown in Figure 4.4.

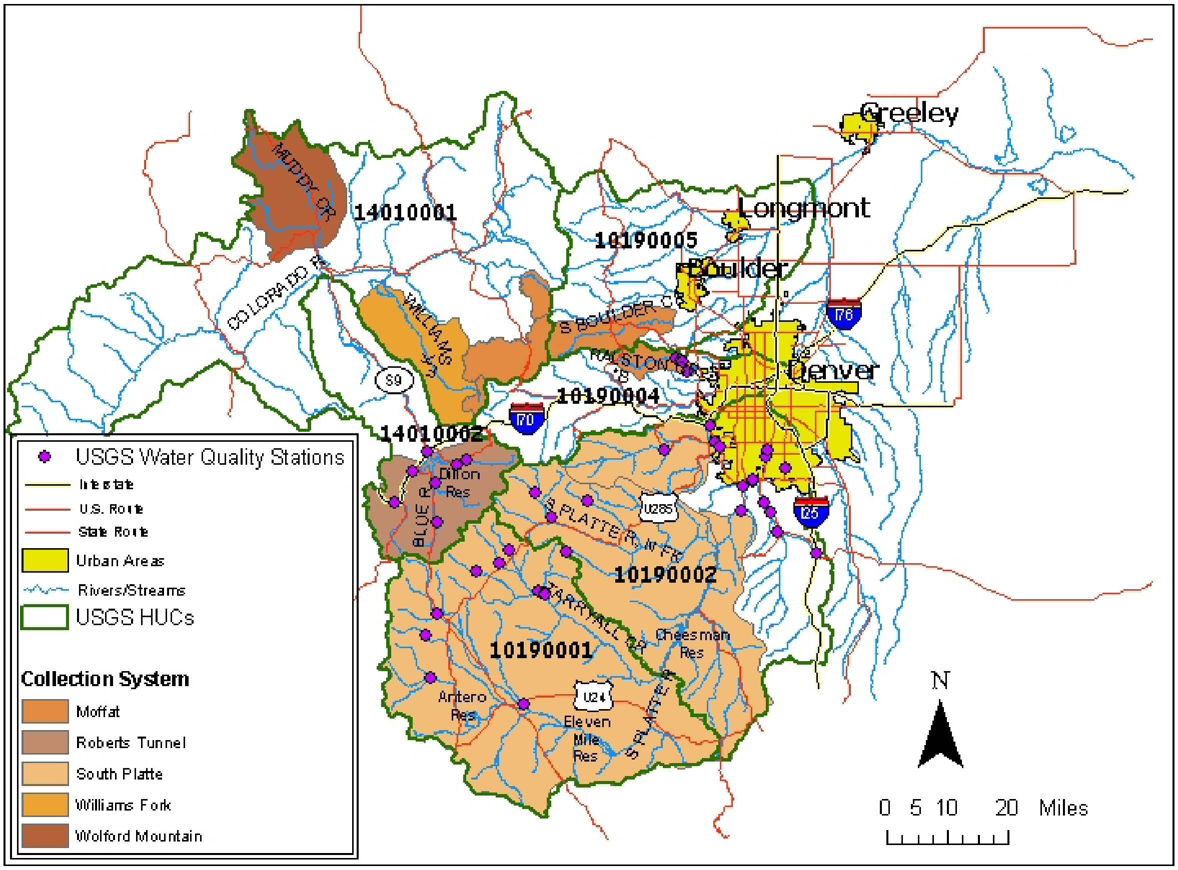


Figure 4.4: The sampling frequency analysis framework for the Denver Water source area monitoring program design. Data sources: Denver Water: collection system; USEPA: USGS HUCs, cities, hydrography, and roads; USGS: water quality stations.

The Denver Water source area is supplied mainly by snowmelt/runoff. This suggests that the water quality data reflect seasonality corresponding to both the temperature and flow of the water. To address this known characteristic of the data, seasons were defined corresponding to the flow and temperature; and the historic data were grouped accordingly for preliminary analysis. The seasons determined from the historical data analysis will also be used for mean estimation in the recommended design for handling the seasonality of the data. The flow and temperature data used to define the seasons for each watershed are shown below.

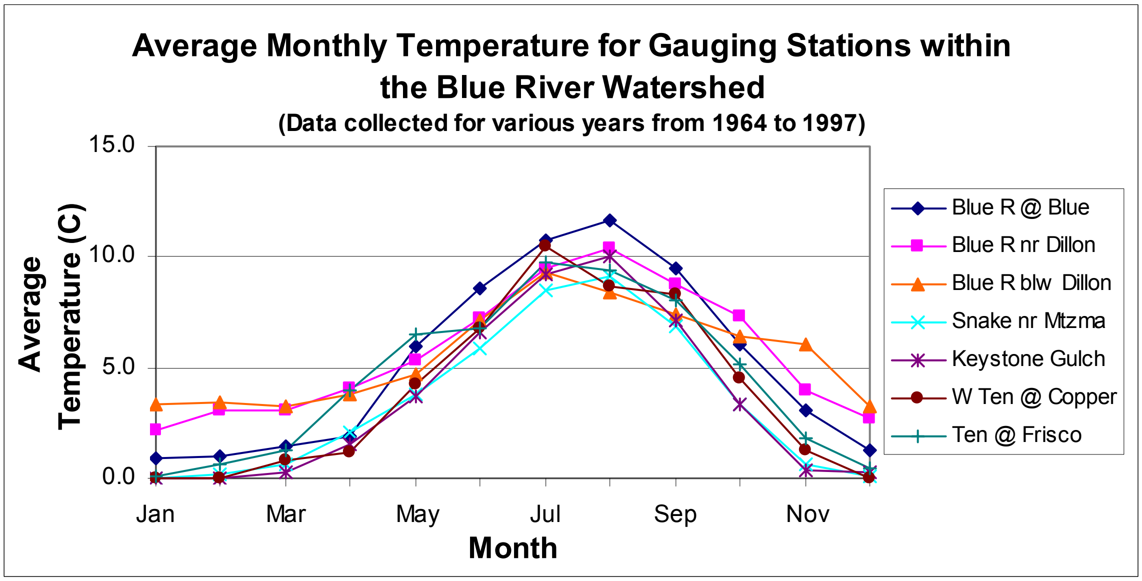


Figure 4.5: Average monthly temperature at selected USGS water quality stations within the Blue River watershed (HUC 14010002) for various periods from 1964-1997.

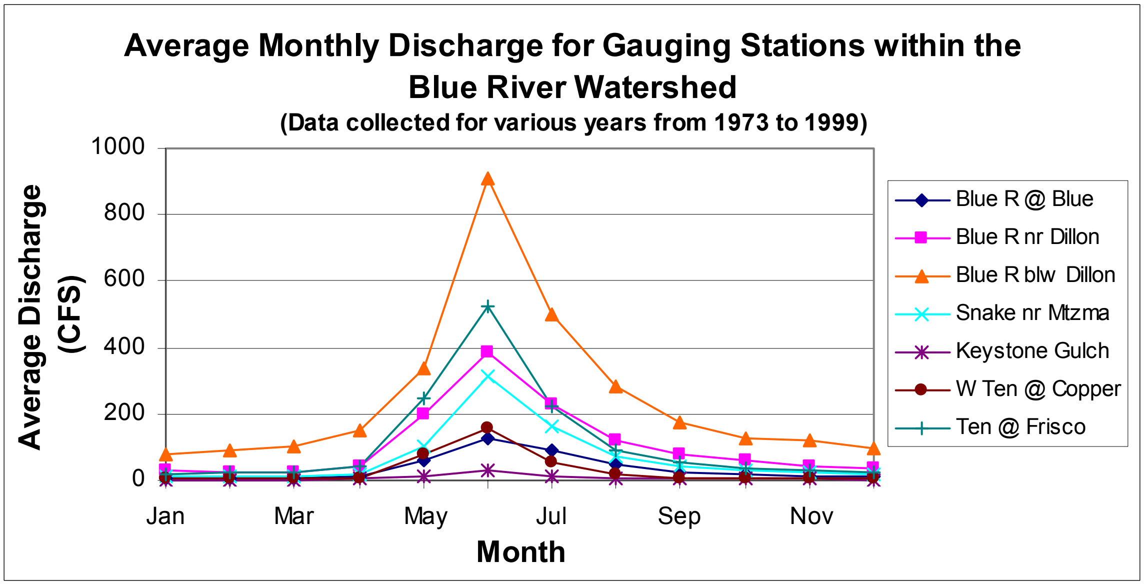


Figure 4.6: Average monthly discharge at selected USGS water quality stations within the Blue River watershed (HUC 14010002) for various periods from 1973-1999.

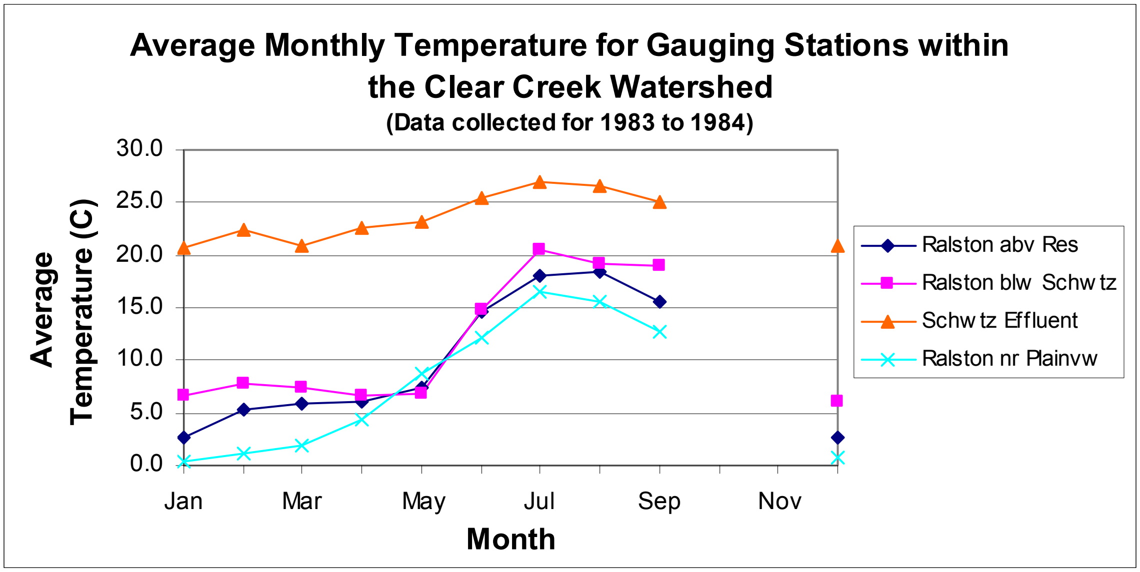


Figure 4.7: Average monthly temperature at selected USGS water quality stations within the Clear Creek watershed (HUC 10190004) from 1983-1984.

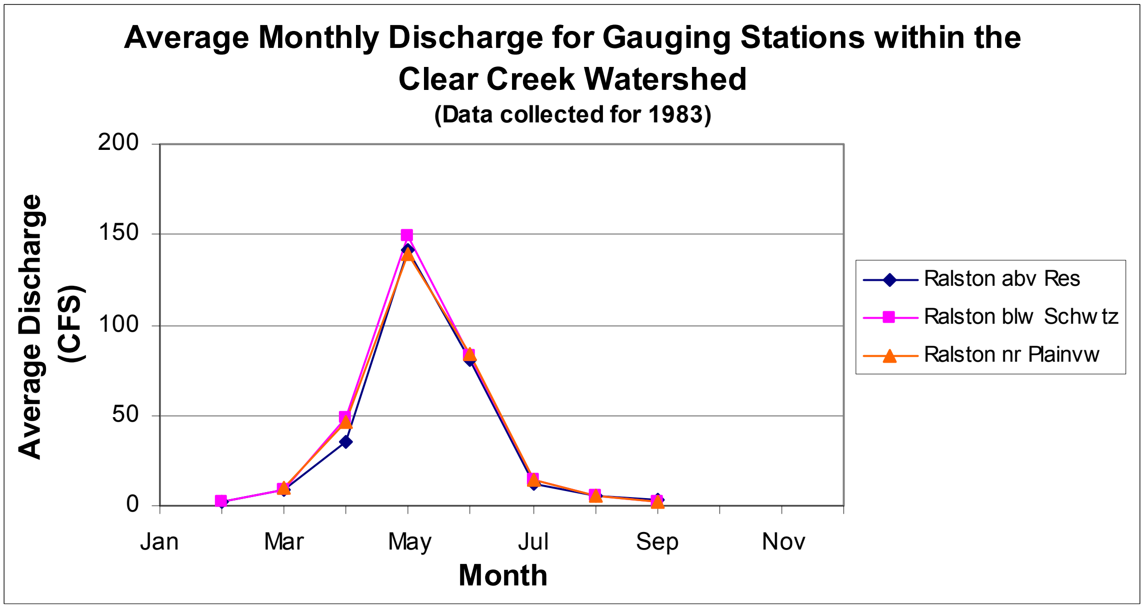


Figure 4.8: Average monthly discharge at selected USGS water quality stations within the Clear Creek watershed (HUC 10190004) for 1983.

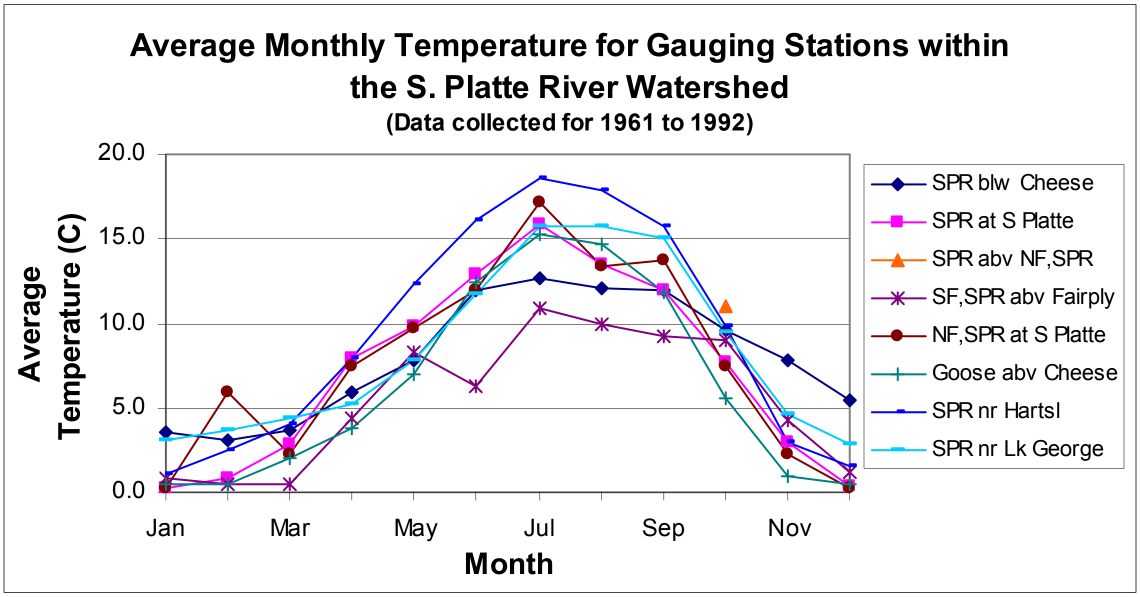


Figure 4.9: Average monthly temperature at selected USGS water quality stations within the South Platte River watershed (HUCs 10190001 & 10190002) various periods from 1961-1992.

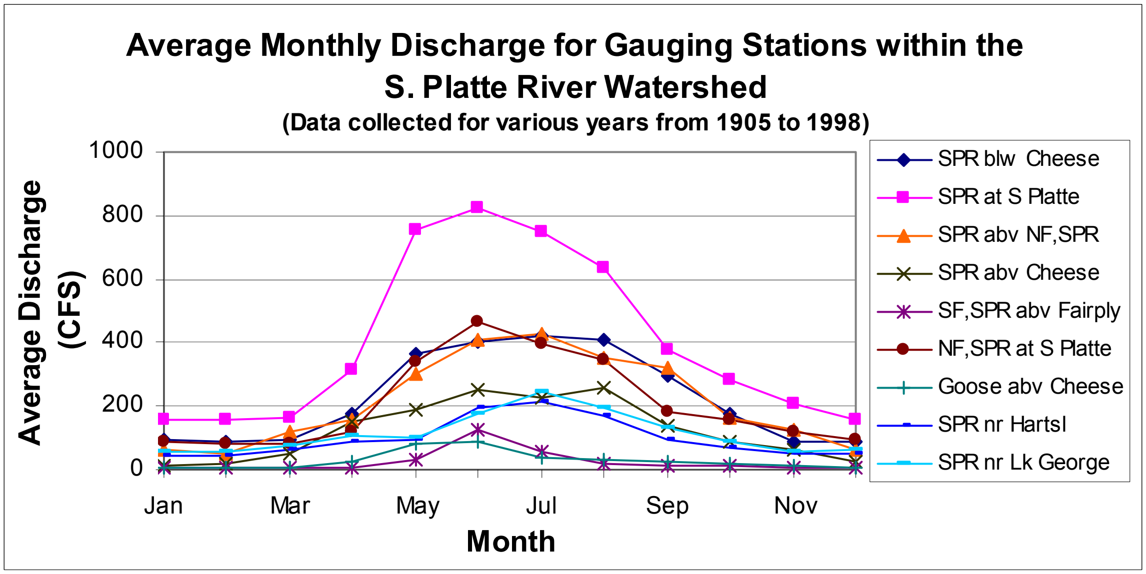


Figure 4.10: Average monthly discharge at selected USGS water quality stations within the South Platte River watershed (HUC 10190001 & 10190002) various periods from 1905-1998.

Notice that no data are shown for the St. Vrain watershed as the USGS does not have any gauging stations within the area of interest for Denver Water. It will be assumed that the flow and temperature for the St. Vrain are comparable to those for the other watersheds. After viewing both the flow and temperature data, two distinct seasons were defined based entirely on judgment. A season corresponding to a period of high stream flow and high temperature was designated for May, June, July, and August. Another season describing low flow and low temperature was assigned to January, February, March, April, September, November, and December. The seasons are shown below in Table 2. Denver Water staff requested that for certain stations, the high flow/high temperature seasons be shifted since spring runoff was known to occur earlier than May for those stations.

Table 4.10: Season designations resulting from analysis of temperature and discharge data for the Denver Water watershed monitoring program.

Season	***Designation***	***Months***
1	Low Flow/Low Temperature	Jan, Feb, Mar, Apr, Sept, Oct, Nov, Dec
2	High Flow/High Temperature	May, June, July, Aug

Season identification allowed the historical data analysis to proceed for determination of the monitoring system sampling frequency. This consisted of finding the variability for each water quality parameter historically sampled in the watersheds, then a required sampling frequency was calculated based on a statistical design criterion. The frequency calculations were completed for a select set of water quality parameters because of the limited data that existed. The water quality parameters used were alkalinity, nitrogen, conductivity, manganese, and phosphorous. Each selected parameter typifies the behavior of a broader group of water quality parameters in the Denver Water source area. Nitrogen and phosphorous data are assumed to be indicative of the nutrient species present in the watersheds. Manganese is used to generally indicate the behavior of metals. Conductivity correlates well to major ion species. Alkalinity represents the behavior of the carbonate species.

As the use of representative water quality parameters may suggest, the sampling frequency estimation process is an approximation. The design team acknowledges this, and the resulting quality of the frequency estimates is considered acceptable for the given use. The goal of this exercise is to gain a grasp on the behavior of the water quality within the watersheds in general. Because the historical data used for this analysis is of unknown quality, having been collected over a long time period with presumably many different sampling/analysis protocols, the resulting sampling frequency and degree of confidence has limited accuracy.

The calculations for the frequency at which samples would be taken differed according to the information desired from the monitoring system (e.g. means, loads, and trends). A description of each method is presented here.

Means

Finding the frequency at which samples would be collected for the determination of means was dictated by the distribution of the population from which the sample was taken. The distribution of the water quality data cannot be precisely identified, but methods exist for approximation. In this case, the water quality data were assumed to be from a normal or lognormal distribution. Many variables come from neither normal nor lognormal distributions, but are assumed so for ease in calculation of sampling frequencies. A probability plot was created for each distribution and a ‘best fit’ was decided upon by visual inspection. Note that data analysis within the final design will be completed using non-parametric methods to combat the ambiguity of the distribution discussed previously.

For water quality data found to be from normal distributions, a sample size equation assuming random and independent samples was used. This is a common method found in standard statistical texts (e.g. Gilbert 1987). It is shown below in Equation 4.2.

$$E = \frac{t_{\frac{\alpha}{2}} * s}{\sqrt{n}} \tag{4.2}$$

where E is the half width of the confidence interval about the estimated mean, t is the student's t value (at a prespecified confidence level (1-α)), s is the standard deviation of the historical data, and n is the number of samples taken within a given period of time.

The confidence interval is a statement of the probability or likelihood that the interval contains the true population mean (in this case). The intervals are wider for data sets having greater variability. Confidence intervals allow uncertainty to be addressed in forms such as: "The mean is 0.50 +/- 0.05 with 95% confidence."

A range of sample sizes (n) was used in the calculation of the confidence interval half width, given the standard deviation and student's t value. The resulting confidence interval half width for each sample size was presented as a percent error of the historical mean as shown in Equation 4.3.

$$Error = \frac{E}{\bar{x}} \qquad (4.3)$$

where the Error is the percent error of the historical mean, E is the half width of the confidence interval, and $\bar{x}$ is the historical mean from existing water quality data.

This error is calculated for sampling frequencies of every other month, monthly, twice per month, weekly, and daily for the historical data in each season. Also, the error for the above frequencies is shown for confidence levels of 90% and 95%.

Data judged to be approximately lognormal were handled in a similar manner to those from normal distributions. Equation 4.4 shows the formula used to calculate the sampling frequency.

$$E_y = \frac{t_{\frac{\alpha}{2}} * s_y}{\sqrt{n}} \qquad (4.4)$$

where E_y is the half width of the confidence interval for the mean of the logs, t is the student's t value at a prespecified confidence level (1-α), s_y is the standard deviation of the logs of the historical data, and n is the number of samples taken within a given period of time.

Again, the error was normalized by dividing the half width of the confidence interval by the historical mean. For the lognormal distribution, the half widths of the confidence interval were not equal, so the sum of the half widths was divided equally for calculating the percentage error of the historical mean. This method is represented below in Equation 4.5.

$$Error = \frac{\left(\frac{e^{\bar{y}+E_y} - e^{\bar{y}-E_y}}{2} \right)}{e^{\bar{y}}} \qquad (4.5)$$

where the Error is the percent error of the historical lognormal mean, E_y is the half width of the confidence interval in log terms, and $e^{\bar{y}}$ is the historical lognormal mean. This error is calculated for sampling frequencies of every other month, monthly, twice per month, weekly, and daily for the historical data in each season. Also, the error for the above frequencies is shown for confidence intervals of 90% and 95%. An example of the format used in presenting the results of sampling frequency estimation is shown in Figure 4.9 for estimating a specific conductance mean in the South Platte Headwaters watershed with 95% confidence. A complete results section for all watersheds and water quality parameters is presented in Appendix E.

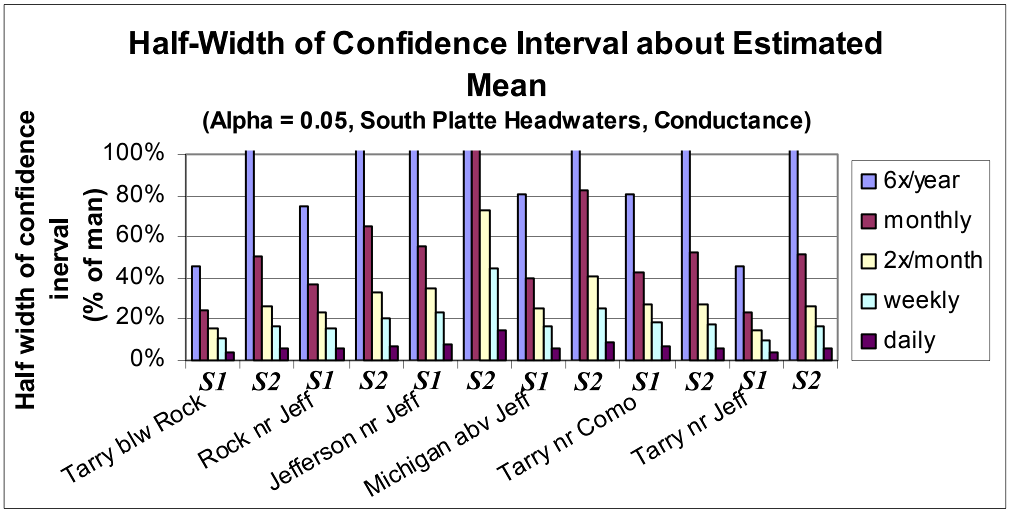


Figure 4.9: Half width of 95% confidence interval about estimated mean as percentage of historical mean for specific conductance at various water quality stations within the South Platte headwaters watershed – general sampling frequency results format for mean estimation.

