

WATERSHED SCALE IMPACTS OF
POLLUTANTS IN AN ALPINE
GROUNDWATER SYSTEM

by

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ABSTRACT

Watershed-scale groundwater characterization can be a challenge due to the scarcity of and the inherent uncertainties associated with publicly available data, and the high costs associated with additional field scale investigations. In two representative locations within the Blue River Watershed of Summit County Colorado, we have combined publicly available data with limited supplemental fieldwork to evaluate the groundwater hydrology and potential anthropogenic effects on water quality. Public data was obtained from: water-well logs available from the Colorado State Engineer's Office (CSEO) and one year of surface water quality data, collected for thesis research performed within the Blue River Watershed in 2000-2001. Collected field data included: physical and chemical analyses of soil from the borings of four monitoring wells, one year of hydraulic head measurements, monthly water-quality analyses and one year of monthly stream-water quality data.

Based on existing data, aquifer properties (aquifer material, depth to water, thickness, hydraulic conductivity) were estimated. These estimates compared favorably to information obtained directly in the field. The hydraulic conductivity (K) estimate derived from the compilation of CSEO values, was estimated at 10^{-2} to 10^{-3} cm/sec. This was comparable to the K values estimated by actual particle analysis of soils collected during drilling ($\sim 10^{-2}$ cm/s).

Hydraulic head of the groundwater at the study areas was at an elevation lower than the surface water, indicating a weak groundwater-surface-water connection, with surface water recharging the groundwater.

Groundwater samples collected along the Blue River drainage had little temporal variation in each well; but showed significant spatial variations across the watershed. Surface water samples from the head of the Blue River, Penn Creek and Swan River show chemical signatures of the natural mountain drainage waters. Elevated SO₄ signatures in the waters of Frisco Terrace (FT) are associated with local historical mining activities. Some waters within FT also show a potential on-site wastewater system (OWS) signature, with elevated Cl and NO₃ constituents.

Three of the four monitoring wells have chemical signatures that are essentially identical to the local surface water systems, implying groundwater and surface water at those locations are connected. One monitoring well shows groundwater chemistry signatures with lower total dissolved solids (TDS) and SO₄ but higher Cl and NO₃ than the available local surface water compositions, indicating that groundwater at this location may not be well connected to the local surface water system.

Anthropogenic constituents (such as TDS, chloride, nitrate, and sulfate) progress from the unpopulated background site, through Blue River Estates, to their highest concentrations in the Frisco Terrace site nearest to Lake Dillon. Groundwater impacts from anthropogenic effects within this watershed are apparent.

Keywords: *Summit County, Colorado, Hydrology, Aquifer, Groundwater, Water Quality, Wastewater*

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CHAPTER 1: INTRODUCTION

1.1 Background

Onsite wastewater treatment systems provide approximately 25% of the United States' population with a means of disposing of wastewater, (Kirkland, 2001). With a significant portion of households relying on these localized wastewater treatment systems, it is imperative that the cumulative effect of multiple systems on water quality and quantity be quantified. The Blue River Watershed, a mountain watershed in Summit County, Colorado (Figures 1-1), is an example of such a system, which incorporates the use of both centralized and decentralized wastewater treatment systems {i.e. On-site Wastewater Systems (OWS)}. An integral watershed feature of interest in Summit County is the Dillon Reservoir, a key drinking water source for the city of Denver, which is fed by the watershed drainage system being investigated by this project. This watershed (The Upper Blue River) is currently being evaluated by Colorado School of Mines, with funding from the National Decentralized Water Resources Capacity Development Project (NDWRCDP), to develop and test a methodology for assessing the water quality impacts of decentralized wastewater systems. A component of the larger scale evaluation described above is this field scale groundwater characterization, designed to enhance the understanding of the transport/fate of microbes and chemicals in this specific watershed, and to enable the corresponding site scale model development to be based on realistic site-specific parameters.

Defining and characterizing the groundwater in Summit County is important for several reasons. First, it is often not clear whether aquifer systems in these mountain watersheds are comprised primarily of sediments (i.e., a typical heterogeneous porous-

media aquifer) or of fractured bedrock. This distinction has serious implications on OWS pollutant transport and connection between the drinking-water source (aquifer) and the surface-water system (Poeter et al., 2003). For example, drinking-water wells located in a nearby watershed, Turkey Creek Watershed, were drilled primarily into fractured bedrock, with very little or no overburden present to act as filtration media for their OWS systems. This creates serious effluent discharge and flow concerns at this site. In a sedimentary aquifer such as the one found in the Blue River study area, an estimation of the depth of porous materials between OWS effluent and the top of the water table is crucial because the soils serve as a treatment media for OWS pollutants. In addition, the strength and nature of the GW-SW interaction depends on the character of the subsurface materials.