Trends

The sampling frequency required for the detection of trends was estimated using Equation 4.6 shown below which assumes that data are sampled from normal distributions (Lettenmaier 1976). When data are routinely analyzed for trend, both seasonality and non-normality will be accounted for by the recommended trend detection analysis method in the new design, which is the seasonal Kendall test for trend (a seasonal, nonparametric statistical test). Estimation of sampling frequencies for nonparametric tests is often difficult. For this reason, normality was assumed for all the data used in sampling frequency estimation. Log transforming skewed data sets was not performed because a trend in log space is exponential, and the proposed monitoring system will be concerned primarily with linear trends.

$$trend = \sqrt{\frac{12 * s_{rd}{}^{2} * (t_{\alpha,\nu} + t_{\beta(1),\nu})^{2}}{n}} \tag{4.6}$$

where 'trend' is the minimum magnitude, in measured units, that is detectable, s^2 is the variance of the historical data, t is the student's t value (at a given confidence level, 1-α, and power, 1-β), and n is the number of samples taken within a given period of time.

This sampling frequency estimation is not exact, but provides a general indication of the minimum detectable trend for a given number of samples. A complicating factor in trend analysis is variation added by seasonal or other cycles, making it difficult to detect long-term trends. To help remedy this situation in frequency estimation, the variance in Equation 4.6 represents a regional deseasonalized variance (s_{rd}^2) within a watershed. This modification to the original equation is required because trends will be detected over years not seasons (as with mean estimation). Along with deseasonalizing the variance, historical data were collapsed on a regional basis to produce a single estimate of sampling frequency for the detection of trends. In other words, a sampling frequency was determined on a regional basis instead of the station-by-station sampling frequency calculations performed for means. The s_{rd}^2 is defined below in Equation 4.7.

$$S_{rd}^{\ 2} = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n}\left(x_{ij} - \bar{x}_j\right)^2}{\sum\left(M - n * g\right)} \tag{4.7}$$

where s_{rd}^2 is the regional deseasonalized variance, i=1 … m is the number of samples for a specific j=1 … n seasons , x_{ij} is the water quality data value for the i^{th} sample in the j^{th} season, $\bar{x}_j$ is the mean of the water quality data for season j, M is the total number of water quality data values, and g is the quantity of water quality stations within the region of interest. Application of the knowledge that the historical data are known to be represented by 2 distinct seasons (as defined for Denver Water), Equation 4.7 can be further reduced to Equation 4.8.

$$S_{rd}^{\ 2} = \frac{\sum_{i=1}^{m_1}\left(x_{i1} - \bar{x}_1\right)^2 + \sum_{i=1}^{m_2}\left(x_{i2} - \bar{x}_2\right)^2}{\sum\left(M - 2 * g\right)} \tag{4.8}$$

The sampling frequency estimation for determining the minimum detectable trend was also normalized to the historical mean of the data. This detectable trend, as a percentage of the mean, was calculated for sampling frequencies of every other month, monthly, twice per month, weekly, and daily. Also, confidence levels of 80% and 90% were used in the calculations along with power levels of 80% and 90%. An example of the results format is shown in Figure 4.10 for the South Platte Headwaters watershed with a confidence level of 90% and 80% power for a 5 year detectable trend. A complete display of results can be viewed in Appendix F.

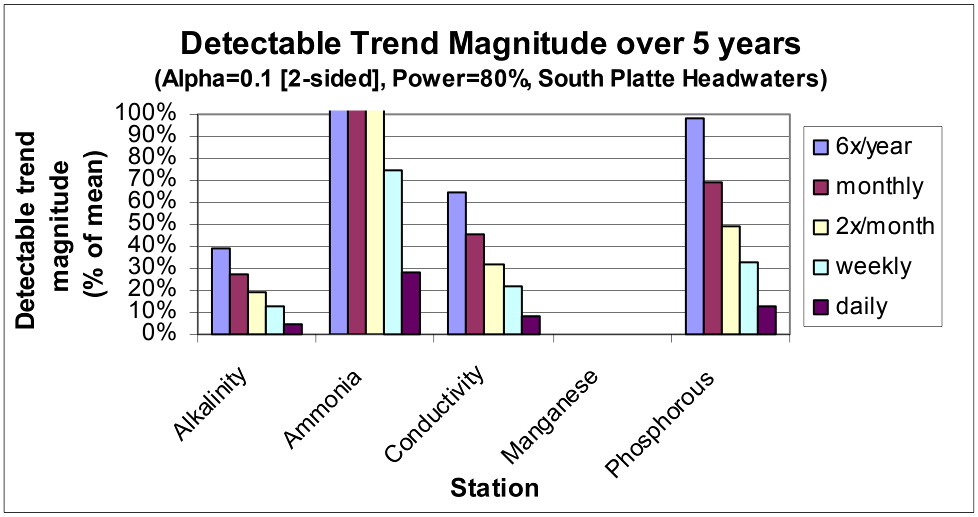


Figure 4.10: Minimum detectable specific conductance trend over 5 years as a percentage of the historical mean for various water quality stations within the South Platte headwaters watershed – general sampling frequency results format for trend detection.

Load estimation

The sampling frequency required for estimating loads with a known uncertainty was determined in a manner similar to that for means. A mean and standard deviation provided as output from a USGS computer program entitled “Loadest” were used in

Equations 4.2 and 4.3 above. All distributions were considered normal. Output for the South Platte watershed is shown below.

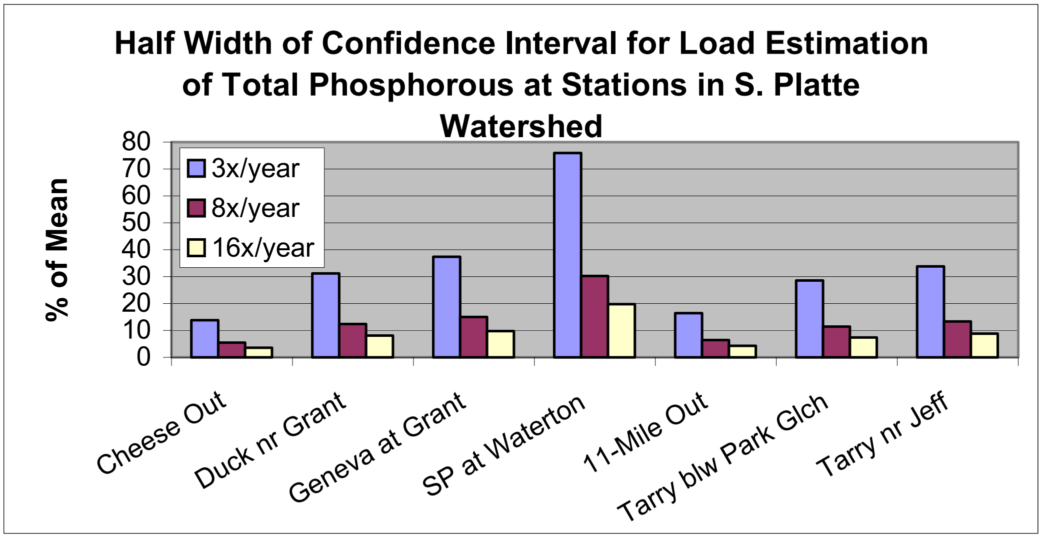


Figure 4.11: Half width of 95% confidence interval about estimated mass load as percentage of historical mean for total phosphorous at various water quality stations within the South Platte headwaters watershed – general sampling frequency results format for load estimation.

Results

A sampling frequency for each sampling site identified earlier was determined to be 8 samples during the high flow season and 4 samples during the low flow season. Although this frequency did not hold true for all sampling locations, on the whole, this is the “best compromise” result of the sample size estimation process – and should provide good results on the whole. More specifically, this sampling frequency would provide an average error of +/- 50% when estimating the means of water quality parameters. For trend detection, the proposed sampling frequency should provide a minimum detectable trend of approximately 70% of the mean for the variables used in the these calculations and under the conditions stated in Figure 4.10. Seasonal loads would be estimated with a confidence interval half-width of approximately 15% of the mean.

CHAPTER 5.0 RECOMMENDED ACTIONS FOR DENVER WATER TO EFFECTIVELY UTILIZE THE WATERSHED MONITORING PROGRAM DESIGN

Certain actions are necessary for Denver Water to implement this monitoring system design and begin generating high quality, usable information. Water quality information system design is an iterative process that does not end upon the completion of the initial design. As described earlier, some of the techniques utilized in this system design are rough approximations that require updating. Also, certain components of the monitoring design that are not discussed within this document must be checked to make sure they support the direction and goals of the current system. The following is a list of areas where Denver Water should be proactive in dealing with the source watershed monitoring system.

- *Data collection procedures*: a well designed monitoring network should include documentation describing the collection of data. Minimizing the variance in water quality data is not only done by efficient design techniques, but also through consistent data collection procedures. Areas of focus should be field sampling operations and procedures, laboratory analysis methods and operations, and data storage and retrieval. This is a case where a sound investment up front will result in a quality program.

- *Information generating and reporting procedures*: The recommended data analysis procedures for the Denver Water monitoring program were described in section 3.3. Actually ramping these prescribed procedures into a routine analysis and reporting system will be essential for producing the type and quality of information needed to meet the stated goals. Data analysis software such as Minitab, WQStat Plus, and Excel, exists to ease the transition to routine analysis and interpretation of data and reporting of information. Also, a documented agenda for reporting generated information should be constructed. A part of this task entails developing the media by which the newly generated information will be transferred, for example web-based or printed reports, newsletters, etc. If possible, gaining knowledge with respect to the end use of the data is beneficial for future adjustments to the system.

Micro Sampling Location

For each sampling location, the mixing of a water body becomes important to describe the water quality. This is especially true for Denver Water as a grab sample will be used to represent the entire cross section of water flowing past a specific point. Where a tributary or outfall enters a water body, analysis should be completed to ensure complete mixing of the sampling site. Sanders et al. (1983) present a practical method for this determination. Assuming the constituent distribution from the tributary or outfall is normally distributed, the distance from the outfall or tributary that a sample must be taken in a straight, uniform river/stream is given by Equation5.1.

$$L_y = \frac{\sigma_y{}^2 * u}{0.46 * d * u^*} \qquad (5.1)$$

where σ_y is the distance from the farthest lateral boundary to the point of injection, u is the mean stream velocity, d equals the depth of flow, u^* is defined as the shear velocity, which is equivalent to $\sqrt{}(gRs_e)$, where g is the acceleration due to gravity, R is the hydraulic radius, and S_e is the slope of the energy gradient.

The equation is very practical with the assumption that the slope of the energy gradient is equivalent to the bed slope of the stream/river (steady flow). Additionally, no temperature or concentration stratification should exist in the stream/river and the flow of the tributary or outfall should be negligible compared to the river/stream. In general, the distance for lateral mixing will be larger (thus limiting) than that for complete vertical mixing, which has a similar method for determining mixing length. As this method is empirical, it is by nature not precise and merely an estimation. Additional analysis could confirm any suspicions of incomplete mixing.

The micro location should also be well documented so that samples are taken from the same site every time. Samples taken from differing locations add to the overall variability measured in the water quality data when actually the variability lies in the sampling technique.

LITERATURE CITED

Adkins, N.C. 1993. A Framework for Development of Data Analysis Protocols for Ground Water Quality Monitoring. Technical Report No. 60, Colorado Water Resources Research Institute, Colorado State University, Fort Collins, Colorado.

Colorado Department of Local Affairs. 2000. *Demographic Data for the State of Colorado.* http://www.dlg.oem2.state.co.us/demog/demog.htm

Colorado Department of Public Health and Environment. 1999 *Classifications and Numeric Standards South Platte River Basin, Laramie River Basin, Republican River Basin, Smoky Hill River Basin.* Regulation No. 38, 140 p. Denver, CO.

Colorado Department of Public Health and Environment. 1999 *Classifications and Numeric Standards.* Regulation No. 38, 140 p. Denver, CO.

Corbridge Jr., James N. and Teresa A. Rice. *Vranesh's Colorado Water Law*. Revised Edition. 1999. University Press of Colorado, 628p. Niwot, CO.

Duan, N. 1983. Smearing estimate: a nonparametric retransformation method. *Journal of the American Statistical Association*. **78**(383).

EarthInfo, Inc. 1996. *United States Geological Survey Quality of Water: West 1 Surface*. Boulder, CO.

Ferguson, R.I. 1986. River loads underestimated by rating curves. *Water Resources Research*. **22**(1):74-76.

Gilbert, Richard O. 1987. *Statistical Methods for Environmental Pollution Monitoring*. Van Nostrand Reinhold, 320 p. New York, NY.

Greve, Adrienne I. 1999. Cooperative Design of a Water Quality Monitoring System for the Big Thompson River Watershed, Colorado. M.S. Thesis. Colorado State University, 129 p. Fort Collins, CO.

Lettenmaier, D.P. 1976. Detection of trends in water quality data from records with dependent observations. *Water Resources Research* **12**(5):1037-1046.

Lettenmaier, D.P., E.R. Hooper, C. Wagoner and K.B. Faris. 1991. Trends in stream quality in the continental United States. Water Resources Research, Vol 27(3):327-339.

Loftis, J.C., G.B. McBride and J.C. Ellis. 1991. Considerations of scale in water quality monitoring and data analysis. Water Resources Bulletin, Vol. 27(2):255-264.

National Research Council. 2000. Watershed management for potable water supply: assessing the New York City strategy. Committee to review the New York City watershed management strategy, water science and technology board, commission on geosciences, environment, and resources. National Academy Press, 549 p. Washington, D.C.

Sanders, T.G., R.C. Ward, J.C. Loftis, T.D. Steele, D.D. Adrian, and V. Yevjevich. 1983. *Design of Networks for Monitoring Water Quality*. Water Resources Publications, 328p. Littleton, CO.

USEPA. 1998. Better Assessment Science Integrating Point and Nonpoint Sources, BASINS Version 2.0: User's Manual. *EPA-823-B-98-006*. Office of Water, United States Environmental Protection Agency. Washington, DC.

USEPA. 1997. The safe drinking water act – one year later: success in advancing public health protection. *EPA-810-F-97-002*. Office of Water, United States Environmental Protection Agency. Washington, DC.

USEPA. 1997. State source water assessment and protection programs guidance: final guidance. *EPA-816-R-97-009.* Office of Water, United States Environmental Protection Agency. Washington, DC.

Ward, R.C. 1999. *Management and monitoring of water quality: class notes*. Colorado State University, Fort Collins,CO.

Ward, R.C. and L.J. Gronning. 2000. Quality monitoring of surface water resources for drinking water production. *the blue pages*, International Water Association.

Ward, R.C., J.C. Loftis, and G.B. McBride. 1990. *Design of Water Quality Monitoring Systems*. Van Nostrand Reinhold, 231p. New York, NY.

Ward, R.C., J.C. Loftis, and G.B. McBride. 1986. The "data-rich but information poor" syndrome in water quality monitoring. *Environmental Management* **10**(3): 291-297.

40 CFR 141. 2001. United States Environmental Protection Agency, "National Primary Drinking Water Regulations." *US Code of Federal Regulations.*

40 CFR 143. 2001. United States Environmental Protection Agency, "National Secondary Drinking Water Regulations." *US Code of Federal Regulations.*

66 FR 1671. January 9, 2001. United States Environmental Protection Agency, "Ecoregional Nutrient Criteria." *Federal Register.*

APPENDIX A: SUMMARY STATISTICS METHODS

Box and whisker plots

A center line (the median) splits a rectangle defined by the 75th and 25th percentile (upper and lower bounds respectively), also called the interquartile range (IQR). For methods on determining the median and IQR see description following. The whiskers are lines drawn to one step above and below the rectangle. A step is defined as 1.5 times the height of the IQR. Data points between 1 and 2 steps are displayed as asterisks ("outside values"). Outside values occur fewer than once in a 100 times for data from a normal distribution. Observations further than 2 steps are shown as circles ("far out values"). An example of a box and whiskers plot created in Minitab™ is shown below.

Maximum and minimum values

To quantify the range of values that a data set possesses the maximum and minimum values are determined. This is simply completed by identifying the maximum and minimum values.

Interquartile range

The IQR is defined as the 75th percentile minus the 25th percentile (Helsel and Hirsch 1992). For a data set ordered from smallest to largest:

$$x_i, for\ i = 1, \ldots, n \qquad \text{A.1}$$

Percentiles (P_j) are computed by equation A.2:

$$P_j = x_{(n+1)*j} \qquad \text{A.2}$$

where n = sample size of x_i, $_j$ = fraction of data less than or equal to the percentile value (e.g. 25th, 75th percentile, $_j$ = 0.25, 0.75). Note that non-integer values of (n+1)*j imply linear interpolation between adjacent values.

Sample median estimation

The sample median is a summary value that is not severely affected by outliers. It is simply $P_{0.50}$ from the IQR definition given previously. It is the central value of the distribution when the data are ranked in order of magnitude. For a data set ordered from smallest to largest:

$$x_i, for\ i = 1, \ldots, n \qquad \text{A.3}$$

The sample median ($P_{0.50}$) is calculated by Equation A.4:

$$P_{0.50} = x_{\frac{(n+1)}{2}} \text{ ;when n is odd} \qquad \text{A.4}$$

$$P_{0.50} = 0.5 * (x_{\frac{n}{2}} + x_{\left(\frac{n}{2}\right)+1}) \text{ ;when n is even} \qquad \text{A.5}$$

where n is the sample size of x_i.

Sample mean estimation

The sample mean is a measure of central tendency, which is influenced strongly by outlying values. The sample mean, $\bar{x}$, is computed as the sum of all data values x_i, divided by the sample size, n. As discussed prior, the sample means will be estimated on a seasonal basis to address seasonality with the water quality data. If annual sample mean estimates are desired the results should be flagged as the data analysis protocol dictates seasonal estimation. Sample mean estimation is dependent upon the statistical distribution from which the data were drawn. Within the context of this monitoring program data will be assumed to be drawn from either a normal or lognormal distribution. Although water quality data are known to be poorly behaved to either distribution their use is warranted as many methods used herein are independent of the distribution (nonparametric). Assuming the data were drawn randomly from a normal distribution, the sample mean is calculated using Equation A.6.

$$\bar{x} = \frac{1}{n} * \sum_{i=1}^{n} x_i \qquad \text{A.6}$$

where n is the sample size of x_i, for i,…,n data points. In the case that data are determined to be from a lognormal distribution, the sample mean is estimated according to Equation A.7.

$$\hat{\mu} = \exp(\bar{y} + \frac{s_y^{\ 2}}{2}) \qquad \text{A.7}$$

where $\bar{y}$ and s_y^2 are the sample mean and variance of the log transformed values.

Sample variance

The sample variance of a data set is defined as a measure of spread. Similar to the sample mean, it is strongly influenced by outlying values. The sample variance for data known to be drawn from a normal distribution is defined by Equation A.8.

$$s^2 = \frac{1}{n-1} * \sum_{i=1}^{n} (x_i - \bar{x})^2 \qquad \text{A.8}$$

where n is the sample size of x_i, for i,…,n data points and $\bar{x}$ is the sample mean determined earlier. Similarly, the sample variance of data drawn randomly from a lognormal distribution is represented by Equation A.9.

$$s_y{}^2 = \frac{1}{n-1} * \sum_{i=1}^{n} (y_i - \bar{y})^2 \qquad \text{A.9}$$

where n is the sample size of y_i, for i,…,n data points and $\bar{y}$ is the sample mean determined earlier for lognormally distributed data.

Confidence intervals

It is also advantageous to attach the level of uncertainty portraying the reliability, or lack thereof, associated with estimates of the mean. The confidence interval will be used for this purpose where it is defined as an interval having a stated probability of containing the true population mean. For data found to be from a normal distribution a confidence interval is calculated by Equation A.10 (Helsel and Hirsch 1992).

$$\bar{x} - t_{1-\frac{\alpha}{2},n-1} * \frac{s}{\sqrt{n}} \le \mu \le \bar{x} + t_{1-\frac{\alpha}{2},n-1} * \frac{s}{\sqrt{n}} \qquad \text{A.10}$$

where n is the sample size of x_i, for i,…,n data points (used in estimation of the sample mean), s is the sample standard deviation (from Equation X), and $t_{1-\alpha/2,\, n-1}$ is the value that cuts off $(100*\alpha/2)\%$ of the upper tail of the student's t distribution that has n-1 degrees of freedom. In the case of a lognormally distributed data set, the confidence limits about the true population mean is defined by Equation A.11.

$$\exp(\bar{y} + \left(0.5 * s_y{}^2\right) + \left(\frac{s_y * H_\alpha}{\sqrt{n-1}}\right) \le \mu \le \exp(\bar{y} + \left(0.5 * s_y{}^2\right) + \left(\frac{s_y * H_{1-\alpha}}{\sqrt{n-1}}\right) \qquad \text{A.11}$$

where n is the sample size of y_i, for i,…,n data points used in estimation of the sample mean, $\bar{y}$, s_y and s_y^2 are the sample standard deviation and variance respectively (from Equation X), and $H_{1-\alpha}$ and H_α are the tabulated values (Land 1975) for the $[100*(1-\alpha)]\%$ upper and $[100*\alpha]\%$ lower confidence limits about the true mean.

Probability plots

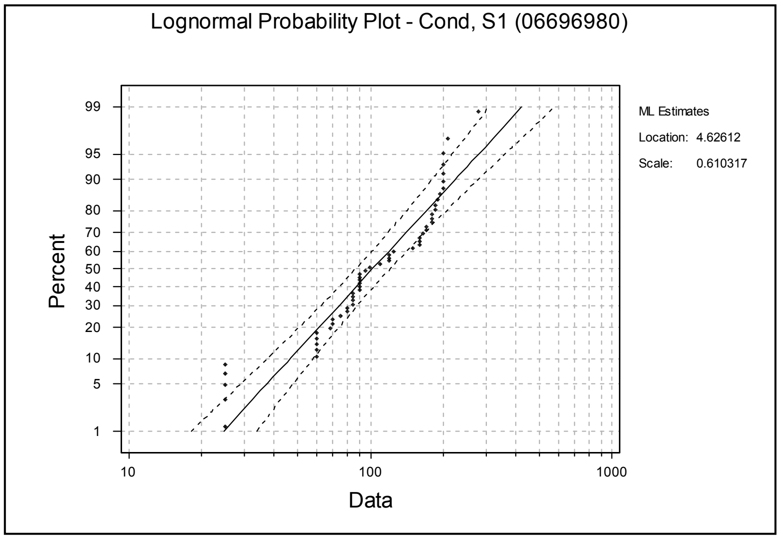
To distinguish if data exhibits behavior indicative of being drawn from a normal or lognormal distribution is completed by using probability plots. Probability plots are constructed by plotting the cumulative probabilities (displayed as percentage probability of occurrence) versus the data (or log transformed data) on probability paper. Depending on whether the data or log transformed data form a good linear fit with the estimated cumulative probabilities dictates what distribution is estimated for the source of the data. For a data set ordered from smallest to largest:

$$x_i, \mathit{for}\ i = 1,\ldots,n \tag{A.12}$$

Plotting positions are determined (method shown from Helsel and Hirsch (1992)) by Equation A.13.

$$p_i = \frac{(i - 0.4)}{(n + 0.2)} \tag{A.13}$$

where n is the sample size of x_i. For each plotting position (p_i), the corresponding value of the standard normal distribution is found such that $\text{prob}(Z \le \phi^{-1}(p) = p)$. This value of the standard normal distribution, Z, is used as the cumulative probability and plotted versus the raw and log transformed data. An example of this process for log transformed data as completed in the Minitab statistical software is shown in the figure below.



Note that other methods exist for determining a statistical distribution fit to a data set. If a method is found that expatiates the process, then it should be used. Consistency in methods is the key for producing defensible data.

APPENDIX B: SEASONAL KENDALL TREND METHODS

Seasonal Kendall Trend Test

The Seasonal Kendall trend analysis will be carried out using WQStat Plus (IDT 1998). The computations for both the seasonal Kendall slope estimator and the Seasonal Kendall hypothesis test for trend are given below. For more detailed insight into these procedures see the existing literature on the topic (Gilbert 1987, Hirsch et al. 1982).

Table C.1: Data for a given site (Gilbert 1987)

		Season			
		1	2	3	K
	1	x_{11}	x_{21}	…	x_{K1}
year	2	x_{12}	x_{22}	…	x_{K2}
	…				
	L	x_{1L}	x_{2L}	…	x_{K3}
		S_1	S_2	…	S_K

Let x_{il} be the datum for the ith season of the lth year, K is the number of seasons, and L the number of years. Table C.1 shows data with seasonal cycles present for a given sampling site. The null hypothesis of the trend test (H_O) states that the x_{il} are independent of the time (season and year) they were collected. The alternative hypothesis (H_A) against which H_O is tested states that for one or more seasons the data are not independent of time.

The Mann-Kendall test statistic, S, is computed for each season. Let S_i be this statistic for the ith season.

$$S_i = \sum_{k=1}^{n_i-1} \sum_{l=k+1}^{n_i} \operatorname{sgn}(x_{il} - x_{ik}) \tag{B.1}$$

where n_i is the number of samples in season i over years, x_{il} is the datum for the ith season of the lth year, x_{ik} is the datum for the ith season of the kth year, $l > k$, and:

$$\begin{aligned} \operatorname{sgn}(x_{il} - x_{ik}) &= 1 \quad \mathit{if}\ x_{il} - x_{ik} > 0 \\ &= 0 \quad \mathit{if}\ x_{il} - x_{ik} = 0 \\ &= -1 \quad \mathit{if}\ x_{il} - x_{ik} < 0 \end{aligned} \tag{B.2}$$

The variance for each season, i, can then be computed as follows:

$$VAR(S_i) = \frac{1}{18}\left[n_i(n_i-1)(2n_i+5) - \sum_{p=1}^{g_i} t_{ip}(t_{ip}-1)(2t_{ip}+5) - \sum_{q=1}^{h_i} u_{iq}(u_{iq}-1)(2u_{iq}+5)\right]$$

$$+ \frac{\sum_{p=1}^{g_i} t_{ip}(t_{ip}-1)(t_{ip}-2)\sum_{q=1}^{h_i} u_{iq}(u_{iq}-1)(u_{iq}-2)}{9n_i(n_i-1)(n_i-2)} + \frac{\sum_{p=1}^{g_i} t_{ip}(t_{ip}-1)\sum_{q=1}^{g_i} u_{iq}(u_{iq}-1)}{2n_i(n_i-1)} \qquad \text{B.3}$$

where g_i is the number of groups of tied data in season i, t_{ip} is the number of tied data in the p^{th} group for season i, h_i is the number of sampling times (or time periods) in season i that contain multiple data, u_{iq} is the number of multiple data in the q^{th} time period in season i, and n_i is the number of samples for the ith season over years.

After the S_i and the $Var(S_i)$ are computed, then pool across the K seasons to compute the pooled variance and the Z value to test H_O that no trend exists.

$$S' = \sum_{i=1}^{K} S_h \qquad \text{B.4}$$

$$VAR(S') = \sum_{i=1}^{K} VAR(S_i) \qquad \text{B.5}$$

$$\begin{aligned} Z &= \frac{(S'-1)}{[VAR(S')]^{\frac{1}{2}}} && \mathit{if}\ S' > 0 \\ Z &= 0 && \mathit{if}\ S' = 0 \\ Z &= \frac{(S'+1)}{[VAR(S')]^{\frac{1}{2}}} && \mathit{if}\ S' < 0 \end{aligned} \qquad \text{B.6}$$

H_O: no trend exists, is rejected versus the H_A: an upward or downward trend exists when the following conditions are true:

$$\text{no trend, reject } H_o \text{ if } |Z| > Z_{1-\frac{\alpha}{2}} \qquad \text{where } Z_{1-\frac{\alpha}{2}} \text{ is a table vaue and } \alpha = 0.05$$

The magnitude of the slope can be determined by first computing the slope between each pair of observations across years for the ith season (N_i) using the following equation:

$$Q_i = \frac{x_{il} - x_{ik}}{1 - k} \qquad \text{B.7}$$

where x_{il} is the datum for the ith season of the lth year, x_{ik} is the datum for the ith season of the kth year, and l>k.

This is done for each of the K seasons, then the $N' = N_1' + N_2' + \ldots + N_K'$ individual slope estimates are ranked and the median is found. This median is the seasonal Kendall slope estimator.

A 100(1-α)% confidence interval about the true slope can be obtained using the methods discussed in Section 16.5 of Gilbert (1987).

APPENDIX C: REGRESSION BASED NONPARAMETRIC LOAD ESTIMATION TECHNIQUE

The instantaneous load of a solute or pollutant is the product of its concentration and the discharge of water. Over a period of time the load equates to the following:

$$L = \int_{0}^{t} CQdt \qquad \text{C.1}$$

where C is the concentration of the solute or pollutant, Q is the discharge, and t is the time period for which the load is determined. The availability of concentration and discharge data tend to exist at different time scales. Usually discharge data is available at hourly increments, but concentrations are not. This situation is dealt with by replacing the concentrations in the equation above with estimates produced from an observed empirical relationship or rating curve. Traditionally, the rating curve has been the least squares regression equation with lo g transformed data.

$$\log Ci = \beta_0 + \beta_1 \log Qi \qquad \text{C.2}$$

Ferguson (1986) showed that the rating curve method introduced bias to the load estimation when retransformation of the estimates to real space was done. Loads were shown to be underestimated by as much as 50%. Ferguson suggests the use of a bias correction factor for correcting the underestimation. The rating curve with the bias correction is described as the quasi maximum likelihood estimator. For this estimator, the residuals (in natural log units) are assumed to be normal. An alternative to this parametric approach is a smearing estimator proposed by Duan (1982) which implements a bias correction factor equal to the average of the exponentiated log regression residuals:

$$\hat{L}_{SM}(i) = \hat{L}_{RC}(i) \frac{1}{M} \sum_{j=1}^{M} \exp(e(j)) \qquad \text{C.3}$$

where L_{SM} is the load estimated using the smearing estimator, L_{RC} is the rating curve estimate of the load, M is the number of concurrent values of response and explanatory variables, and e(j) is the average of the exponentiated log regression residuals.

According to Gilroy et al. (1990), the smearing technique corrects the bias introduced in retransformation to real space relatively well. For instance, the smearing estimator had a root mean square error comparable to a unbiased estimator in Gilroy et al. (1990) under the assumptions of normality and independence of the residuals. Given the common occurrence where the actual model is non-normal it is assumed that the smearing estimate, with no model necessary model assumptions, will produce a load estimate with equivalent or better root mean square errors than unbiased parametric estimators.

APPENDIX D: DENVER WATER MONITORING PROGRAM COST COMPARISON

A comparitive cost analysis was performed for Denver Water's current and proposed monitoring system. The purpose of the analysis was to estimate the increased cost associated with the proposed monitoring system (a cost increase for the proposed system is inevitable as more samples will be taken at the same number of sampling sites). Specifically, the difference in sampling and analysis costs for each monitoring system was compared. Costs for equipment, maintenance, data analysis, and reporting were not accounted for, but are costs associated with all monitoring systems. Also, it should be noted that the cost estimations calculated were based on a series of assumptions and resulting values are merely approximations. For example, Denver Water does not have a defined rate structure for water analysis so assumptions were made to attach costs to different analytical methods.

A methodology was formulated that enabled cost estimates for both the current and proposed monitoring programs to be comparable. This methodology was a result of collaboration between Bruce Hale, Denver Water chemist and Justin Twenter, Colorado State University graduate student. Synopses of Bruce Hale's initial methodology and a modified version compiled by Justin Twenter are shown below for reference. Note that the conditions listed in Twenter's notes were those used in the cost analysis for which results are shown. In general, the current and proposed sampling sites were grouped into zones for estimation of sampling costs. Then, depending on the information goal being addressed at a sampling site, analysis costs were estimated for Denver Water and three other analytical laboratories. The sum of these two values represent the total estimated cost for sampling and analysis.

"Bruce Hale's Method" [received this information via e mail from Bruce Hale, Denver Water Department on 23 Jan 2001]

Pricing watershed collection and analysis

Sample collection:

1. I rated collection differently depending upon how far from the lab samples are collected. I made 3 zones: Zone 1, within 15 mile radius (covers the Platte confluence, DIA, Ralston, etc.), Zone 2, within 30 mile radius (includes Cheesman Res., Roberts Tunnel, Fraser R., Gross Res., etc.), and Zone 3, within 45 mile radius (includes Antero, Williams Fork, Dillon, Elevenmile, etc.). All distances are from Marston.
2. I made all my time estimates for a group of 4 samples or less. The estimate per sample (for a 5th or 6th sample) would be 1/4th of the estimate for the first 4.
3. For labor expense, I rated the number of tech hours spent, by zone (assume $20/hr labor- the rate of WQ Investigator 2 [step 8] or WQ Investigator 3 [step 4]): In Zone 1, one tech can take 4 samples in 4 hours (on the average)-$80 per trip or $20/sample. In Zone 2, we generally use 2 techs, and collecting 4 samples takes about 6 hours (12, total), for $240 per trip, or $60/sample. In Zone 3, we generally use 2 techs, and collecting 4 samples takes 8 hours (on the average), for $320 per trip, or $80/sample.
4. I also rated vehicle expense by zone, using the factor of $0.52/mile (as per Cheryl McKinney). Assume that to get to each radius distance, one would travel 25% extra mileage, therefore, to get to DIA (14 miles, as the crow flies) it takes about 35 miles

round trip, times 0.52, gives about $20 per trip in Zone 1. In Zone 2, it's $40/trip, and in Zone 3, it's about $60/trip.

5. Field analyses: I'm in a quandary over whether field analyses should be included in the cost of collection, or in the cost of analytical work. Field analyses include: temperature, pH, specific cond., and turbidity. The typical lab charge for each of these would be about $4, $10, $8, and $12, respectively ($34, total). I tend to think the hourly rate, above, should be higher to include these costs, especially for Zone 1. In such a scheme, the minimum charge per sample (including labor, travel, and analysis) would be $35.
6. Hence, the total cost for collection of samples in Zone 1 would be approx. $35/sample, for Zone 2, $70/sample, and in Zone 3, $100/sample.

Sample analysis:

1. Here are the prices we could charge for the analytical work we perform on samples taken from the watershed which require the "basic" parameter set.
    - T. coli-E. coli: $25
    - T. Hardness: $12
    - T. Alkalinity: $12
    - DO (Hach): $12
    - NH3 (Hach): $12
    - Flow: $8 (a field flow measurement would be included in the price of collection?)
    - TOC: $30
    - TSS: $12
    - Metals prep: $10
    - T. & Diss. Fe: $10x2=$20
    - T. & Diss. Mn: $10x2=$20
    - T. phos: $30

The total charge for these tests would be $203. These prices are within ±$5/test of the going rate in most labs.

2. We have been talking of purchasing an automated ammonia/T. phosphorus analyzer. With this instrument, we could:
    - Increase the throughput for both analyses.
    - Improve the MRL for ammonia below 0.01-0.02 mg/L (the Hach MRL is 0.05 mg/L), a necessity for environmental samples.
    - Improve the holding time constraints for ammonia (they must be analyzed within 24hrs by the Hach method, and within 28 days by auto analyzer).
    - Reduce the overall expense for both tests, from $42 to $30 per sample. A Lachat automated ammonia/T. phosphorus analyzer (the only one capable of doing TOTAL phos w/ an in-line digestion) costs approximately $50K. The proposed WS sampling program will generate 286 NH3/Tphos samples per year. The

yearly savings from using an automated ammonia/T. phosphorus analyzer would be approximately $3.4K. Over the lifetime of the instrument, more than half of its cost would be made back from time savings over our present methods. Further, by reducing the cost and time of NH3/Tphos analysis, the WQ Section may offer it as a reasonable analytical service for others who wish to piggyback on our watershed monitoring efforts.

3. The upcoming purchase of our ICP/MS will reduce the cost of metals (iron and manganese) analyses from $10 to $8/element, or a $8 savings per routine WS sample. Having both the ICP/MS and the NH3/Tphos analyzer would be tantamount to discounting the cost of the above tests by 10%, to $183/sample.
4. Of course, we test some locations for more than the "basics". I have not developed costs for any of these analyses, except Anions (EPA 300.0):
    - Most labs charge more if the requester asks for individual components (such as nitrate and nitrite, $10 each) than for all 7 components, $60. This price is competitive with what other labs charge.
    - We now perform this test on all terminal reservoir influents. These 3 locations alone would generate 48 samples/year under our proposed program, worth nearly $2.9K in anion analyses.

General notes by Justin Twenter on the cost analysis procedure used [16 May 2001]:

1. Sample collection costs stated by Hale did not coincide with the description given (see "Bruce_Hale's_Method" worksheet).

    Assumptions used for the analysis:

    (1) Cost of field analyses is factored into Labor charge calculated,
    (2) the travel cost can be subdivided into a "per sample" quantity for accounting purposes, and
    (3) flow is charged as a "field analysis" rather than a "basic" analysis (therefore cost is absorbed by labor).
2. The zone in which each sampling site is located was selected by J. Twenter subjectively based on zone definitions below -- these should be checked.
3. Assumption: cost incurred when the assumed 4 samples per collection trip is not fulfilled is not accounted for.
4. Denver Water analysis prices are used in determination of the total program cost -- the other prices (from outside labs) given are for comparison purposes.
5. Calculation Methodology (used in creation of "Cost" worksheet):
    - Zone Designation:
        i. Zone 1 - 15 mile radius measured from Marston Reservoir/facilities
        ii. Zone 2 - 30 mile radius measured from Marston Reservoir/facilities
        iii. Zone 3 - 45 mile radius measured from Marston Reservoir/facilities
        iv. Zone 4 - 60 mile radius measured from Marston Reservoir/facilities

        *(see the attached worksheet - "Cost" - to see which sampling sites were assigned to each zone)

- Labor Cost:

  *(it was assumed (per Hale) that 4 samples or less would be collected)

  *(the tech fee of $20.00 per hour was used (per Hale))

    i. Zone 1 - 4 samples collected in 4 hours (1 technician required @ 20.00/hr) = $20.00 per sample
    ii. Zone 2 - 4 samples collected in 6 hours (2 technicians required @ 20.00/hr) = $60.00 per sample
    iii. Zone 3 - 4 samples collected in 8 hours (2 technicians required @ 20.00/hr) = $80.00 per sample
    iv. Zone 4 - 3 samples collected in 8 hours (2 technicians required @ 20.00/hr) = $110.00 per sample

  *(note that it was assumed that only 3 samples could be collected in a 8 hour time period)

- Travel Cost

  *(Assumption of 25% extra mileage, round-trip, required in addition to distance as the crow flies)

  *(Assumption of $0.52 per mile vehicle cost per Hale (from Cheryl McKinney))

  i. Zone 1 - (15 miles x 2) x 1.25 x 0.52 = $20.00 per trip = $5.00 per sample
  ii. Zone 2 - (30 miles x 2) x 1.25 x 0.52 = $40.00 per trip = $10.00 per sample
  iii. Zone 3 - (45 miles x 2) x 1.25 x 0.52 = $60.00 per trip = $15.00 per sample
  iv. Zone 4 - (60 miles x 2) x 1.25 x 0.52 = $78.00 per trip = $20.00 per sample

- Field Material Cost

  i. Temperature, pH, specific conductivity, and turbidity analysis (which is completed in the field) are priced at a flat rate of $10.00 as technician fees are factored into the labor calculated above - leaving materials required for completion of the analysis as the only cost.

Figure D.1 displays the zones created along with Denver Water's monitoring sites. Only the proposed set of Denver Water monitoring sites are displayed because the proposed sites are the same as the current with an additional six locations per the new source watershed monitoring system design. Recall that Zone 1 is a 15 mile radius from Marston Reservoir/facilities, Zone 2 is a 30 mile radius, Zone 3 is a 45 mile radius, and Zone 4 is a 60 mile radius. The purpose of Figure D.1 is to present the distribution of sampling sites per zone for reference to the cost analysis results.

Tables D.1a through D.1c contain estimated analysis costs for Denver Water and three commercial analytical water quality laboratories. Costs were determined for each parameter given price lists from the commercial labs and estimated costs from Denver Water (per Bruce Hale). A total analysis cost was calculated for each sampling suite intended for use in the Denver Water monitoring system. Total costs for Denver Water and the laboratories per suite are considered comparable even though some laboratories cannot complete certain analyses and therefore do not represent a true “total” cost. Accounting for missing analyses costs reveals that Denver Water is the most economical solution for analytical measurement of water quality samples. Note that field sampling was not included in analysis costs as described in the methodology.

FIGURE D.1: SAMPLING ZONES FOR DENVER WATER SAMPLING SITES DEFINED FOR PROPOSED AND CURRENT MONITORING SYSTEM COST ANALYSIS. DATA SOURCES:

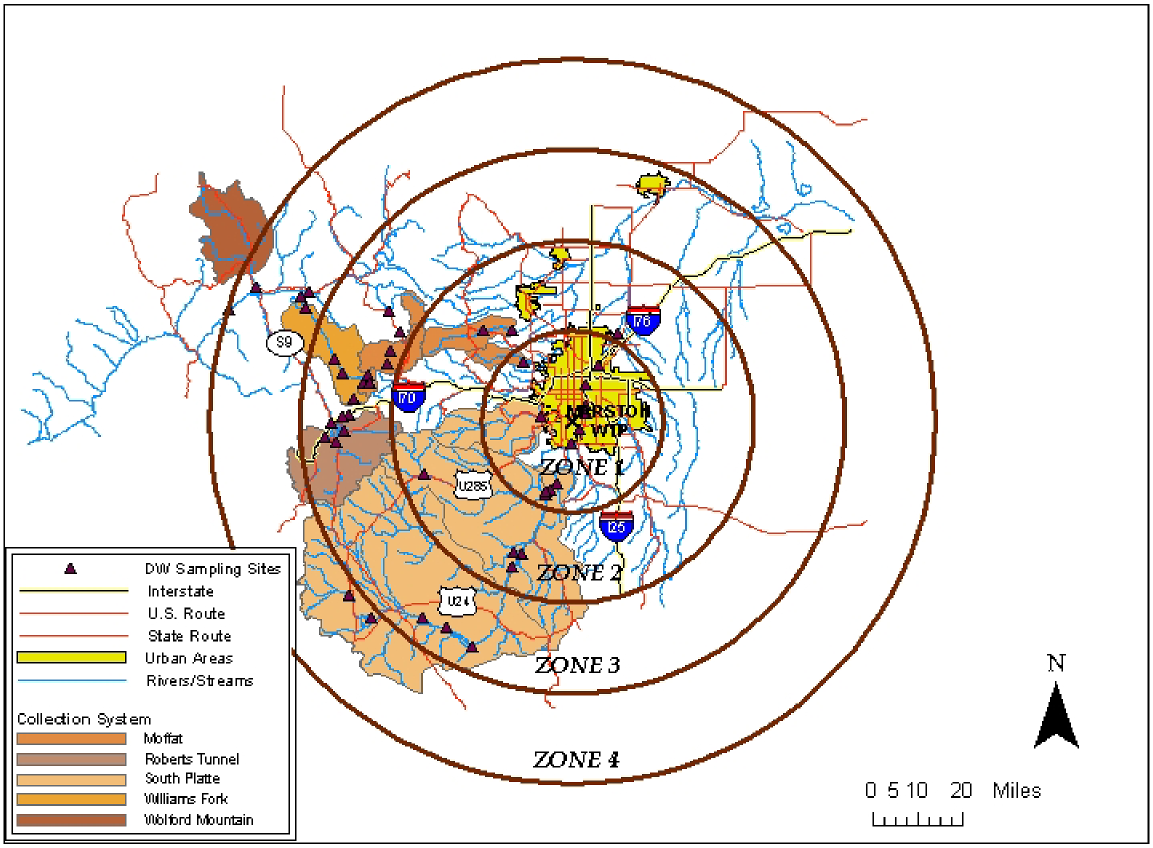


Table D.2 shows the combined cost analysis for both sampling and analysis of Denver Water’s current and proposed monitoring system. The costs are disaggregated into travel, labor, field, and analysis components.

TABLE D.1a: DENVER WATER

WS-TL1("basic")					**WS-TL2**					**WS-TL3**				
	Denver	*Stewart*	*Warren*	*Accu*		*Denver*	*Stewart*	*Warren*	*Accu*		*Denver*	*Stewart*	*Warren*	*Accu*
	Water	*Env*	*Lab*	*Labs*		*Water*	*Env.*	*Lab*	*Labs*		*Water*	*Env.*	*Lab*	*Labs*
Coli (MPN)	25	75	n/a	30	Coli (MPN)	25	75	n/a	30	Coli (MPN)	25	75	n/a	30
Temperature	n/c	n/c	n/c	n/c	Temperature	n/c	n/c	n/c	n/c	Temperature	n/c	n/c	n/c	n/c
pH	n/c	n/c	n/c	n/c	pH	n/c	n/c	n/c	n/c	pH	n/c	n/c	n/c	n/c
Tot Hardness	12	18	18	25	Tot Hardness	12	18	18	25	Tot Hardness	12	18	18	25
Tot Alkalinity	12	18	13	15	Tot Alkalinity	12	18	13	15	Tot Alkalinity	12	18	13	15
Specific Cond.	n/c	n/c	n/c	n/c	Specific Cond.	n/c	n/c	n/c	n/c	Specific Cond.	n/c	n/c	n/c	n/c
Turbidity	n/c	n/c	n/c	n/c	Turbidity	n/c	n/c	n/c	n/c	Turbidity	n/c	n/c	n/c	n/c
DO (titr)	12	18	16	n/a	DO (titr)	12	18	n/a	n/a	DO (titr)	12	18	16	n/a
NH^3	12	18	20	12	NH^3	12	18	20	12	NH^3	12	18	20	12
Flow	n/c	n/c	n/c	n/c	Flow	n/c	n/c	n/c	n/c	Flow	n/c	n/c	n/c	n/c
TOC	30	n/a	n/a	30	TOC	30	n/a	n/a	30	TOC	30	n/a	n/a	30
TSS	12	18	15	12	TSS	12	18	15	12	TSS	12	18	15	12
Fe	10	18	15	11	Fe	10	18	15	11	Fe	10	18	15	11
Fe, diss.	10	18	15	11	Fe, diss.	10	18	15	11	Fe, diss.	10	18	15	11
Mn	10	18	15	11	Mn	10	18	15	11	Mn	10	18	15	11
Mn, diss	10	18	15	11	Mn, diss	10	18	15	11	Mn, diss	10	18	15	11
Tot Phosphorus	30	35	15	25	Tot Phosphorus	30	35	15	25	Tot Phosphorus	30	35	15	25
(metals prep)	10	18	12	15	(metals prep)	10	18	12	15	(metals prep)	10	18	12	15
					F		25	24		F		25	24	
					Cl		22	12		Cl		22	12	
					NO^2		25	20	25	NO^2		25	20	25
					Br		18	n/a		Br		18		
					NO^3		30	20	25	NO^3		30	20	25
					o-phos		25	18		o-phos		25	18	
					SO^4	60	30	24	70	SO^4	60	30	24	70
					TKN	65	40	17	65	Mo	15	18	18	11
										Mo, diss.	15	18	18	11
TOTAL	**$195**	**$290**	**$169**	**$208**		**$320**	**$505**	**$288**	**$393**		**$285**	**$501**	**$323**	**$350**

TABLE D.1b: DENVER WATER

WS-TL4	*Denver Water*	*Stewart Env*	*Warren Lab*	*Accu Labs*	**WS-TL5**	*Denver Water*	*Stewart Env.*	*Warren Lab*	*Accu Labs*	**WS-TL6**	*Denver Water*	*Stewart Env.*	*Warren Lab*	*Accu Labs*
Coli (MPN)	25	75	n/a	30	Coli (MPN)	25	75	n/a	30	Coli (MPN)	25	75	n/a	30
Temperature	n/c	n/c	n/c	n/c	Temperature	n/c	n/c	n/c	n/c	Temperature	n/c	n/c	n/c	n/c
pH	n/c	n/c	n/c	n/c	pH	n/c	n/c	n/c	n/c	pH	n/c	n/c	n/c	n/c
Tot Hardness	12	18	18	25	Tot Hardness	12	18	18	25	Tot Hardness	12	18	18	25
Tot Alkalinity	12	18	13	15	Tot Alkalinity	12	18	13	15	Tot Alkalinity	12	18	13	15
Specific Cond.	n/c	n/c	n/c	n/c	Specific Cond.	n/c	n/c	n/c	n/c	Specific Cond.	n/c	n/c	n/c	n/c
Turbidity	n/c	n/c	n/c	n/c	Turbidity	n/c	n/c	n/c	n/c	Turbidity	n/c	n/c	n/c	n/c
DO (titr)	12	18	16	n/a	DO (titr)	12	18	16	n/a	DO (titr)	12	18	16	n/a
NH^3	12	18	20	12	NH^3	12	18	20	12	NH^3	12	18	20	12
Flow	n/c	n/c	n/c	n/c	Flow	n/c	n/c	n/c	n/c	Flow	n/c	n/c	n/c	n/c
TOC	30	n/a	n/a	30	TOC	30	n/a	n/a	30	TOC	30	n/a	n/a	30
TSS	12	18	15	12	TSS	12	18	15	12	TSS	12	18	15	12
Fe	10	18	15	11	Fe	10	18	15	11	Fe	10	18	15	11
Fe, diss.	10	18	15	11	Fe, diss.	10	18	15	11	Fe, diss.	10	18	15	11
Mn	10	18	15	11	Mn	10	18	15	11	Mn	10	18	15	11
Mn, diss	10	18	15	11	Mn, diss	10	18	15	11	Mn, diss	10	18	15	11
Tot Phosphorus	30	35	15	25	Tot Phosphorus	30	35	15	25	Tot Phosphorus	30	35	15	25
(metals prep)	10	18	12	15	(metals prep)	10	18	12	15	(metals prep)	10	18	12	15
F		25	24		Na		18	15	11	Na		18	15	11
Cl		22	12		K		18	15	11	K		18	15	11
NO^2		25	20	25	Mg		18	15	11	Mg		18	15	11
Br		18	n/a		Ca	40	18	15	11	Ca	40	18	15	11
NO^3		30	20	25	Zn	10	18	18	11	Zn	10	18	18	11
o-phos		25	18		Zn, diss.	10	18	18	11	Zn, diss.	10	18	18	11
SO^4	60	30	24	70	Cd	15	18	18	11	Cd	15	18	18	11
Uranium (avail)	15	n/a	n/a	53	Cd, diss	15	18	18	11	Cd, diss	15	18	18	11
										Mo	15	18	18	11
										Mo, diss.	15	18	18	11

TOTAL	***$270***	***$465***	***$287***	***$381***		***$285***	***$434***	***$301***	***$296***		***$315***	***$470***	***$337***	***$318***

TABLE D.1c: DENVER WATER

WS-TL8														
	Denver	*Stewart*	*Warren*	*Accu*										
	Water	*Env*	*Lab*	*Labs*										
Coli (MPN)	25	75	n/a	30										
Temperature	n/c	n/c	n/c	n/c										
pH	n/c	n/c	n/c	n/c										
Tot Hardness	12	18	18	25										
Tot Alkalinity	12	18	13	15										
Specific Cond.	n/c	n/c	n/c	n/c										
Turbidity	n/c	n/c	n/c	n/c										
DO (titr)	12	18	16	n/a										
NH^3	12	18	20	12										
Flow	n/c	n/c	n/c	n/c										
TOC	30	n/a	n/a	30										
TSS	12	18	15	12										
Fe	10	18	15	11										
Fe, diss.	10	18	15	11										
Mn	10	18	15	11										
Mn, diss	10	18	15	11										
Tot Phosphorus	30	35	15	25										
(metals prep)	10	18	12	15										
Mo	15	18	18	11										
Mo, diss.	15	18	18	11										

TOTAL	***$225***	***$326***	***$205***	***$230***										

TABLE D.2: SAMPLING AND ANALYSIS COST ASSOCIATED WITH EACH DENVER WATER MONITORING SITE – BOTH CURRENT AND PROPOSED.