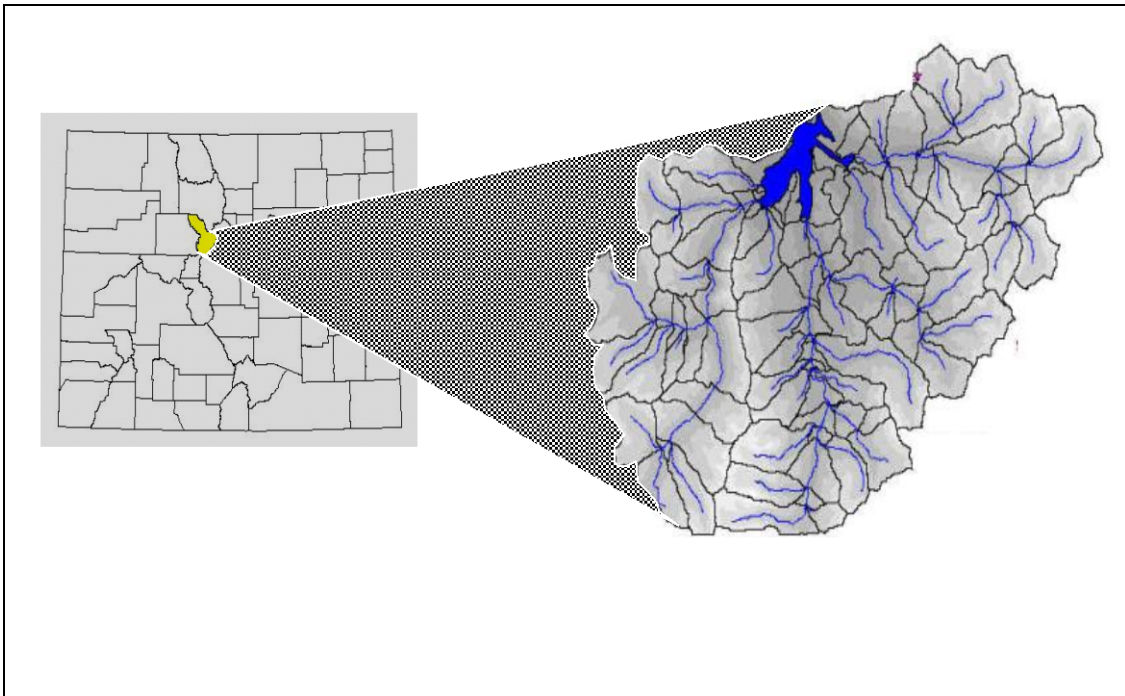


Figure 1-1: Location of Summit County Colorado

Delineation of general hydraulic properties specific to the aquifer in question, is necessary to better understand groundwater flow and pollutant transport characteristics and subsequently to allow for the construction of watershed-scale groundwater and pollutant transport models. Finally, in watersheds where potential pollution of surface-water bodies from OWS effluent is of concern, identifying the potential for ground and surface water interaction is key. In the Blue River watershed, the eutrophication of Lake Dillon with nutrients such as nitrogen (N) and phosphorus (P) is an ongoing problem, with other researchers having identified OWS's as a potential cause of the P pollution (Lewis et al., 1984). These issues are addressed in this preliminary characterization of the groundwater system in the Blue River watershed.

Watershed management is a rapidly developing science, increasing in popularity as land use managers and city planners; particularly in this drought conscious portion of the Western United States, begin to recognize the need for evaluation of water quality and protection of water resources as well as the need for better environmental management techniques within their districts. Unfortunately, there is a remarkable shortage of high-quality data associated with water quantity and quality for use by these regulators for initial evaluation of the average watershed. One common publicly available data source of watershed information is the State Engineers Water Well Database. In Colorado, this database is compiled and managed by the Colorado State Engineer's Office (CSEO). Though these databases are not a source of highly detailed information in many cases, similar databases are available in most states and thus a methodology for deriving information from this source is integral. In addition to state well logs, three dual-port monitoring wells and one single port monitoring well were installed utilizing low cost shallow auger installation techniques, to obtain site-specific data used to estimate site-specific groundwater parameters at two areas of concern within this watershed. These wells were used to monitor chemical changes of wastewater pollutants over time, and to define the natural chemicals and hydraulic head and

hydraulic conductivity (K) values for the groundwater specifically in our two areas of concern. Surface water data collected by the Colorado School of Mines and the United States Geological Survey (U.S.G.S.) in this watershed as well, allowed for the evaluation of surface-water-quality data in comparison with the groundwater assessments performed in this study. Each of these data sources is described in more detail in a subsequent section. The results of this groundwater characterization will be incorporated to provide “realistic parameters” for input and to verify the results of models designed to estimate and predict the transport of anthropogenic chemicals within this watershed.

This research will also serve as a template to be used by other counties and states to help them more completely to characterize their groundwater systems when modeling transport of anthropogenic chemicals.

1.2 Statement of Research

An understanding of the hydrogeology of this watershed is necessary to determine which portions of the water system could be potentially affected by OWS systems. Hydrologic concerns which play a role in determining the quality of the groundwater and the overall health of this hydrologic system include concepts such as: if there is an occurrence of base flow groundwater with in surface flow (streams) in these areas of concern, if there are groundwater / surface water interactions at all with in this system, or if the depth and quality of soil in the vadose zone possesses properties which may effect effluent from OWS systems which travels through it. In a separate part of this project, research was conducted investigating the surface water quality of the Upper Blue River watershed. Surface water results are discussed in detail in Guelfo (2003), and partially in the Conclusions and Overall Results Discussion chapters of this thesis. Groundwater and Surface water evaluations were performed in the same geographic area, Blue River Watershed, Summit County Colorado.

1.3 Objectives

The overall characterization efforts to completely define the hydrology and water quality in the upper Blue River Watershed included surface water and stream flow sampling as well as groundwater characterizations. Surface water analyses came from the Upper Blue River and some of its tributaries including but not limited to: Ten Mile Creek, Pennsylvania Creek and Swan River. The groundwater characterization executed for this thesis was performed primarily in two specific areas within this watershed. Blue River Estates and Frisco Terrace were selected specifically as characteristic sites, (See Figure 1-2) to be evaluated to provide data to for the watershed-scale modeling portion of this project as well as to facilitate hydraulic pollutant-transport evaluations.

The general goals of this project were to:

- Look at typical groundwater aquifer information that may be available in any given watershed, and try to determine what details can be extracted about the system from the existing available data.
- Define the general hydraulic properties of this aquifer, useful when estimating flow and pollutant transport (e.g., hydraulic conductivity, bulk density, porosity, etc.).

The specific purposes of the groundwater study were to:

- Assess the general character of the aquifer used as a drinking-water source by households in the Blue River watershed (e.g., depth to groundwater, sedimentary versus fracture bedrock aquifer, degree of heterogeneity).
- Discern if OWS in FT and BRE are significant sources of nitrogen (N) and phosphorus (P) inputs in this watershed, potentially aiding in the eutrophication of

Lake Dillon based on groundwater water quality data and hydraulic and pollutant transport information.

- Determine if Blue River Watershed aquifer conditions are generally conducive to groundwater/surface-water interactions, which would be required for OWS to impact surface water, as the OWS effluent is released into the subsurface initially.