						(Proposed)	***(Current)***	***Travel Cost***	***Labor Cost***	***Field Cost***	***Analysis Cost***	***Total Cost***	***Total Cost***
Watershed	***Site ID***	***Site Name***	***Type***	***Suite ID***	***Zone***	***Smpls/yr***	***Smpls/yr***	***(/Smpl)***	***(/Smpl)***	***(mat.)***	***(/Smpl)***	***(proposed)***	***(current)***
Blue Lake (BL)	001	Blue R Inlet @ Dillon Res	Storage Res In/Out	TL5	3	8	3	$15	$80	$10	$285	$3,117	$1,169
	002	Snake R Inlet @ Dillon Res	Storage Res In/Out	TL5	3	8	3	$15	$80	$10	$285	$3,117	$1,169
	003	Ten Mile C Inlet @ Dillon Res	Storage Res In/Out	TL6	3	8	3	$15	$80	$10	$315	$3,357	$1,259
	004	Blue R Outlet @ Dillon Res	Storage Res In/Out	TL6	3	8	3	$15	$80	$10	$315	$3,357	$1,259
	005	E Portal of Roberts Tunnel	Storage Res In/Out	TL8	3	8	3	$15	$80	$10	$225	$2,637	$989
	006	Straight C 1.3 miles abv Dillon div structure	Due diligence	TL5	3	2	3	$15	$80	$10	$285	$779	$1,169
	007	Straight C blw Dillon div structure	Due diligence	TL5	3	2	3	$15	$80	$10	$285	$779	$1,169
	021	Blue R blw Green Mtn Res	Colorado R Agrmt	TL1	2	4		$10	$60	$10	$195	$1,099	$0

						(Proposed)	(Current)	Travel Cost	Labor Cost	Field Cost	Analysis Cost	Total Cost	Total Cost
Watershed	**Site ID**	**Site Name**	**Type**	**Suite ID**	**Zone**	**Smpls/yr**	**Smpls/yr**	**(/Smpl)**	**(/Smpl)**	**(mat.)**	**(/Smpl)**	**(proposed)**	**(current)**
Ralston C (RL)	001	S Boulder C @ Pine Cliff	Storage Res In/Out	TL1	2	8	3	$10	$60	$10	$195	$2,198	$824
	002	S Boulder C @ S Boulder canal div	Terminal Res Inf	TL4	2	16	6	$10	$60	$10	$270	$5,596	$2,099
	003	Ralston C @ Long Lk headgate	Terminal Res Inf	TL4	1	16	6	$5	$20	$10	$270	$4,878	$1,829
Colorado River	001	Muddy C u/s of Wolford Mtn Res	Colorado R Agrmt	TL1	4	4		$20	$110	$10	$195	$1,338	$0
	002	Colorado R @ Gore Trail trailhead	Colorado R Agrmt	TL1	4	4		$20	$110	$10	$195	$1,338	$0
	003	Colorado R N of Parshall	Colorado R Agrmt	TL1	4	4		$20	$110	$10	$195	$1,338	$0
	004	Colorado R blw Williams Fork R	Colorado R Agrmt	TL1	4	4		$20	$110	$10	$195	$1,338	$0
L. Platte (LP)	001	Strontia Springs Res. effluent	Terminal Res. Inf.	TL3	1	16	6	$5	$20	$10	$285	$5,118	$1,919
	002	Chatfield Res eff	Exchange/Irrigation	TL2	1	4	5	$5	$20	$10	$320	$1,420	$1,774
	003	S Platte R blw Dutch C (Littleton)	Exchange/Irrigation	TL2	1	4	5	$5	$20	$10	$320	$1,420	$1,774
	004	S Platte R N of	Exchange/Irrigation	TL2	1	4	5	$5	$20	$10	$320	$1,420	$1,774

						(Proposed)	***(Current)***	***Travel Cost***	***Labor Cost***	***Field Cost***	***Analysis Cost***	***Total Cost***	***Total Cost***
Watershed	***Site ID***	***Site Name***	***Type***	***Suite ID***	***Zone***	***Smpls/yr***	***Smpls/yr***	***(/Smpl)***	***(/Smpl)***	***(mat.)***	***(/Smpl)***	***(proposed)***	***(current)***
		Dartmouth (Englewood)											
	005	S Platte R S of Florida (Denver)	Exchange/Irrigation	TL2	1	4	5	$5	$20	$10	$320	$1,420	$1,774
	006	S Platte R blw conf w/ Cherry C (Denver)	Exchange/Irrigation	TL2	1	4	5	$5	$20	$10	$320	$1,420	$1,774
	007	S Platte R blw conf w/ Sand C (Commerce City)	Exchange/Irrigation	TL2	1	4	5	$5	$20	$10	$320	$1,420	$1,774
	008	S Platte R @ Henderson	Exchange/Irrigation	TL2	1	4	5	$5	$20	$10	$320	$1,420	$1,774
	009	Bear C abv Harriman headgate (Morrison)	Storage Res In/Out	TL1	1	8	3	$5	$20	$10	$195	$1,839	$690
U. Platte (UP)	001	S Platte abv Antero Res @ US 285	Storage Res In/Out	TL1	4	8	3	$20	$110	$10	$195	$2,676	$1,004
	002	S Platte @ Antero Res outlet	Storage Res In/Out	TL1	4	8	3	$20	$110	$10	$195	$2,676	$1,004
	003	Gauge abv Eleven Mile Res	Storage Res In/Out	TL1	3	8	3	$15	$80	$10	$195	$2,397	$899
	004	Eleven Mile Res outlet	Storage Res In/Out	TL1	3	8	3	$15	$80	$10	$195	$2,397	$899

						(Proposed)	(Current)	Travel Cost	Labor Cost	Field Cost	Analysis Cost	Total Cost	Total Cost
Watershed	**Site ID**	**Site Name**	**Type**	**Suite ID**	**Zone**	**Smpls/yr**	**Smpls/yr**	**(/Smpl)**	**(/Smpl)**	**(mat.)**	**(/Smpl)**	**(proposed)**	**(current)**
	005	Cheesman Res outlet	Storage Res In/Out	TL1	2	8	3	$10	$60	$10	$195	$2,198	$824
	006	S Platte R u/s of conf w/ N. Fork	Watershed Character.	TL1	1	8	3	$5	$20	$10	$195	$1,839	$690
	007	S Platte R @ gauge abv Cheesman Res	Storage Res In/Out	TL1	2	8	3	$10	$60	$10	$195	$2,198	$824
	008	S Platte R blw conf of N Fork & S Platte	Terminal Res. Inf.	TL3	1	16	6	$5	$20	$10	$285	$5,118	$1,919
	009	S Platte R u/s of Spinney Mtn Res	Storage Res In/Out	TL1	3	8	3	$15	$80	$10	$195	$2,397	$899
	010	Goose C abv gauge	Storage Res In/Out	TL1	2	8	3	$10	$60	$10	$195	$2,198	$824
	011	N Fork S Platte abv conf with S Platte R	Watershed Character.	TL8	1	8	3	$5	$20	$10	$225	$2,079	$780
Williams Fork (WF)	001	Williams Fork R abv Williams Fork Res	Due diligence	TL8	4	2	3	$20	$110	$10	$225	$729	$1,094
	002	Williams Fork R blw Kinney C blw Leal	Due diligence	TL8	3	2	3	$15	$80	$10	$225	$659	$989
	003	S Fork Williams	Due diligence	TL1	3	2	3	$15	$80	$10	$195	$599	$899

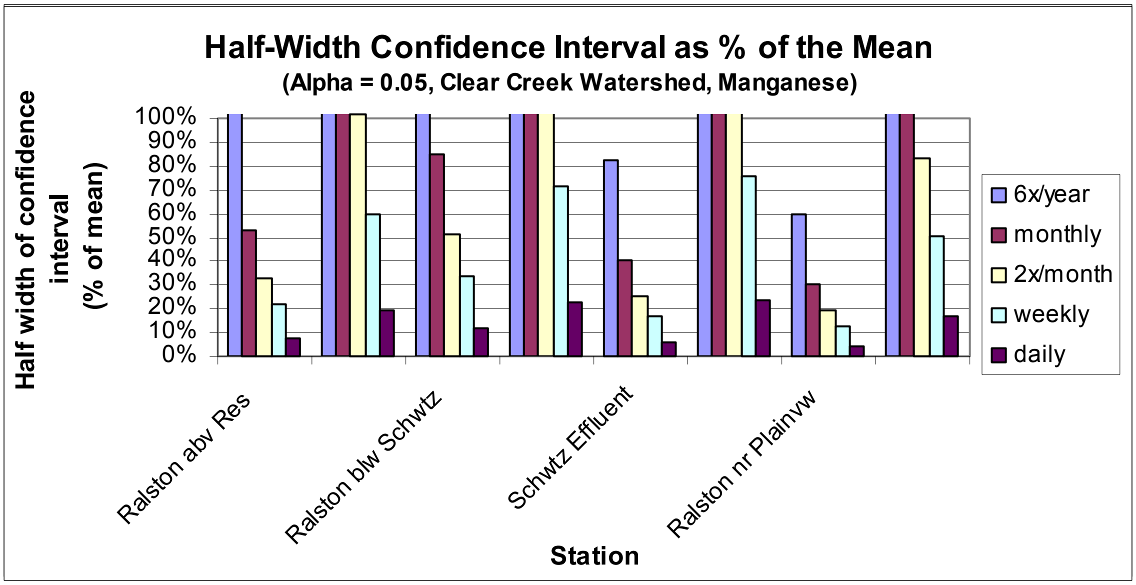
						(Proposed)	(Current)	Travel Cost	Labor Cost	Field Cost	Analysis Cost	Total Cost	Total Cost
Watershed	**Site ID**	**Site Name**	**Type**	**Suite ID**	**Zone**	**Smpls/yr**	**Smpls/yr**	**(/Smpl)**	**(/Smpl)**	**(mat.)**	**(/Smpl)**	**(proposed)**	**(current)**
		Fork R @ S Fork camp/gauge											
	004	Williams Fork R abv bridge @ Sugarloaf camp	Due diligence	TL1	3	2	3	$15	$80	$10	$195	$599	$899
	005	Steelman C @ div dam	Due diligence	TL1	3	2	3	$15	$80	$10	$195	$599	$899
	006	McQueary C abv div dam	Due diligence	TL1	3	2	3	$15	$80	$10	$195	$599	$899
	007	Upper S Fork Williams Fork R	Due diligence	TL1	3	2	3	$15	$80	$10	$195	$599	$899
	008	Bobtail C at gauge	Due diligence	TL1	3	2	3	$15	$80	$10	$195	$599	$899
	009	Williams Fork R blw Williams Fork Res	Colorado R Agrmt	TL8	4	4		$20	$110	$10	$225	$1,458	$0
Frasier River (FR)	001	Vasquez C abv Vasquez Tunnel	Due diligence	TL1	3	2	3	$15	$80	$10	$195	$599	$899
	002	Vasquez C @ div structure	Due diligence	TL1	3	2	3	$15	$80	$10	$195	$599	$899
	003	Fraser R blw conf w/ Vasquez C	Due diligence	TL1	3	2	3	$15	$80	$10	$195	$599	$899

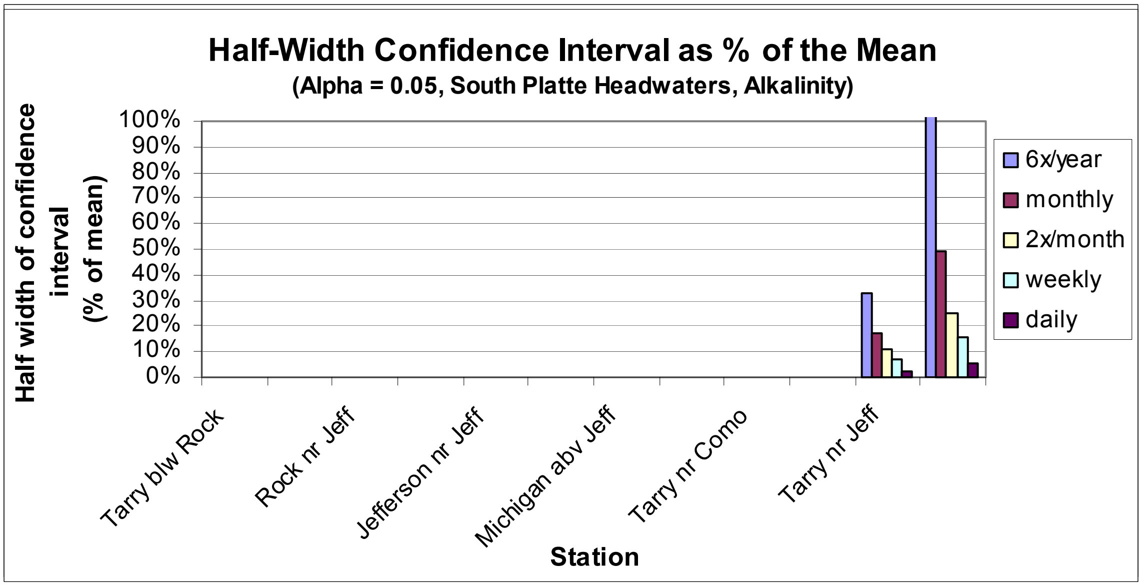
						(Proposed)	***(Current)***	***Travel Cost***	***Labor Cost***	***Field Cost***	***Analysis Cost***	***Total Cost***	***Total Cost***
Watershed	***Site ID***	***Site Name***	***Type***	***Suite ID***	***Zone***	***Smpls/yr***	***Smpls/yr***	***(/Smpl)***	***(/Smpl)***	***(mat.)***	***(/Smpl)***	***(proposed)***	***(current)***
	004	Fraser R @ Tabernash	Due diligence	TL1	3	2	3	$15	$80	$10	$195	$599	$899
												$90,172	**$49,600**

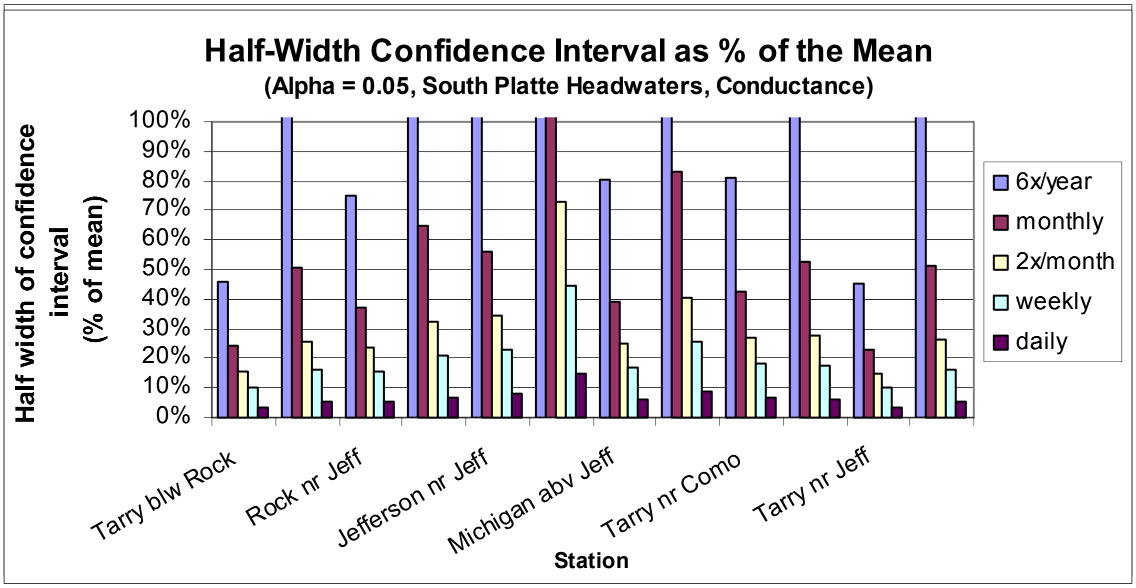
*Note: Combining the watershed abbreviation found in parenthesis under the “Watershed” column and the “Site ID” column with the term “WS” designating “watershed monitoring” is equivalent to the Denver Water sampling ID number (e.g. *WS-FR-001* is the Denver Water sampling ID number for the Vasquez Creek above Vasquez Tunnel site.

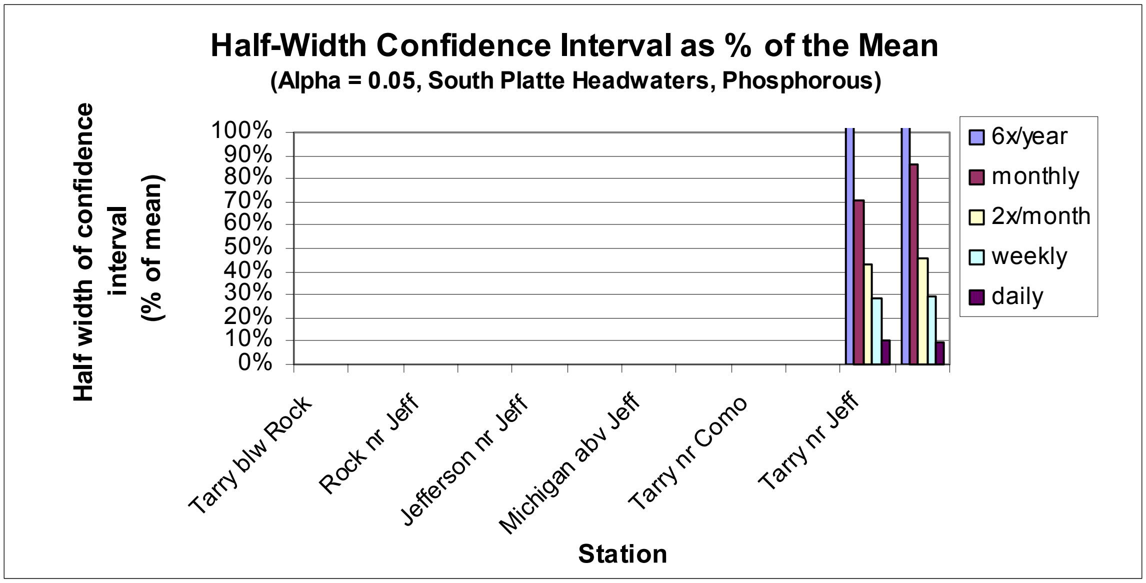
The proposed monitoring system represents an 82% increase in cost for sampling and analysis over the current system.

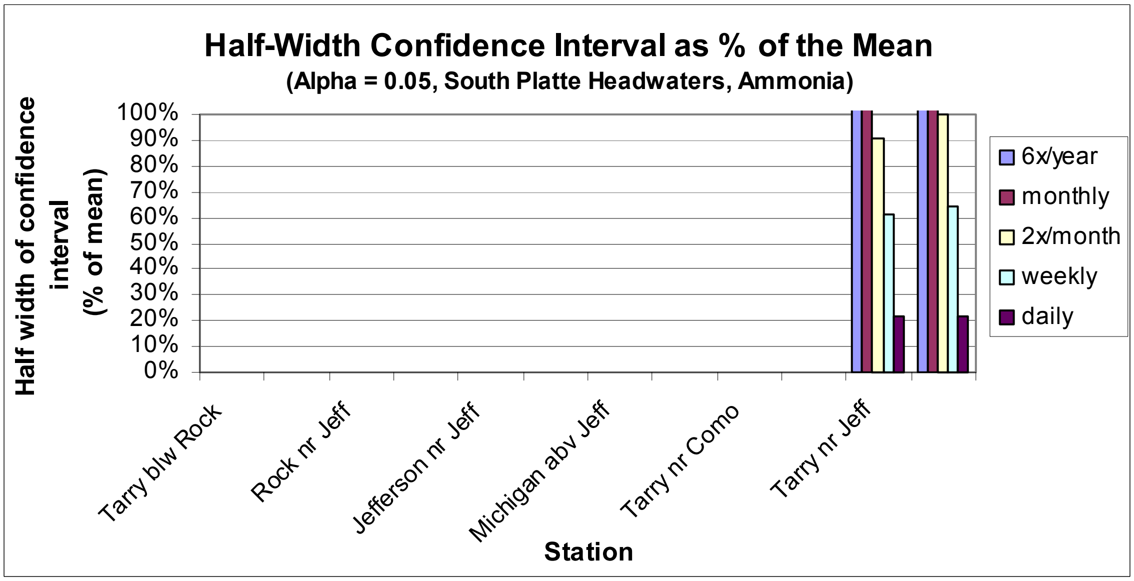
APPENDIX E: SAMPLING FREQUENCY FOR MEAN ESTIMATION RESULTS

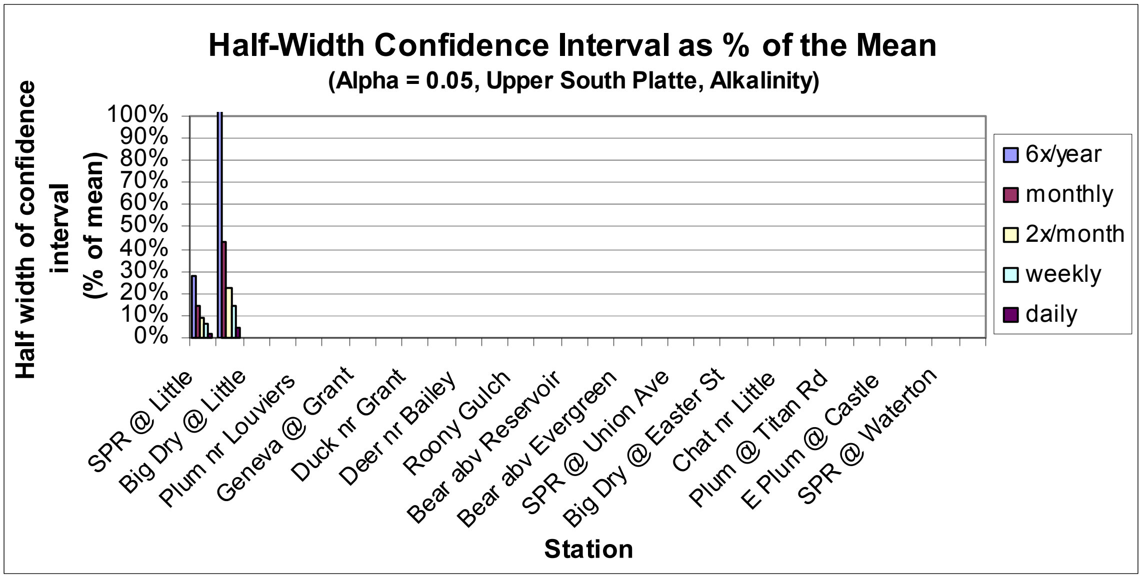

Half-Width Confidence Interval as % of the Mean
(Alpha = 0.05, Clear Creek Watershed, Manganese)
Half width of confidence interval (% of mean)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Ralston abv Res
Ralston blw Schwtz
Schwtz Effluent
Ralston nr Plainvw
Station
6x/year
monthly
2x/month
weekly
daily

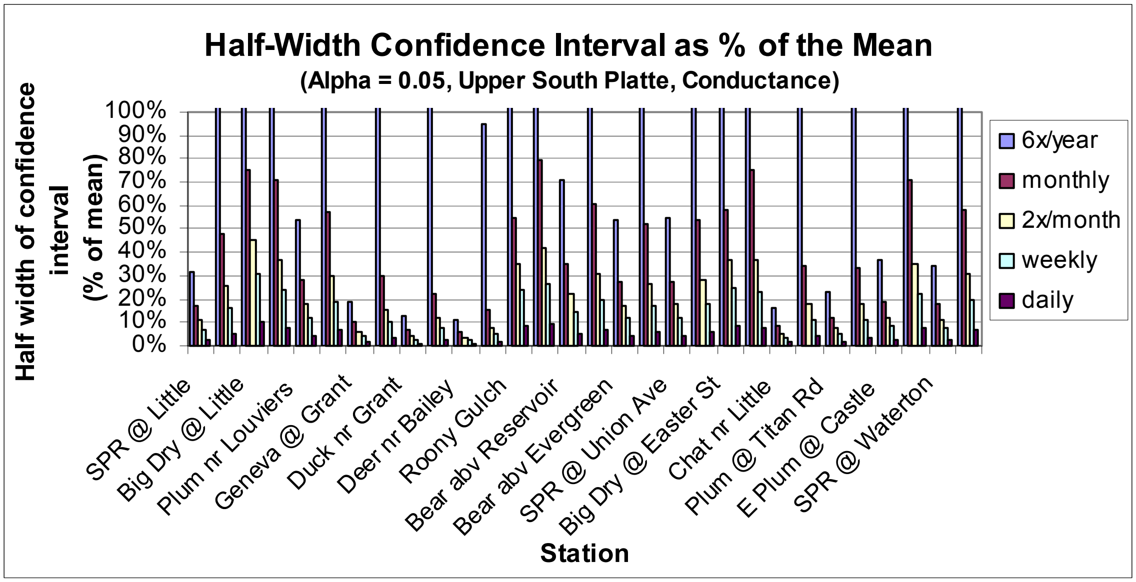

Half-Width Confidence Interval as % of the Mean
(Alpha = 0.05, South Platte Headwaters, Alkalinity)
Half width of confidence interval (% of mean)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Tarry blw Rock
Rock nr Jeff
Jefferson nr Jeff
Michigan abv Jeff
Tarry nr Como
Tarry nr Jeff
Station
6x/year
monthly
2x/month
weekly
daily

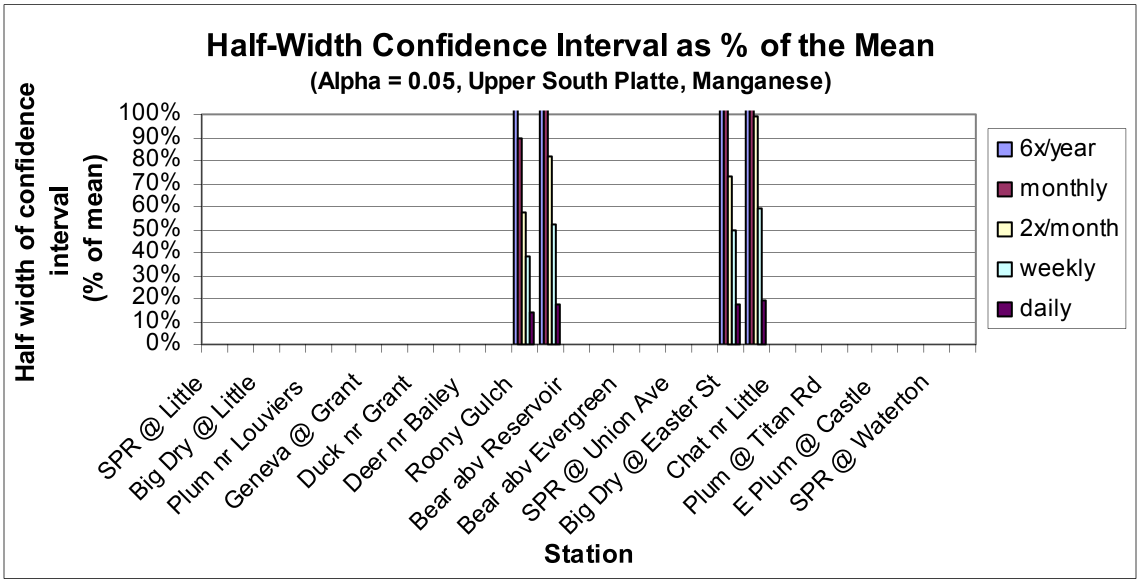

Half-Width Confidence Interval as % of the Mean
(Alpha = 0.05, South Platte Headwaters, Conductance)
Half width of confidence interval (% of mean)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Tarry blw Rock
Rock nr Jeff
Jefferson nr Jeff
Michigan abv Jeff
Tarry nr Como
Tarry nr Jeff
Station
6x/year
monthly
2x/month
weekly
daily

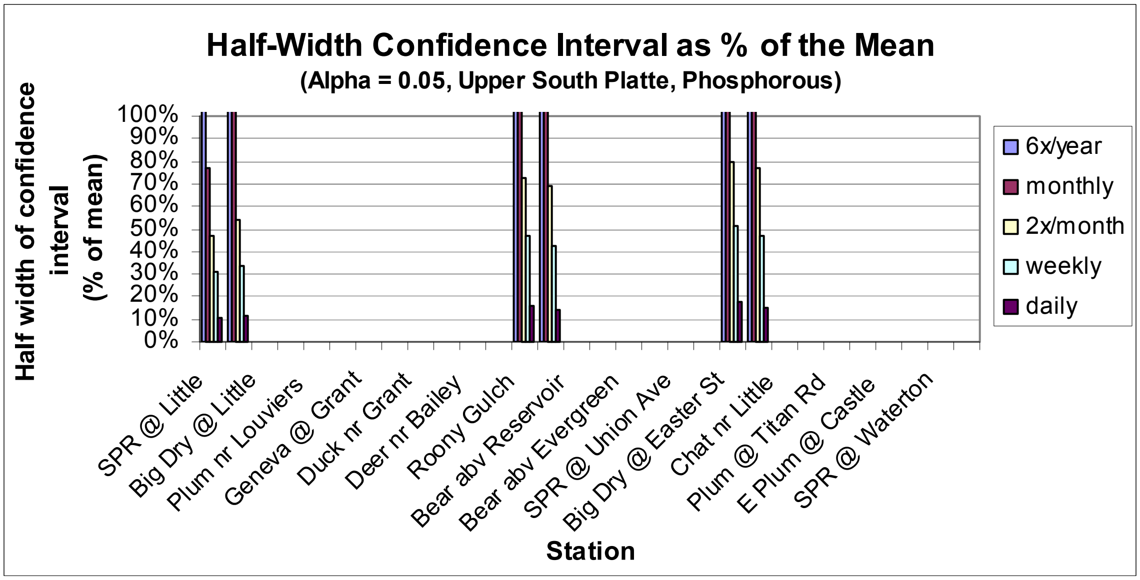

Half-Width Confidence Interval as % of the Mean
(Alpha = 0.05, South Platte Headwaters, Phosphorous)
Half width of confidence interval (% of mean)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Tarry blw Rock
Rock nr Jeff
Jefferson nr Jeff
Michigan abv Jeff
Tarry nr Como
Tarry nr Jeff
Station
6x/year
monthly
2x/month
weekly
daily


Half-Width Confidence Interval as % of the Mean
(Alpha = 0.05, South Platte Headwaters, Ammonia)
Half width of confidence interval (% of mean)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Tarry blw Rock
Rock nr Jeff
Jefferson nr Jeff
Michigan abv Jeff
Tarry nr Como
Tarry nr Jeff
Station
6x/year
monthly
2x/month
weekly
daily


Half-Width Confidence Interval as % of the Mean
(Alpha = 0.05, Upper South Platte, Alkalinity)
Half width of confidence interval (% of mean)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
SPR @ Little
Big Dry @ Little
Plum nr Louviers
Geneva @ Grant
Duck nr Grant
Deer nr Bailey
Roony Gulch
Bear abv Reservoir
Bear abv Evergreen
SPR @ Union Ave
Big Dry @ Easter St
Chat nr Little
Plum @ Titan Rd
E Plum @ Castle
SPR @ Waterton
Station
6x/year
monthly
2x/month
weekly
daily


Half-Width Confidence Interval as % of the Mean
(Alpha = 0.05, Upper South Platte, Conductance)
Half width of confidence interval (% of mean)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
SPR @ Little
Big Dry @ Little
Plum nr Louviers
Geneva @ Grant
Duck nr Grant
Deer nr Bailey
Roony Gulch
Bear abv Reservoir
Bear abv Evergreen
SPR @ Union Ave
Big Dry @ Easter St
Chat nr Little
Plum @ Titan Rd
E Plum @ Castle
SPR @ Waterton
Station
6x/year
monthly
2x/month
weekly
daily


Half-Width Confidence Interval as % of the Mean
(Alpha = 0.05, Upper South Platte, Manganese)
Half width of confidence interval (% of mean)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
SPR @ Little
Big Dry @ Little
Plum nr Louviers
Geneva @ Grant
Duck nr Grant
Deer nr Bailey
Roony Gulch
Bear abv Reservoir
Bear abv Evergreen
SPR @ Union Ave
Big Dry @ Easter St
Chat nr Little
Plum @ Titan Rd
E Plum @ Castle
SPR @ Waterton
Station
6x/year
monthly
2x/month
weekly
daily


Half-Width Confidence Interval as % of the Mean
(Alpha = 0.05, Upper South Platte, Phosphorous)
Half width of confidence interval (% of mean)
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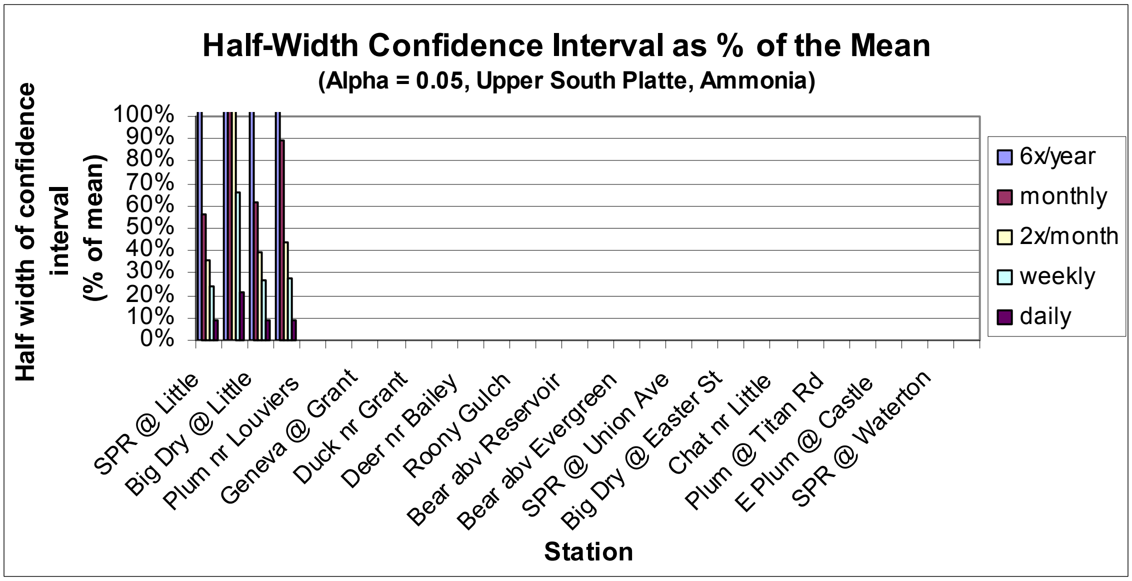
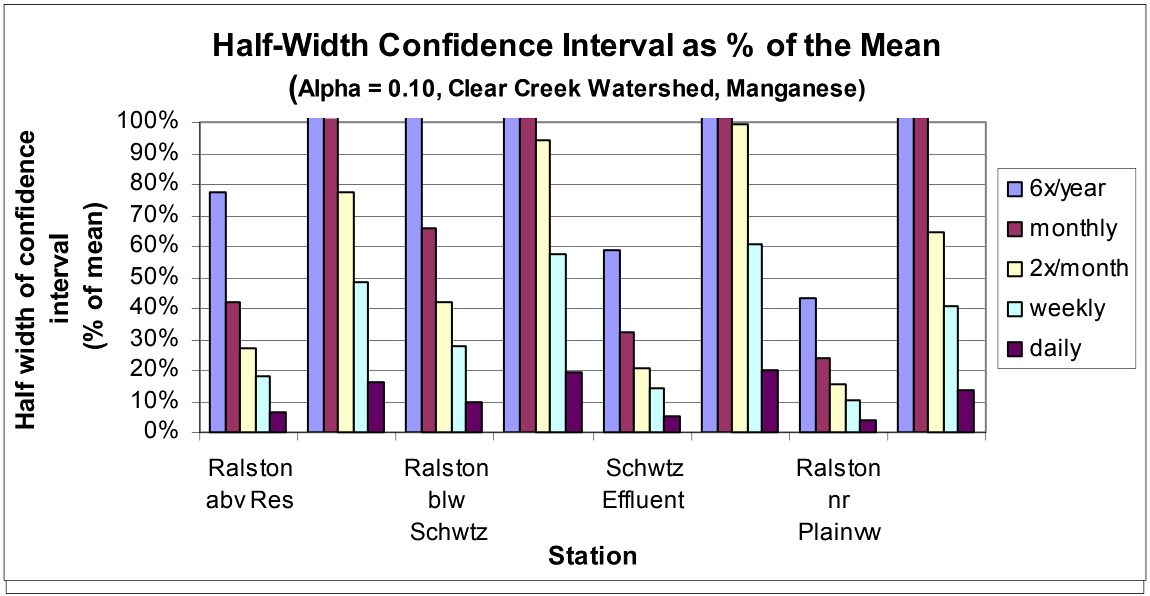
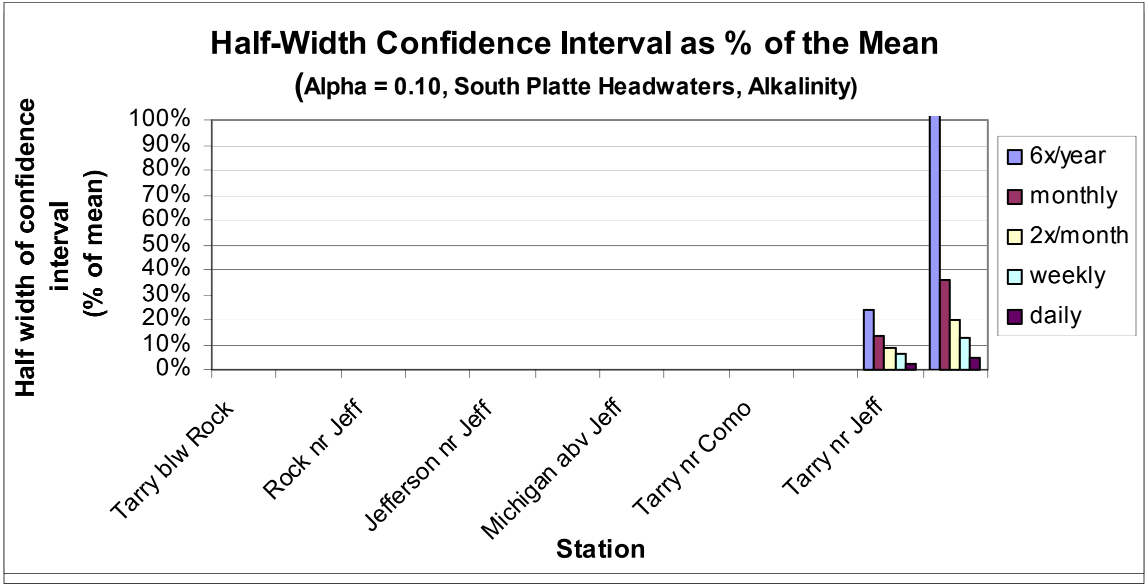
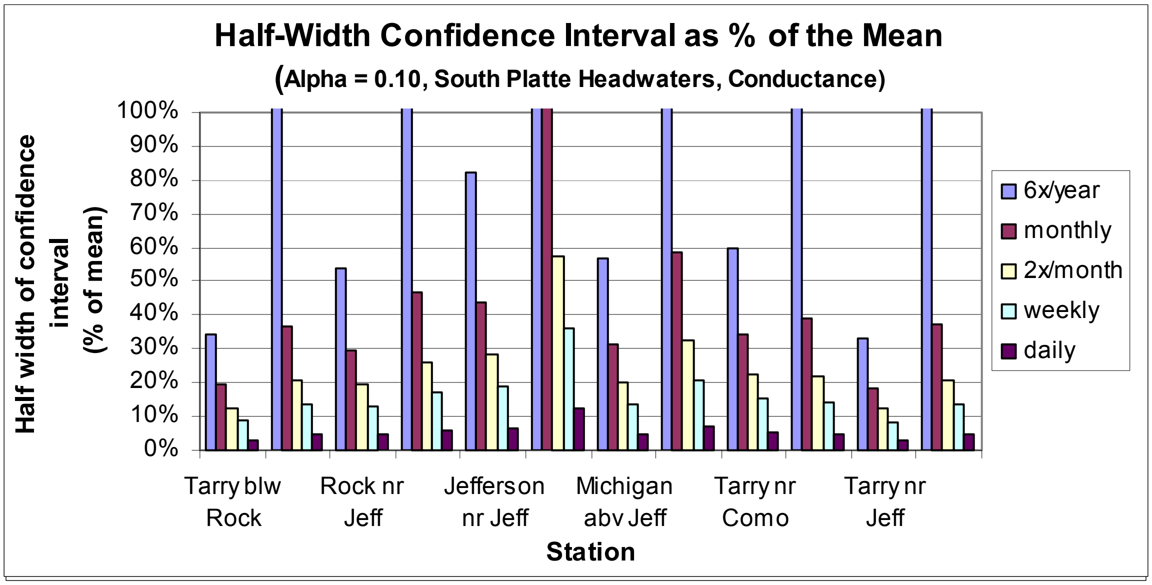
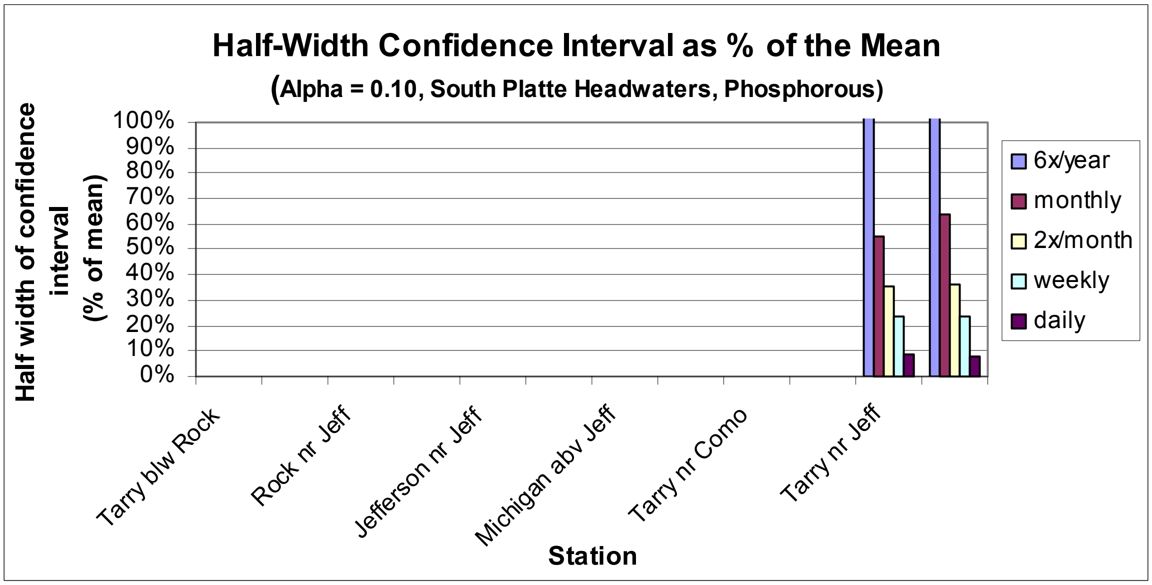
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
SPR @ Little
Big Dry @ Little
Plum nr Louviers
Geneva @ Grant
Duck nr Grant
Deer nr Bailey
Roony Gulch
Bear abv Reservoir
Bear abv Evergreen
SPR @ Union Ave
Big Dry @ Easter St
Chat nr Little
Plum @ Titan Rd
E Plum @ Castle
SPR @ Waterton
Station
6x/year
monthly
2x/month
weekly
daily

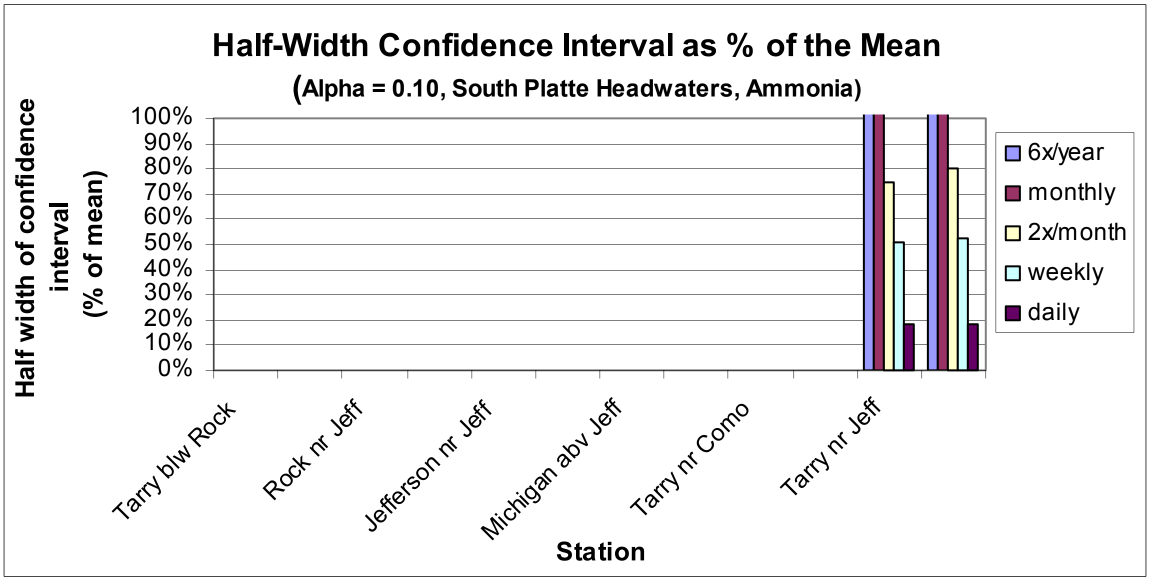

Half-Width Confidence Interval as % of the Mean
(Alpha = 0.05, Upper South Platte, Ammonia)
Half width of confidence interval (% of mean)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
6x/year
monthly
2x/month
weekly
daily
SPR @ Little
Big Dry @ Little
Plum nr Louviers
Geneva @ Grant
Duck nr Grant
Deer nr Bailey
Roony Gulch
Bear abv Reservoir
Bear abv Evergreen
SPR @ Union Ave
Big Dry @ Easter St
Chat nr Little
Plum @ Titan Rd
E Plum @ Castle
SPR @ Waterton
Station

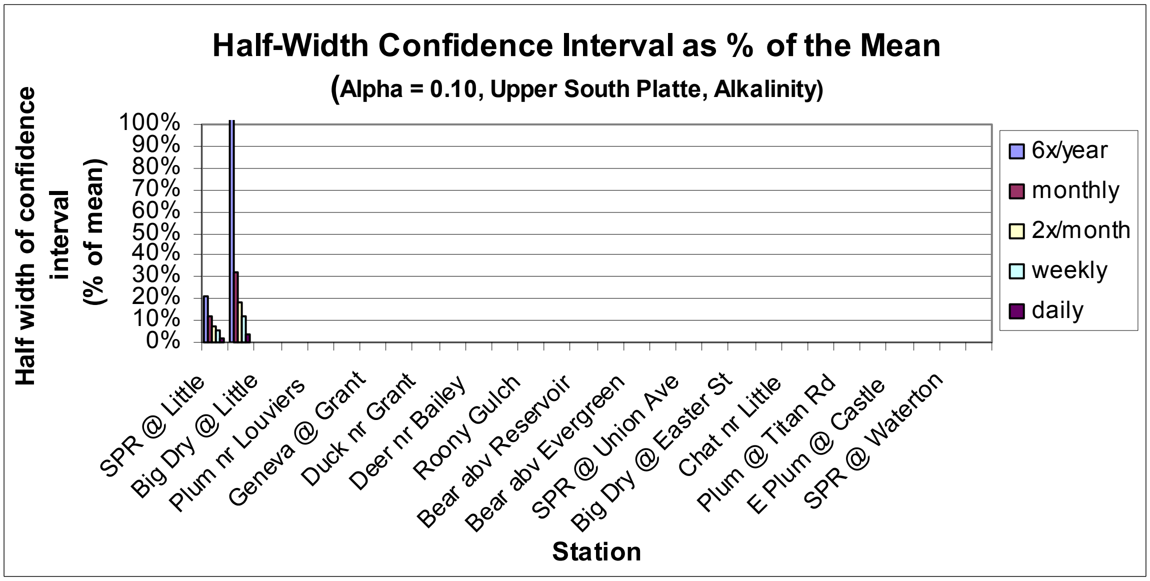

Half-Width Confidence Interval as % of the Mean
(Alpha = 0.10, Clear Creek Watershed, Manganese)
Half width of confidence interval (% of mean)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Ralston abv Res
Ralston blw Schwtz
Schwtz Effluent
Ralston nr Plainw
Station
6x/year
monthly
2x/month
weekly
daily

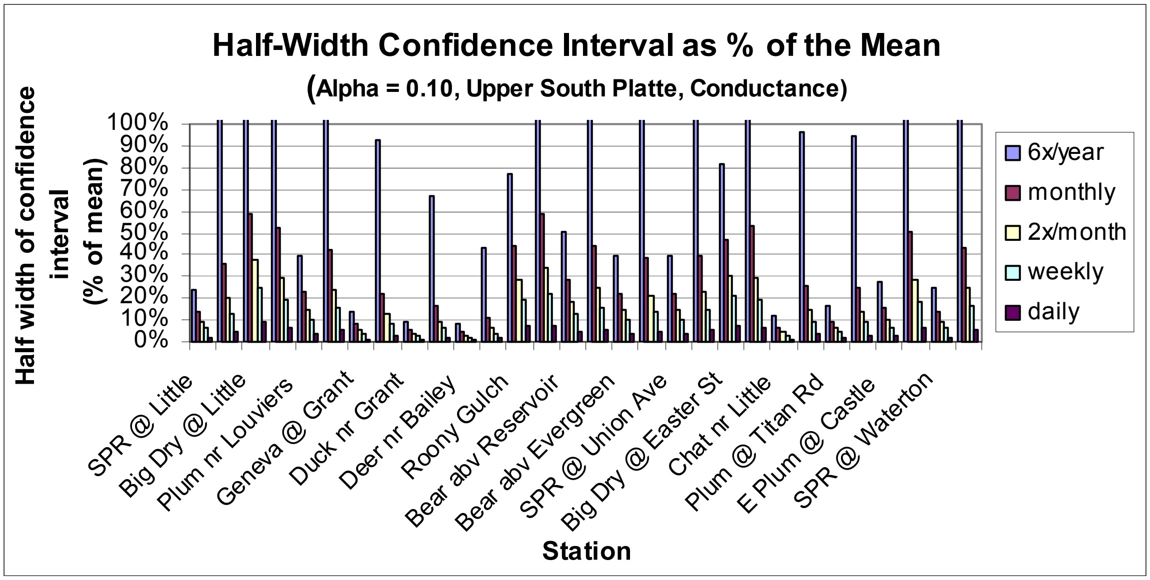

Half-Width Confidence Interval as % of the Mean
(Alpha = 0.10, South Platte Headwaters, Alkalinity)
Half width of confidence interval (% of mean)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Tarry blw Rock
Rock nr Jeff
Jefferson nr Jeff
Michigan abv Jeff
Tarry nr Como
Tarry nr Jeff
Station
6x/year
monthly
2x/month
weekly
daily


Half-Width Confidence Interval as % of the Mean
(Alpha = 0.10, South Platte Headwaters, Conductance)
Half width of confidence interval (% of mean)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Tarry blw Rock
Rock nr Jeff
Jefferson nr Jeff
Michigan abv Jeff
Tarry nr Como
Tarry nr Jeff
Station
6x/year
monthly
2x/month
weekly
daily

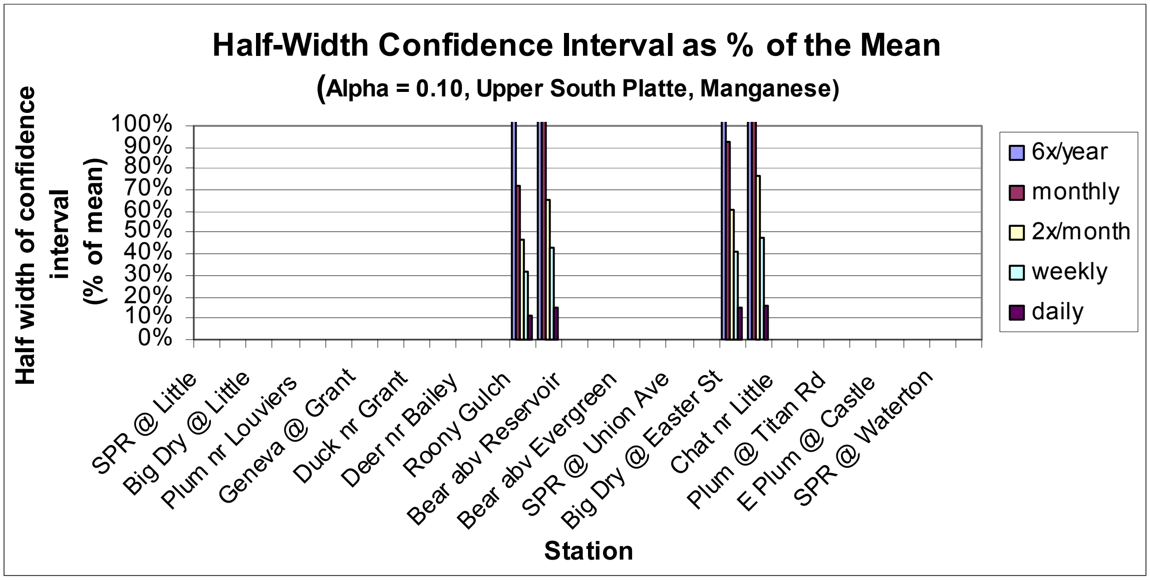

Half-Width Confidence Interval as % of the Mean
(Alpha = 0.10, South Platte Headwaters, Phosphorous)
Half width of confidence interval (% of mean)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Tarry blw Rock
Rock nr Jeff
Jefferson nr Jeff
Michigan abv Jeff
Tarry nr Como
Tarry nr Jeff
Station
6x/year
monthly
2x/month
weekly
daily


Half-Width Confidence Interval as % of the Mean
(Alpha = 0.10, South Platte Headwaters, Ammonia)
Half width of confidence interval (% of mean)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Tarry blw Rock
Rock nr Jeff
Jefferson nr Jeff
Michigan abv Jeff
Tarry nr Como
Tarry nr Jeff
Station
6x/year
monthly
2x/month
weekly
daily

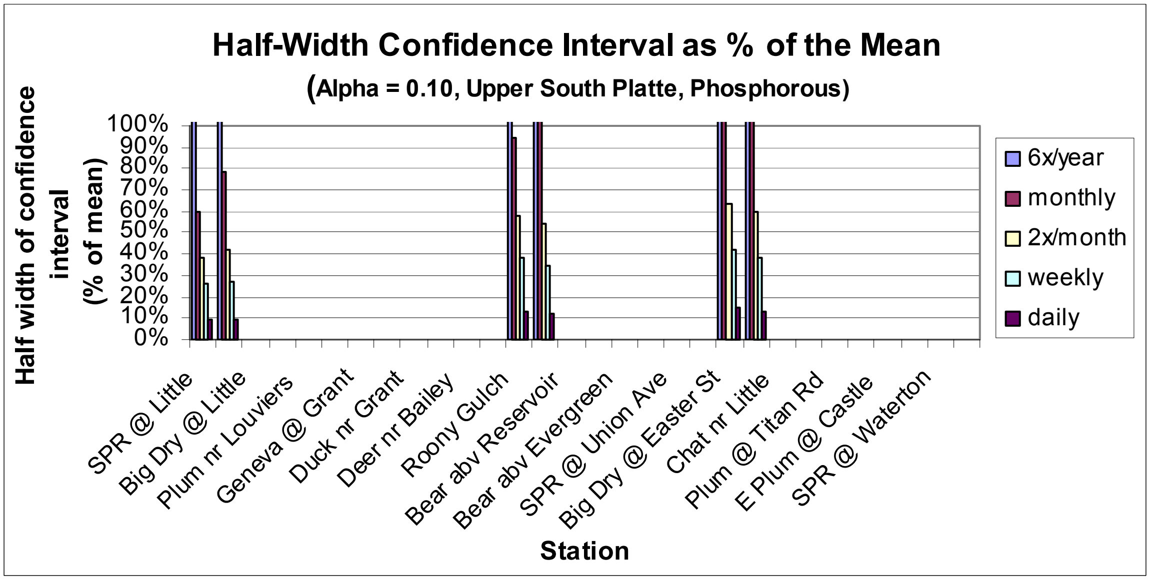

Half-Width Confidence Interval as % of the Mean
(Alpha = 0.10, Upper South Platte, Alkalinity)
Half width of confidence interval (% of mean)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
SPR @ Little
Big Dry @ Little
Plum nr Louviers
Geneva @ Grant
Duck nr Grant
Deer nr Bailey
Roony Gulch
Bear abv Reservoir
Bear abv Evergreen
SPR @ Union Ave
Big Dry @ Easter St
Chat nr Little
Plum @ Titan Rd
E Plum @ Castle
SPR @ Waterton
Station
6x/year
monthly
2x/month
weekly
daily


Half-Width Confidence Interval as % of the Mean

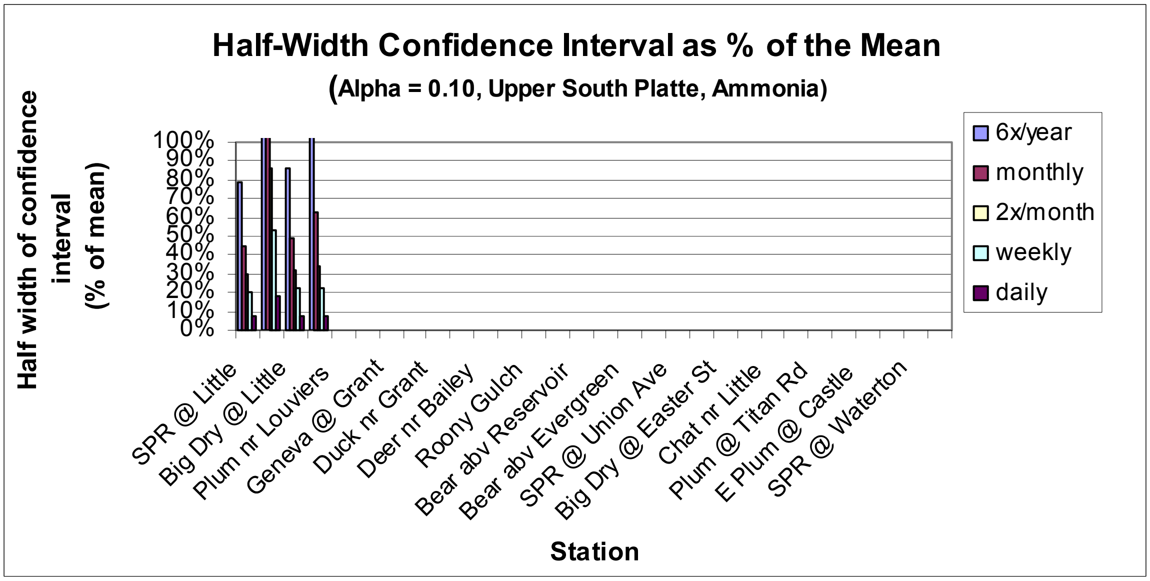
(Alpha = 0.10, Upper South Platte, Conductance)


Half-Width Confidence Interval as % of the Mean

(Alpha = 0.10, Upper South Platte, Manganese)

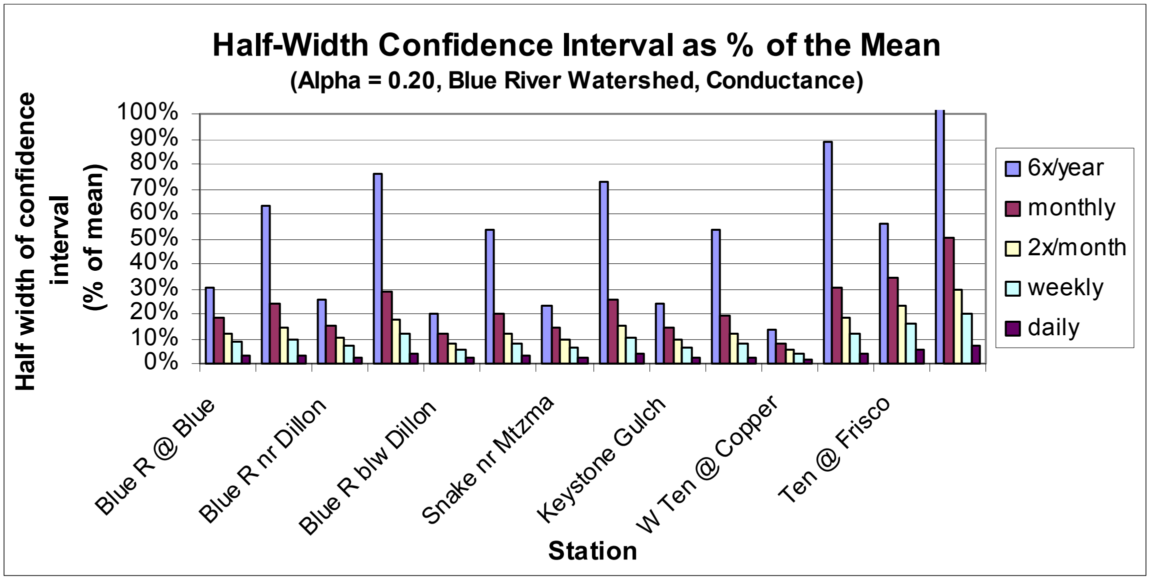

Half-Width Confidence Interval as % of the Mean

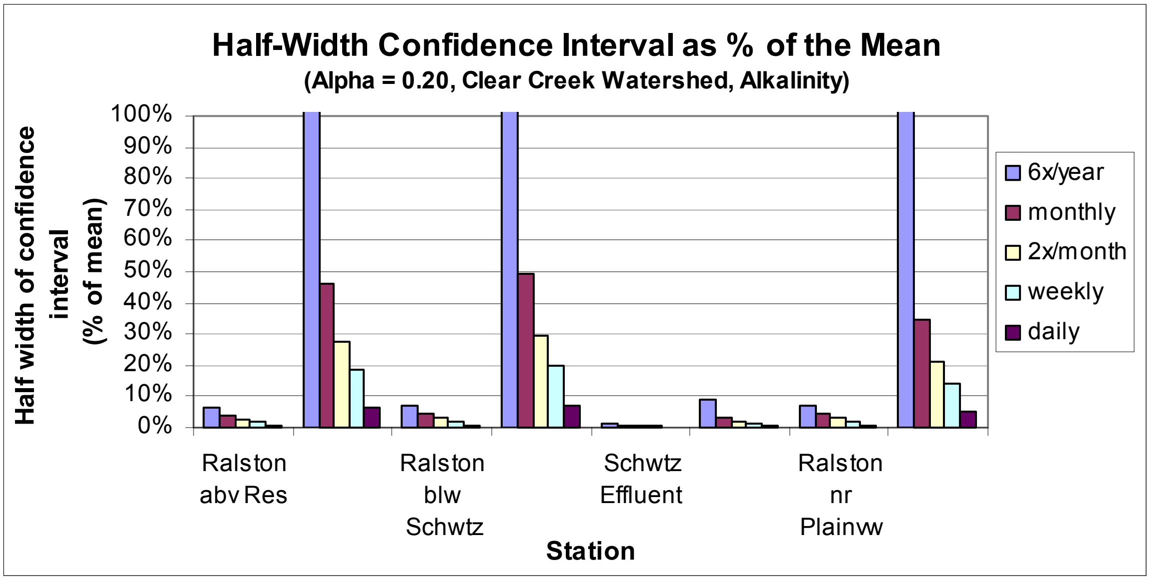
(Alpha = 0.10, Upper South Platte, Phosphorous)

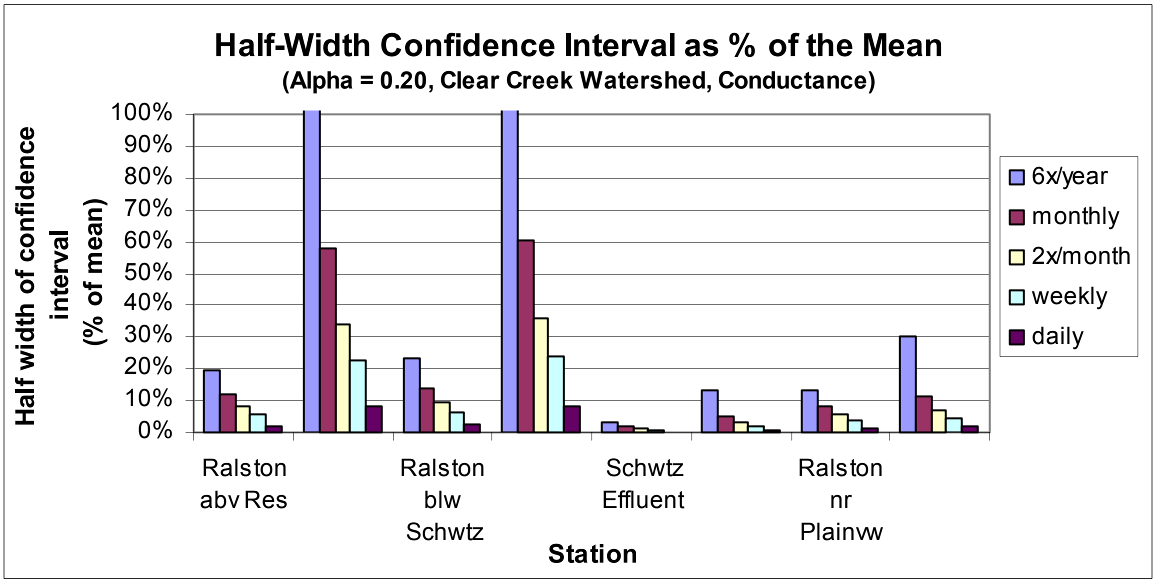


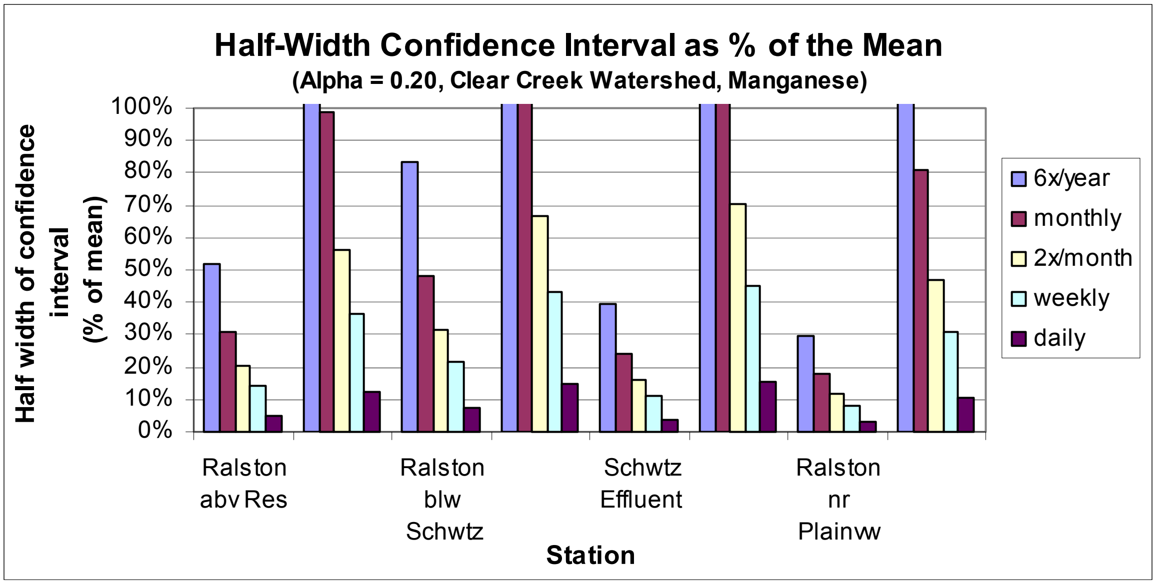
Half-Width Confidence Interval as % of the Mean

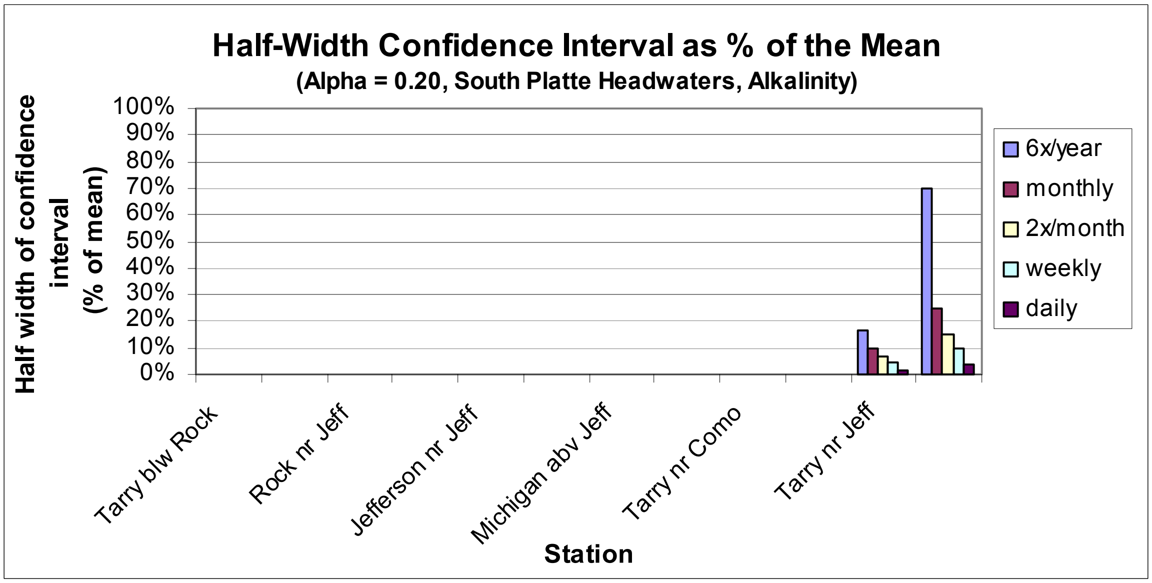
(Alpha = 0.10, Upper South Platte, Ammonia)

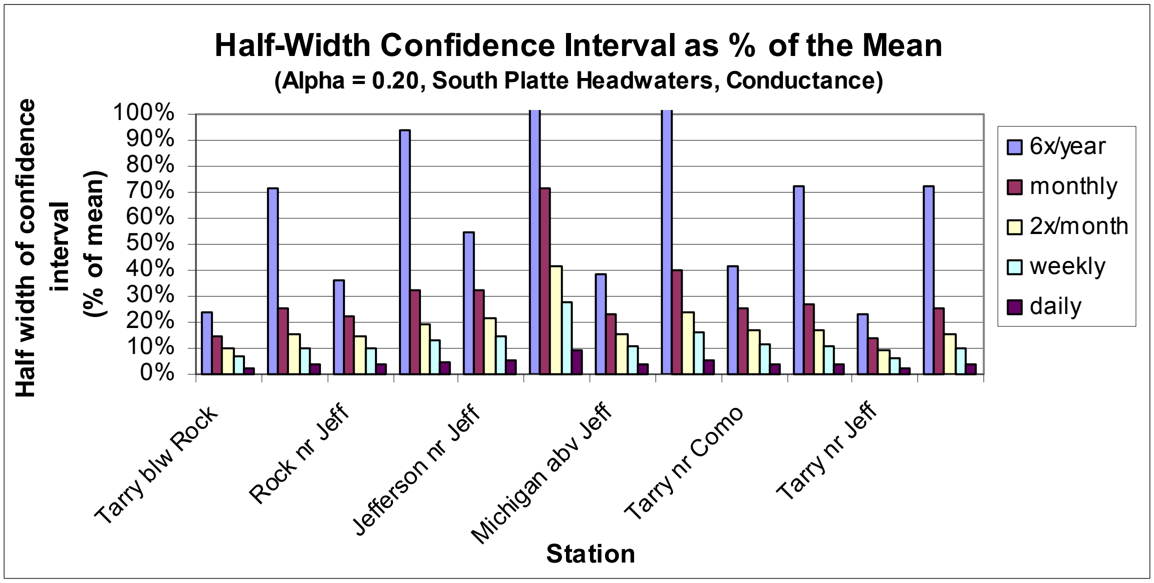

Half-Width Confidence Interval as % of the Mean
(Alpha = 0.20, Blue River Watershed, Conductance)
Half width of confidence interval (% of mean)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Blue R @ Blue
Blue R nr Dillon
Blue R blw Dillon
Snake nr Mtzma
Keystone Gulch
W Ten @ Copper
Ten @ Frisco
Station
6x/year
monthly
2x/month
weekly
daily

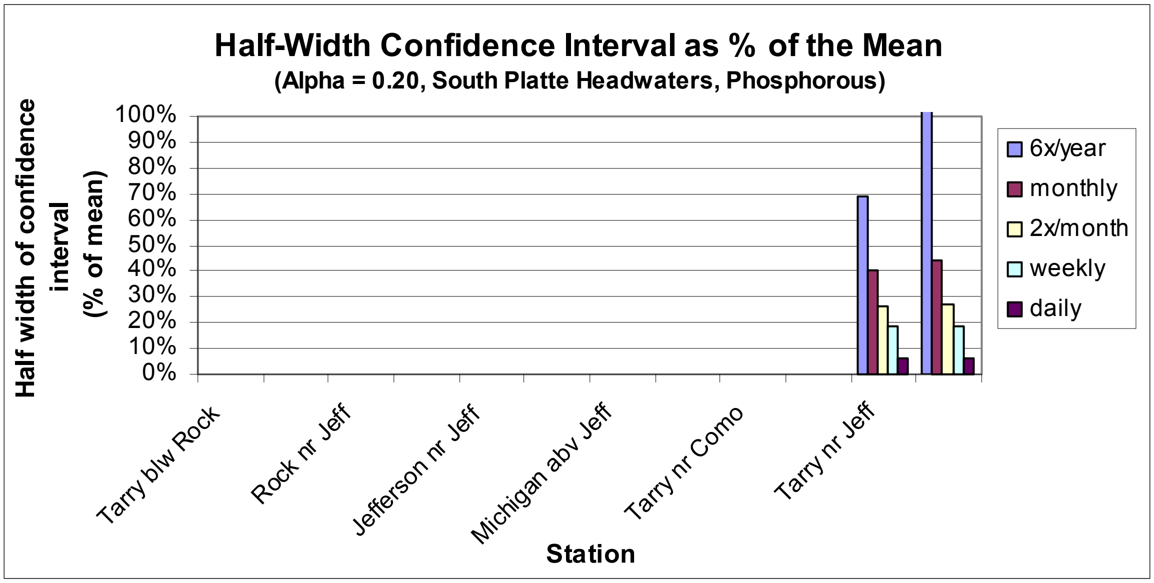

Half-Width Confidence Interval as % of the Mean
(Alpha = 0.20, Clear Creek Watershed, Alkalinity)
Half width of confidence interval (% of mean)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Ralston abv Res
Ralston blw Schwtz
Schwtz Effluent
Ralston nr Plainvw
Station
6x/year
monthly
2x/month
weekly
daily

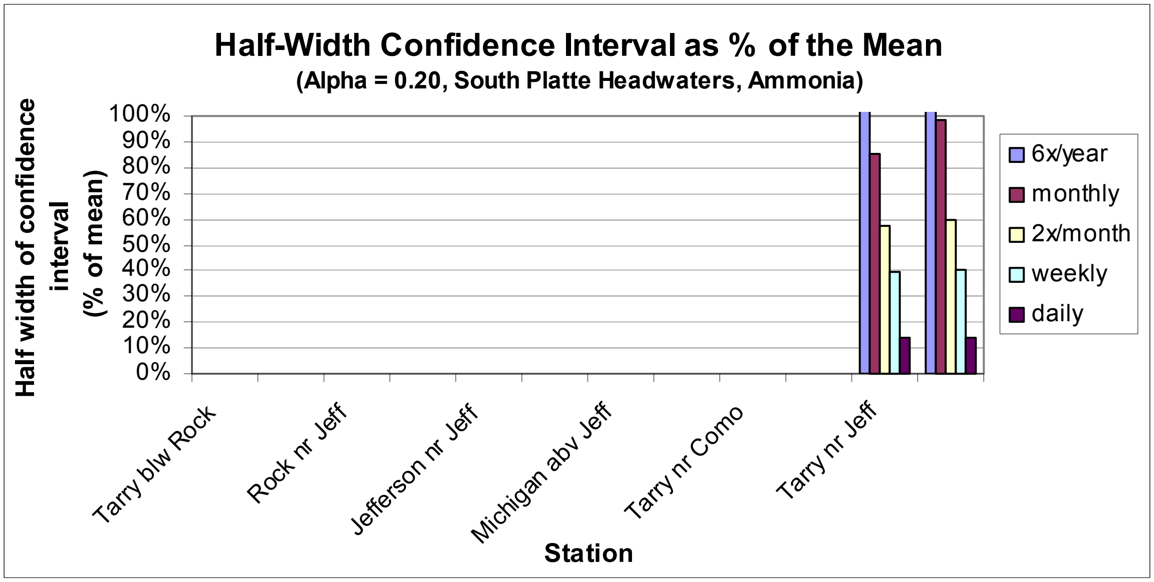

Half-Width Confidence Interval as % of the Mean
(Alpha = 0.20, Clear Creek Watershed, Conductance)
Half width of confidence interval (% of mean)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Ralston abv Res
Ralston blw Schwtz
Schwtz Effluent
Ralston nr Plainvw
Station
6x/year
monthly
2x/month
weekly
daily

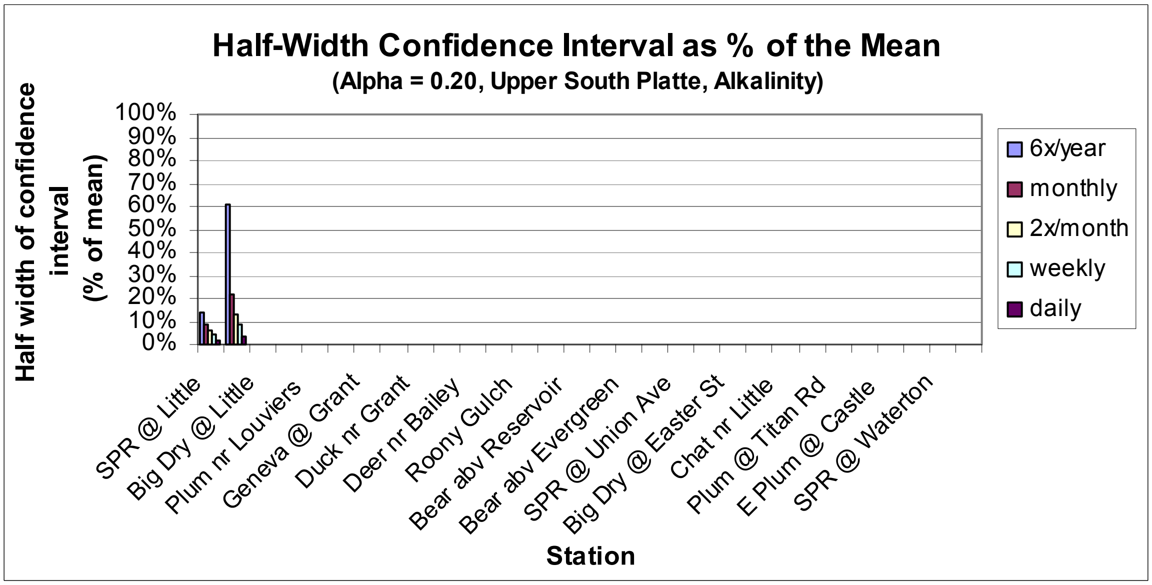

Half-Width Confidence Interval as % of the Mean
(Alpha = 0.20, Clear Creek Watershed, Manganese)
Half width of confidence interval (% of mean)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Ralston abv Res
Ralston blw Schwtz
Schwtz Effluent
Ralston nr Plainvw
Station
6x/year
monthly
2x/month
weekly
daily

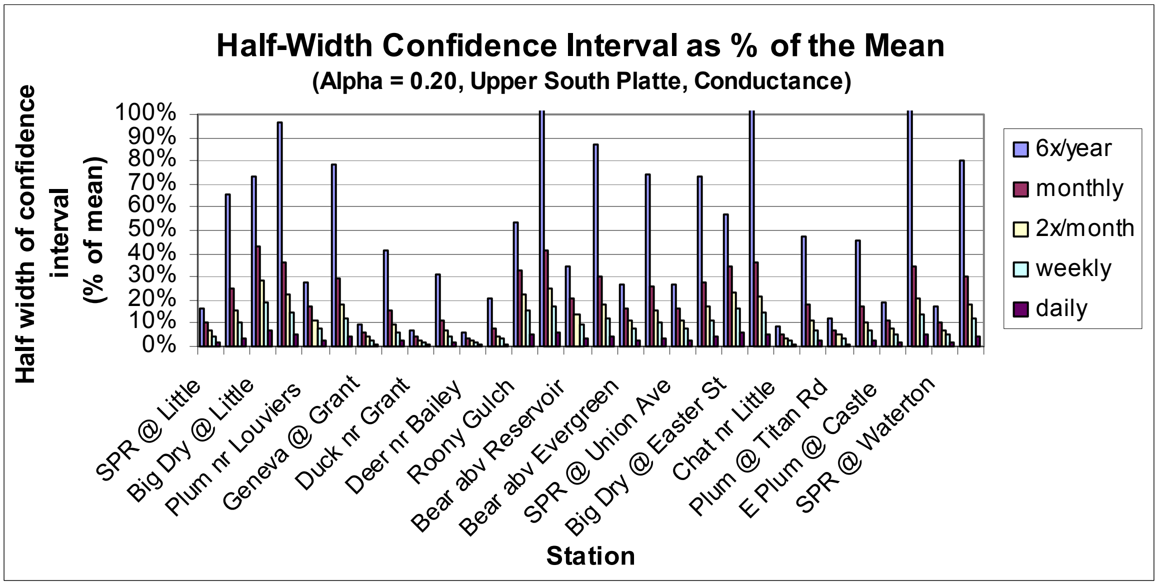

Half-Width Confidence Interval as % of the Mean
(Alpha = 0.20, South Platte Headwaters, Alkalinity)
Half width of confidence interval (% of mean)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Tarry blw Rock
Rock nr Jeff
Jefferson nr Jeff
Michigan abv Jeff
Tarry nr Como
Tarry nr Jeff
Station
6x/year
monthly
2x/month
weekly
daily

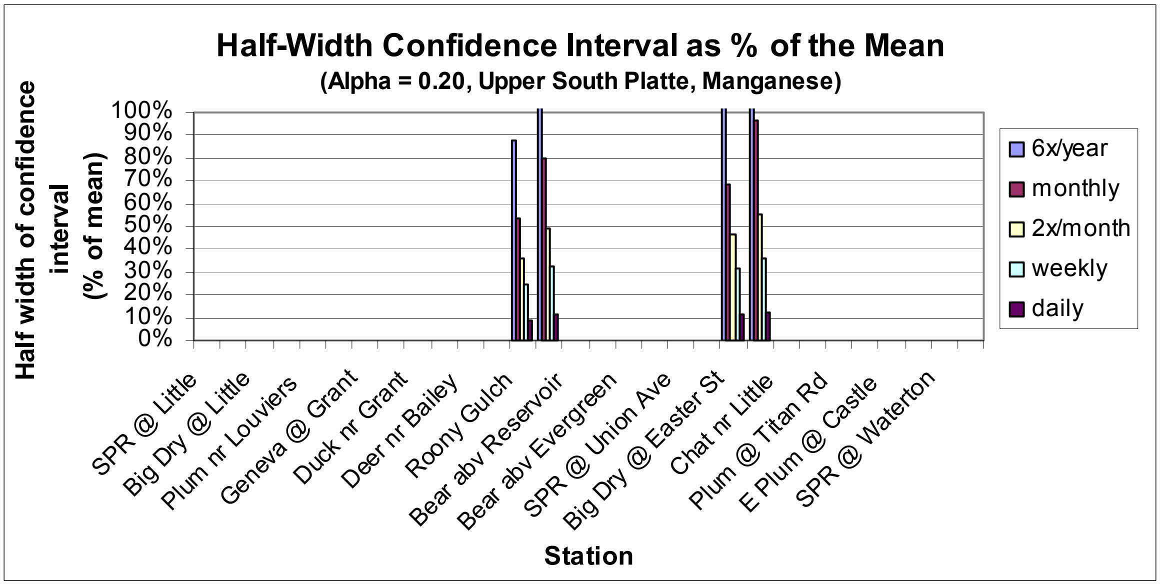

Half-Width Confidence Interval as % of the Mean
(Alpha = 0.20, South Platte Headwaters, Conductance)
Half width of confidence interval (% of mean)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Tarry blw Rock
Rock nr Jeff
Jefferson nr Jeff
Michigan abv Jeff
Tarry nr Como
Tarry nr Jeff
Station
6x/year
monthly
2x/month
weekly
daily

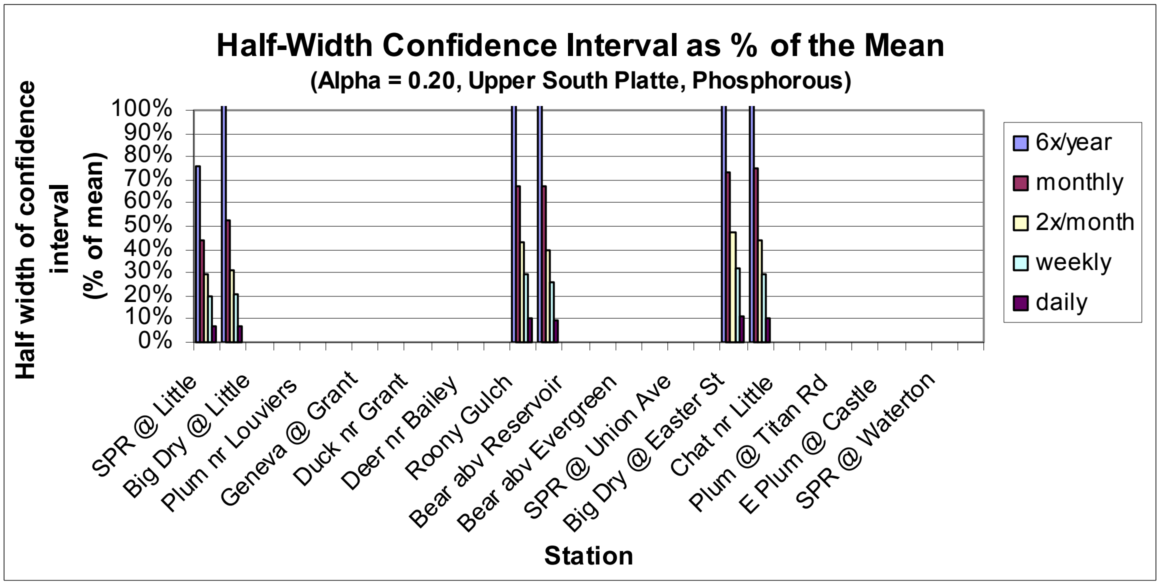

Half-Width Confidence Interval as % of the Mean
(Alpha = 0.20, South Platte Headwaters, Phosphorous)
Half width of confidence interval (% of mean)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
6x/year
monthly
2x/month
weekly
daily
Tarry blw Rock
Rock nr Jeff
Jefferson nr Jeff
Michigan abv Jeff
Tarry nr Como
Tarry nr Jeff
Station

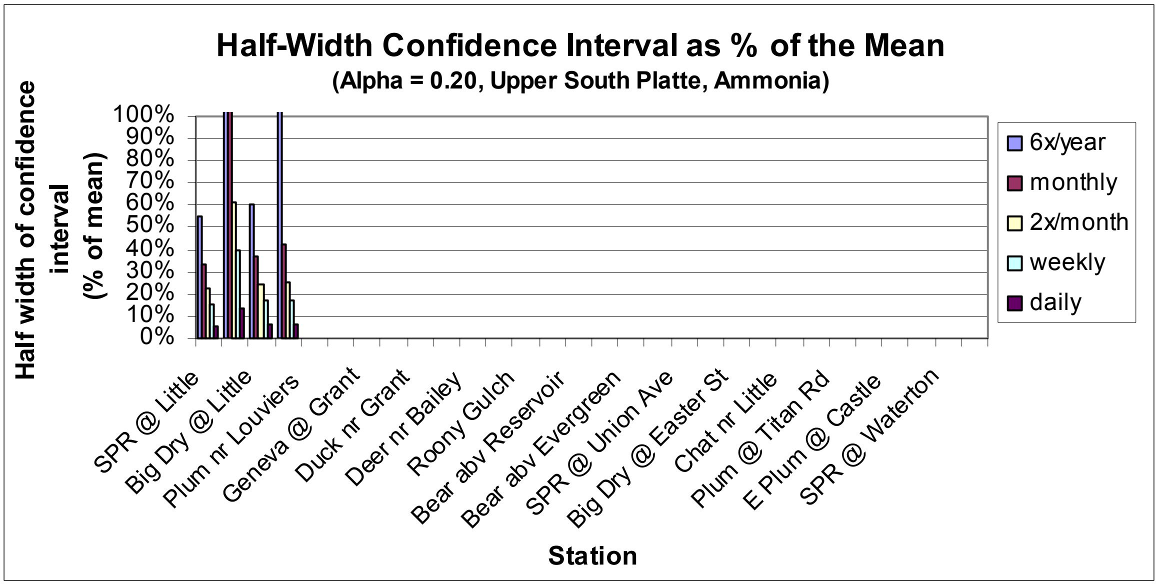

Half-Width Confidence Interval as % of the Mean
(Alpha = 0.20, South Platte Headwaters, Ammonia)
Half width of confidence interval (% of mean)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
6x/year
monthly
2x/month
weekly
daily
Tarry blw Rock
Rock nr Jeff
Jefferson nr Jeff
Michigan abv Jeff
Tarry nr Como
Tarry nr Jeff
Station


Half-Width Confidence Interval as % of the Mean
(Alpha = 0.20, Upper South Platte, Alkalinity)
Half width of confidence interval (% of mean)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
6x/year
monthly
2x/month
weekly
daily
SPR @ Little
Big Dry @ Little
Plum nr Louviers
Geneva @ Grant
Duck nr Grant
Deer nr Bailey
Roony Gulch
Bear abv Reservoir
Bear abv Evergreen
SPR @ Union Ave
Big Dry @ Easter St
Chat nr Little
Plum @ Titan Rd
E Plum @ Castle
SPR @ Waterton
Station

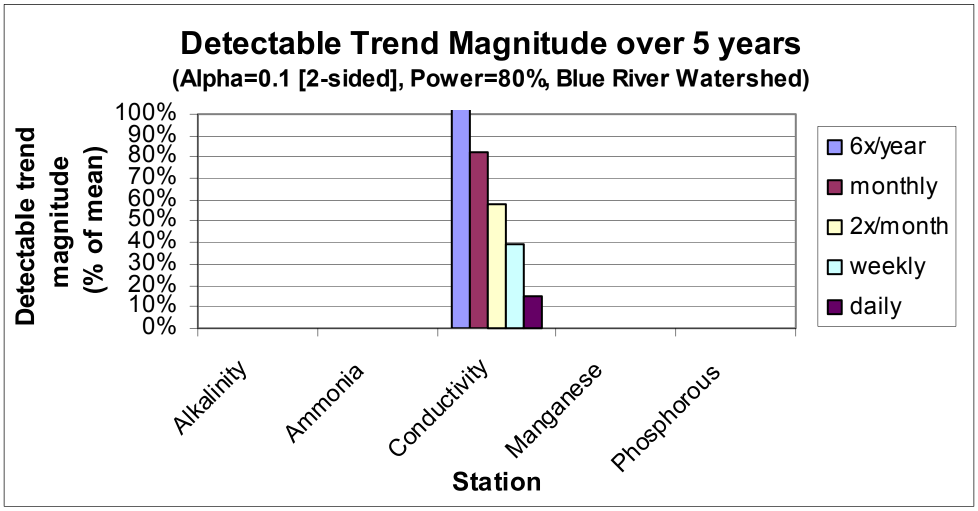

Half-Width Confidence Interval as % of the Mean
(Alpha = 0.20, Upper South Platte, Conductance)
Half width of confidence interval (% of mean)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
6x/year
monthly
2x/month
weekly
daily
SPR @ Little
Big Dry @ Little
Plum nr Louviers
Geneva @ Grant
Duck nr Grant
Deer nr Bailey
Roony Gulch
Bear abv Reservoir
Bear abv Evergreen
SPR @ Union Ave
Big Dry @ Easter St
Chat nr Little
Plum @ Titan Rd
E Plum @ Castle
SPR @ Waterton
Station

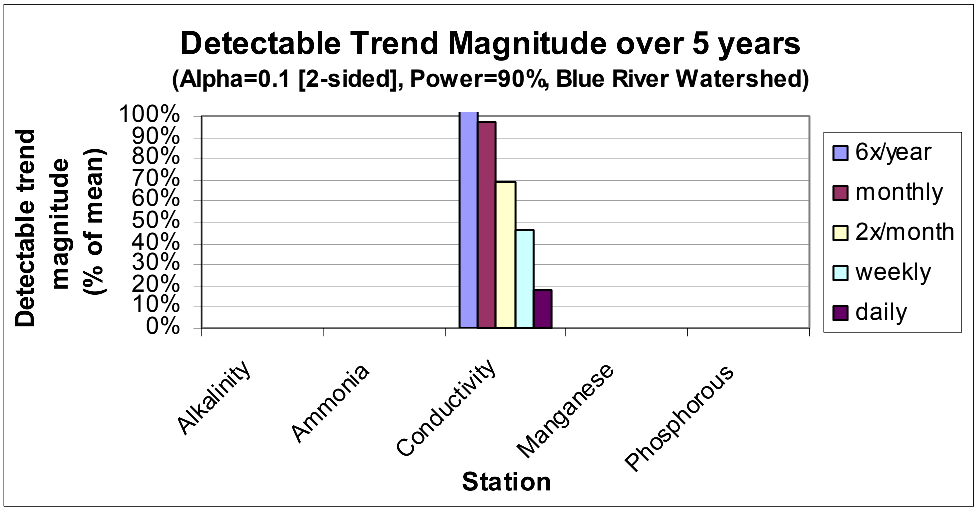

Half-Width Confidence Interval as % of the Mean
(Alpha = 0.20, Upper South Platte, Manganese)
Half width of confidence interval (% of mean)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
6x/year
monthly
2x/month
weekly
daily
SPR @ Little
Big Dry @ Little
Plum nr Louviers
Geneva @ Grant
Duck nr Grant
Deer nr Bailey
Roony Gulch
Bear abv Reservoir
Bear abv Evergreen
SPR @ Union Ave
Big Dry @ Easter St
Chat nr Little
Plum @ Titan Rd
E Plum @ Castle
SPR @ Waterton
Station

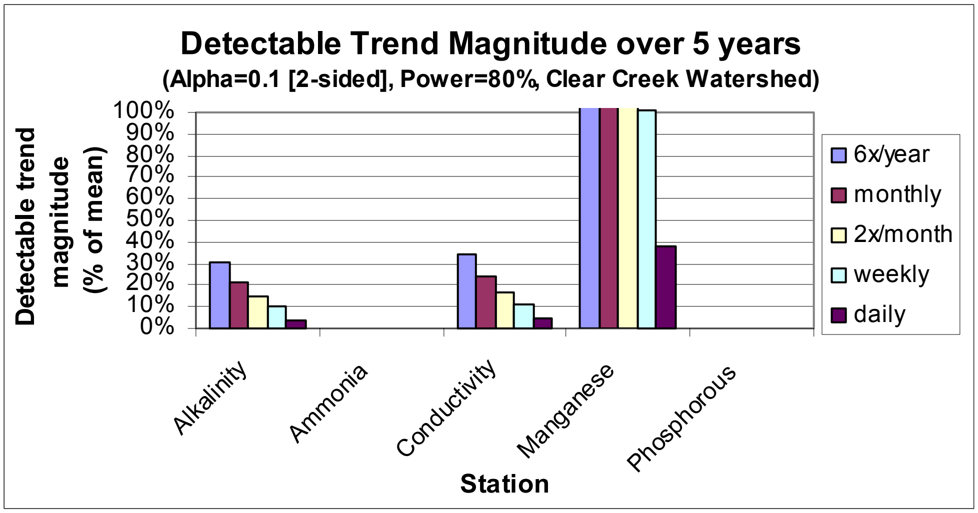

Half-Width Confidence Interval as % of the Mean
(Alpha = 0.20, Upper South Platte, Phosphorous)
Half width of confidence interval (% of mean)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
6x/year
monthly
2x/month
weekly
daily
SPR @ Little
Big Dry @ Little
Plum nr Louviers
Geneva @ Grant
Duck nr Grant
Deer nr Bailey
Roony Gulch
Bear abv Reservoir
Bear abv Evergreen
SPR @ Union Ave
Big Dry @ Easter St
Chat nr Little
Plum @ Titan Rd
E Plum @ Castle
SPR @ Waterton
Station

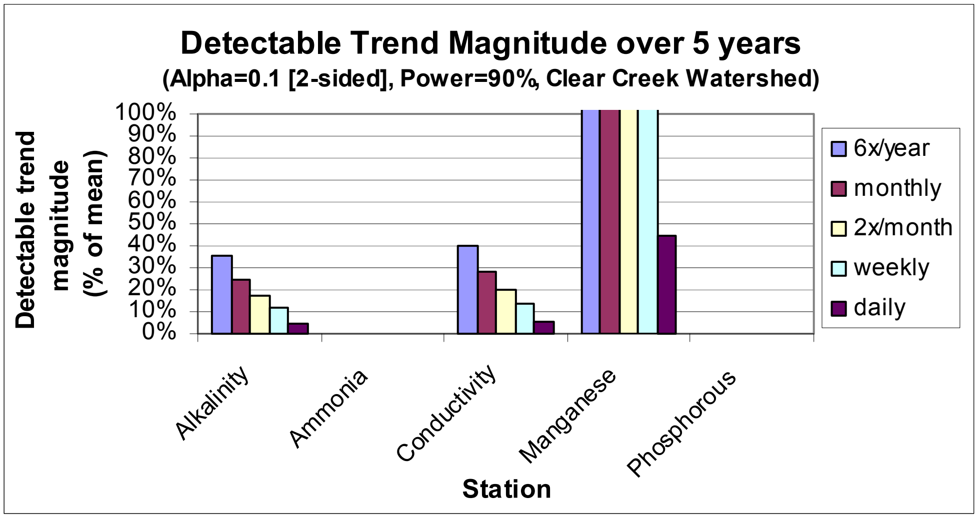

Half-Width Confidence Interval as % of the Mean
(Alpha = 0.20, Upper South Platte, Ammonia)
Half width of confidence interval (% of mean)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
SPR @ Little
Big Dry @ Little
Plum nr Louviers
Geneva @ Grant
Duck nr Grant
Deer nr Bailey
Roony Gulch
Bear abv Reservoir
Bear abv Evergreen
SPR @ Union Ave
Big Dry @ Easter St
Chat nr Little
Plum @ Titan Rd
E Plum @ Castle
SPR @ Waterton
Station
6x/year
monthly
2x/month
weekly
daily

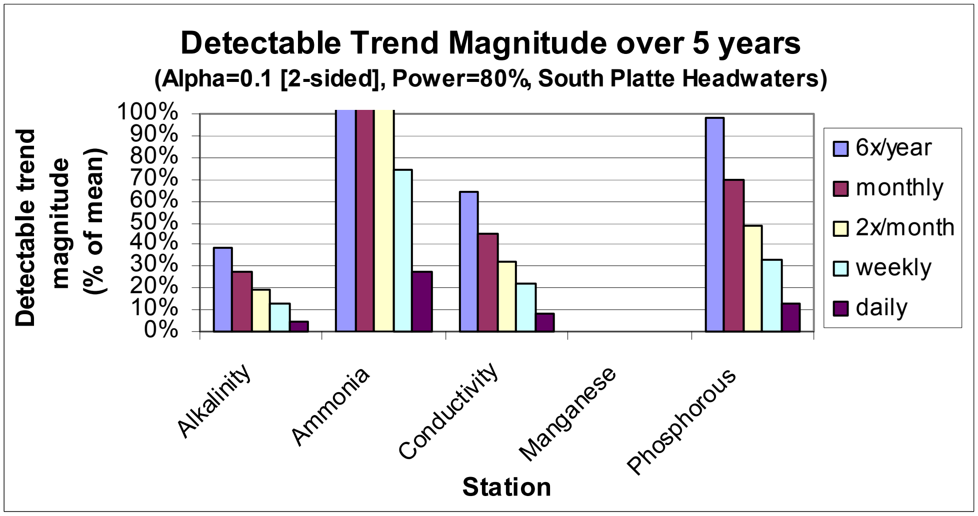
APPENDIX F: SAMPLING FREQUENCY ESTIMATION FOR TREND DETECTION RESULTS

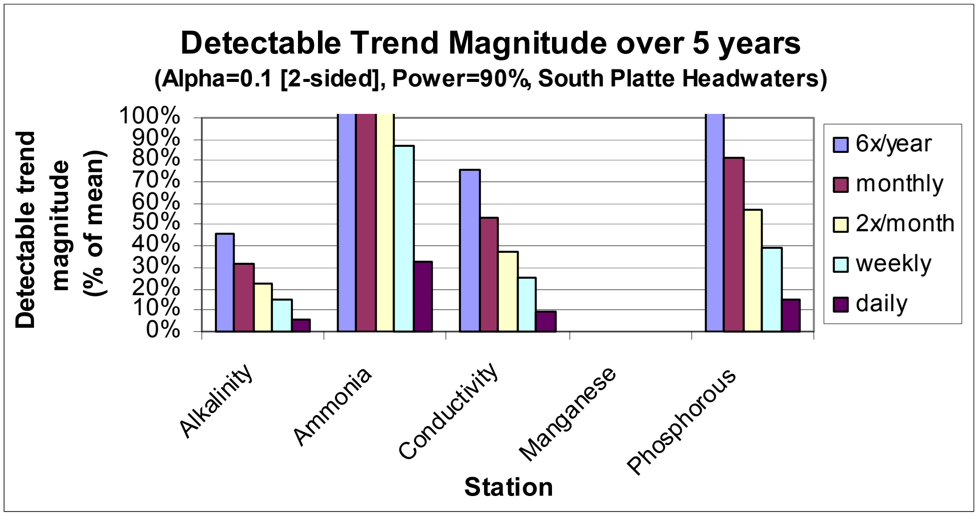

Detectable Trend Magnitude over 5 years
(Alpha=0.1 [2-sided], Power=80%, Blue River Watershed)
Detectable trend magnitude (% of mean)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Alkalinity
Ammonia
Conductivity
Manganese
Phosphorous
Station
6x/year
monthly
2x/month
weekly
daily

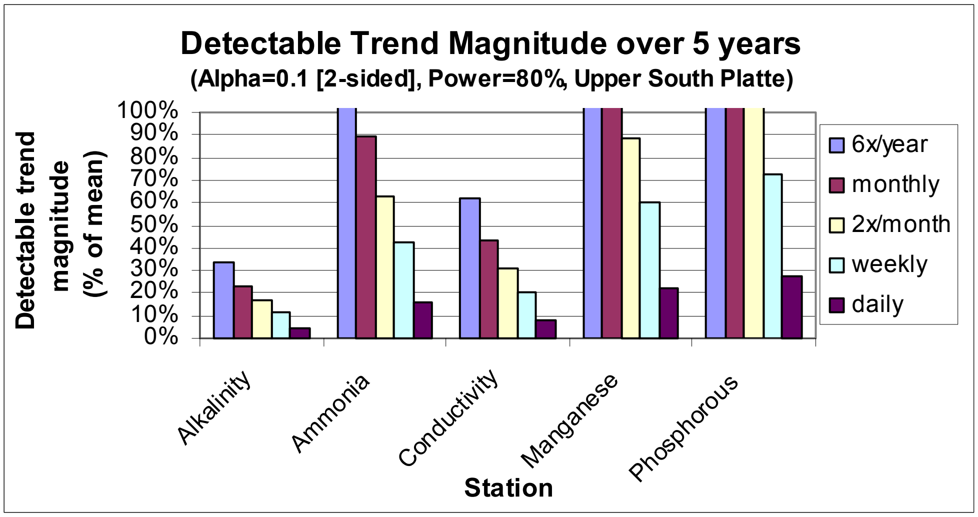

Detectable Trend Magnitude over 5 years
(Alpha=0.1 [2-sided], Power=90%, Blue River Watershed)
Detectable trend magnitude (% of mean)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Alkalinity
Ammonia
Conductivity
Manganese
Phosphorous
Station
6x/year
monthly
2x/month
weekly
daily


Detectable Trend Magnitude over 5 years
(Alpha=0.1 [2-sided], Power=80%, Clear Creek Watershed)
Detectable trend magnitude (% of mean)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Alkalinity
Ammonia
Conductivity
Manganese
Phosphorous
Station
6x/year
monthly
2x/month
weekly
daily

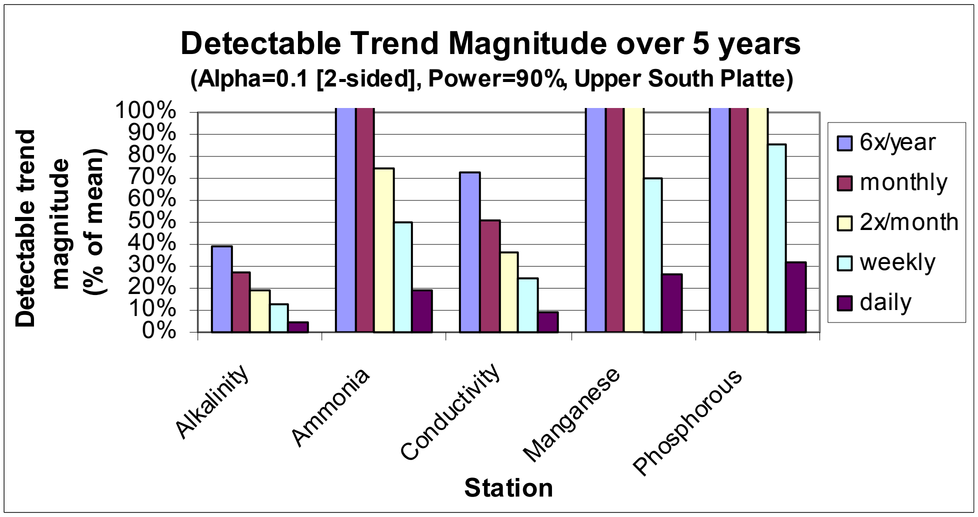

Detectable Trend Magnitude over 5 years
(Alpha=0.1 [2-sided], Power=90%, Clear Creek Watershed)
Detectable trend magnitude (% of mean)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Alkalinity
Ammonia
Conductivity
Manganese
Phosphorous
Station
6x/year
monthly
2x/month
weekly
daily


Detectable Trend Magnitude over 5 years
(Alpha=0.1 [2-sided], Power=80%, South Platte Headwaters)
Detectable trend magnitude (% of mean)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Alkalinity
Ammonia
Conductivity
Manganese
Phosphorous
Station
6x/year
monthly
2x/month
weekly
daily


Detectable Trend Magnitude over 5 years
(Alpha=0.1 [2-sided], Power=90%, South Platte Headwaters)
Detectable trend magnitude (% of mean)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Alkalinity
Ammonia
Conductivity
Manganese
Phosphorous
Station
6x/year
monthly
2x/month
weekly
daily

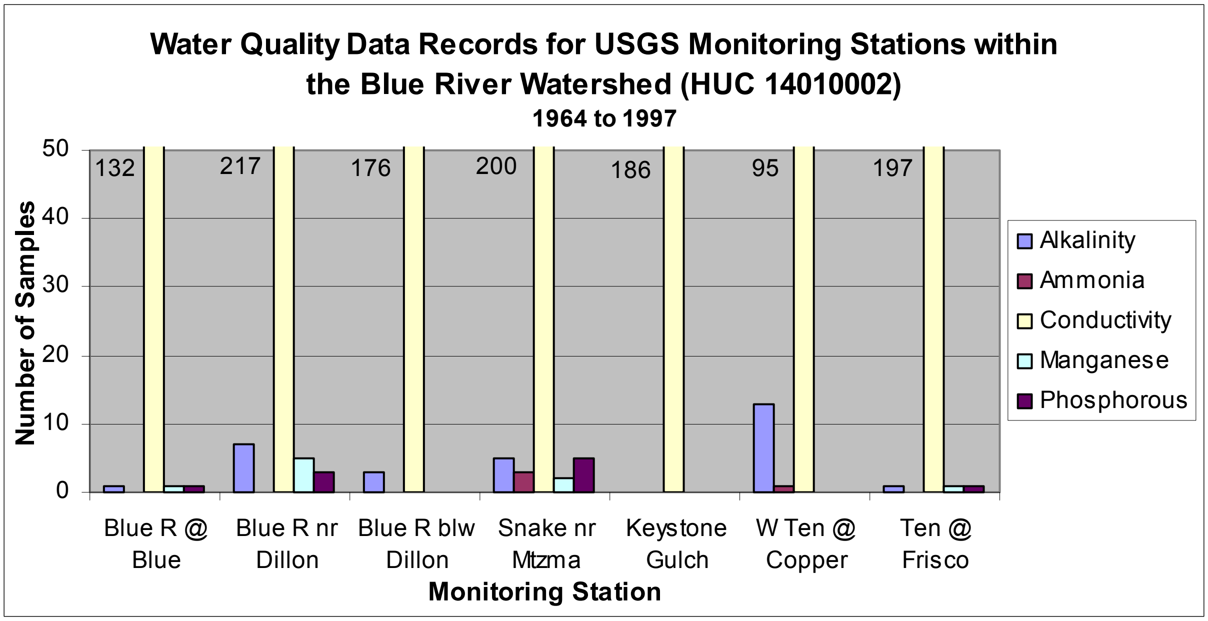


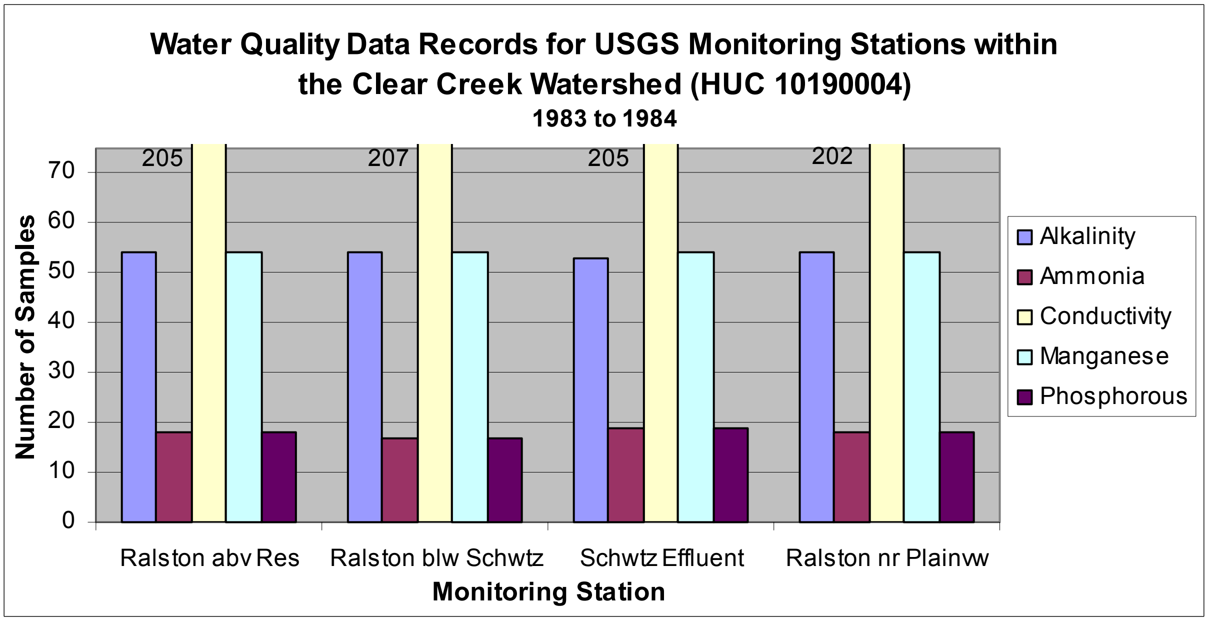
Detectable Trend Magnitude over 5 years
(Alpha=0.1 [2-sided], Power=80%, Upper South Platte)
Detectable trend magnitude (% of mean)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Alkalinity
Ammonia
Conductivity
Manganese
Phosphorous
Station
6x/year
monthly
2x/month
weekly
daily

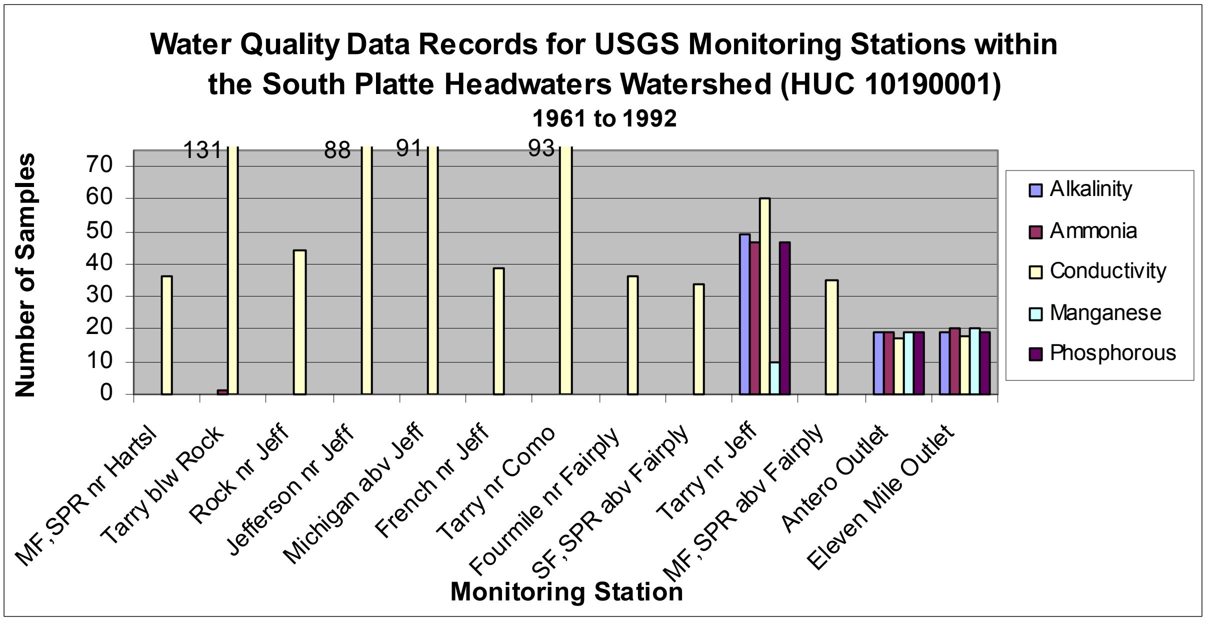


Detectable Trend Magnitude over 5 years
(Alpha=0.1 [2-sided], Power=90%, Upper South Platte)
Detectable trend magnitude (% of mean)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Alkalinity
Ammonia
Conductivity
Manganese
Phosphorous
Station
6x/year
monthly
2x/month
weekly
daily

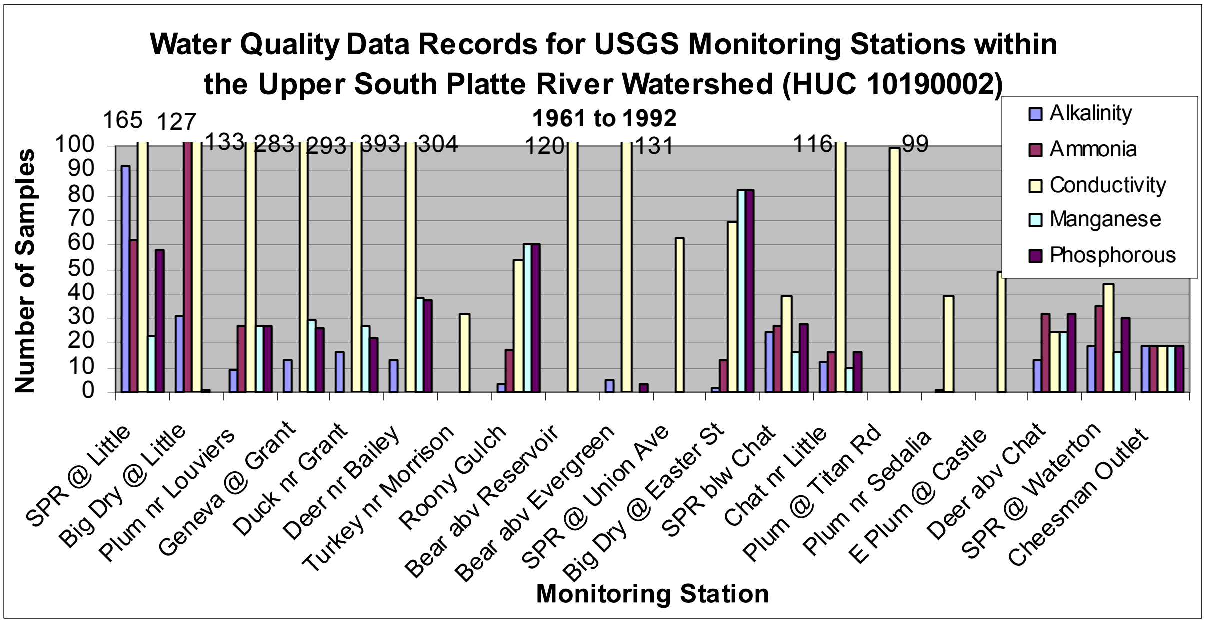
APPENDIX G: USGS WATER QUALITY RECORDS FOR MONITORING STATIONS WITHIN SELECT HYDROLOGIC UNIT CODES (HUC)


Water Quality Data Records for USGS Monitoring Stations within the Blue River Watershed (HUC 14010002)
1964 to 1997
Number of Samples
0
10
20
30
40
50
132
217
176
200
186
95
197
Blue R @ Blue
Blue R nr Dillon
Blue R blw Dillon
Snake nr Mtzma
Keystone Gulch
W Ten @ Copper
Ten @ Frisco
Monitoring Station
Alkalinity
Ammonia
Conductivity
Manganese
Phosphorous


Water Quality Data Records for USGS Monitoring Stations within the Clear Creek Watershed (HUC 10190004)
1983 to 1984
Number of Samples
0
10
20
30
40
50
60
70
205
207
205
202
Ralston abv Res
Ralston blw Schwtz
Schwtz Effluent
Ralston nr Plainvw
Monitoring Station
Alkalinity
Ammonia
Conductivity
Manganese
Phosphorous


Water Quality Data Records for USGS Monitoring Stations within the South Platte Headwaters Watershed (HUC 10190001)

1961 to 1992


Water Quality Data Records for USGS Monitoring Stations within the Upper South Platte River Watershed (HUC 10190002)

1961 to 1992