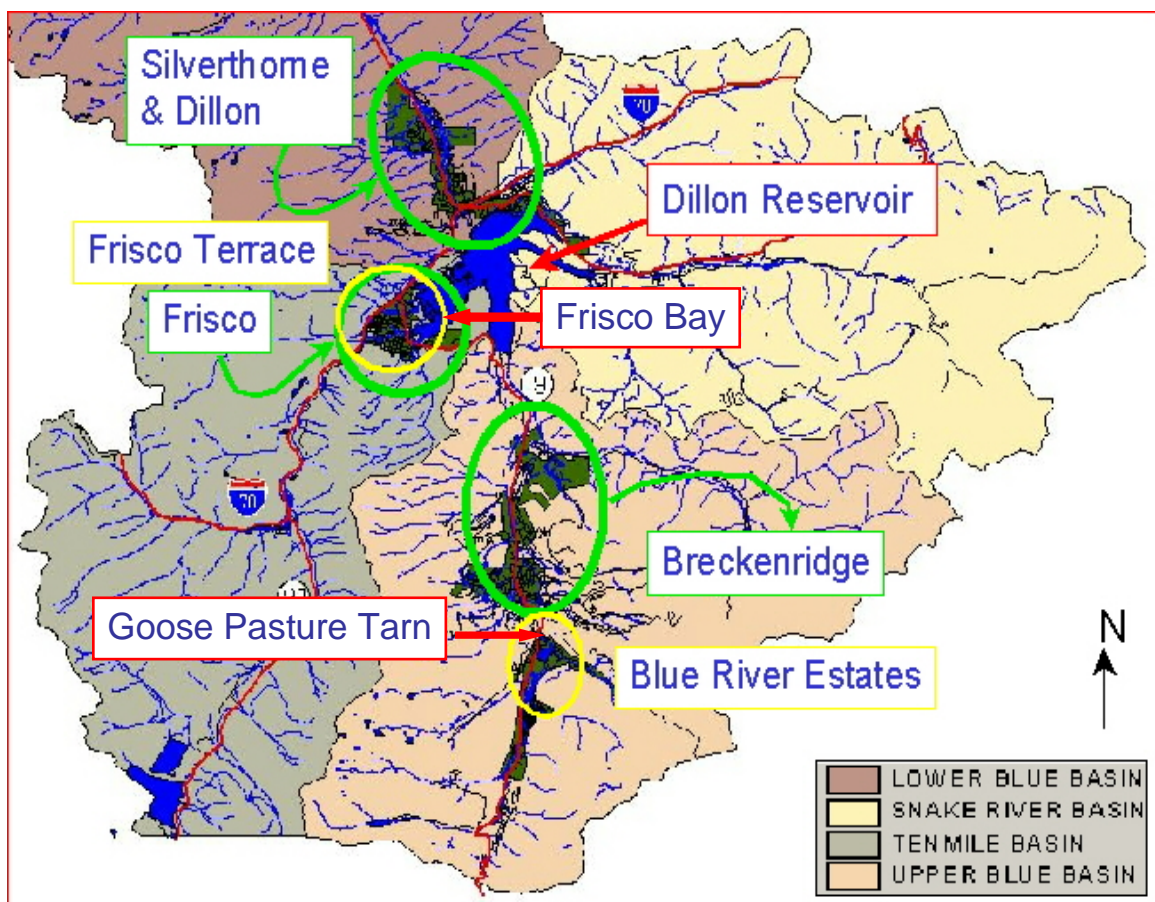


Figure 1-2: Southern Summit County Areas of Concern, Points of Reference and Sub-Watersheds

- Provide information to other team members to facilitate use of the field derived characteristics specific to this system to define the groundwater system and the subsurface lithology of this watershed, and to calibrate the site-specific sensitive parameters in the watershed evaluation models.
- Provide additional information to team members to verify the accuracy of the modeling outputs that were derived during their final modeling of this watershed. Various watershed modeling programs were modified to reflect the natural processes which are occurring in Summit County and the associated Blue River Watershed. Defining whether their derivations of predicted chemical values at specific locations in the watershed are reflective of reality is integral to verifying the programs' usefulness as fate and transport predictability models.

1.4 Study Area

Summit County, Colorado is located approximately 65 miles west of Denver in the central Rocky Mountain Region of the state. The county's boundaries are the Eisenhower Tunnel to the east, the top of Vail Pass to the west, Hoosier Pass to the south, and Green Mountain Reservoir to the north. The highways that serve as major access to the county are I-70 from the East and West, and State Highway 9 from the North and South. Summit County was the fastest growing county in the country from 1970 to 1980 with an increase in population of 232%. Summit County's current population is approximately 24,000 and it remains one of the fastest growing counties in Colorado. The county has four primary population centers in the towns of Dillon, Frisco, Silverthorne, and Breckenridge, which is the oldest town and serves as the county seat. The majority of residents live in unincorporated Summit County. Summit County has an average annual snowfall of 159.4 inches and is the home of four major ski resorts: Arapahoe Basin, Breckenridge, Copper Mountain, and Keystone. Recreation is also

important to the county, with popular summertime activities that include hiking, biking, camping, fishing, boating and river rafting. Elevation ranges in the county from 7,947 feet to 14,270 feet above mean sea level. (Summit County Tourism Web Page, www.co.summit.co.us). Figure 1-2, shown previously, also illustrates the major sub-watersheds in Summit County and specific areas of interest located in Southern Summit County, Colorado. This paper focuses on the Blue River watershed.

Summit County as it is now defined, officially was ratified in August of 1936. As a result of the discovery of gold in the area in 1859, there were population booms in this county in 1860, 1878, and 1898. By June of 1860 there were 8,000 people in the county. The population in 1970 was 2,665. The current resident population is approximately 24,000. Population concentrations can sky rocket to as high as 100,000 on holidays and busy ski weekends, from tourism activities (Jim Raida, Summit County Department of Health and the Environment, Verbal Communication).

Field Area Locations. Two (2) specific portions of Summit County (South of Lake Dillon); Frisco Terrace and Blue River Estates, were selected to evaluate site-specific groundwater components of this project.

The first site, Frisco Terrace, is a subdivision community located at the edge of the Western Arm of the Dillon Reservoir (adjacent to I-70). Frisco Terrace was created in the mid-1960's and is comprised of 1,263 acres, consisting generally of ½ acre parcels each are served by private wells and on-site wastewater systems. Frisco Terrace lies at an elevation of approximately 9175 feet at its western edge, dropping to a flat plain at an average 9125 feet elevation, adjacent to the South Western arm of the Dillon Reservoir.

Monitoring wells were emplaced in two areas in FT, roughly up gradient of the development and roughly down gradient of the development (Figure 1-3):

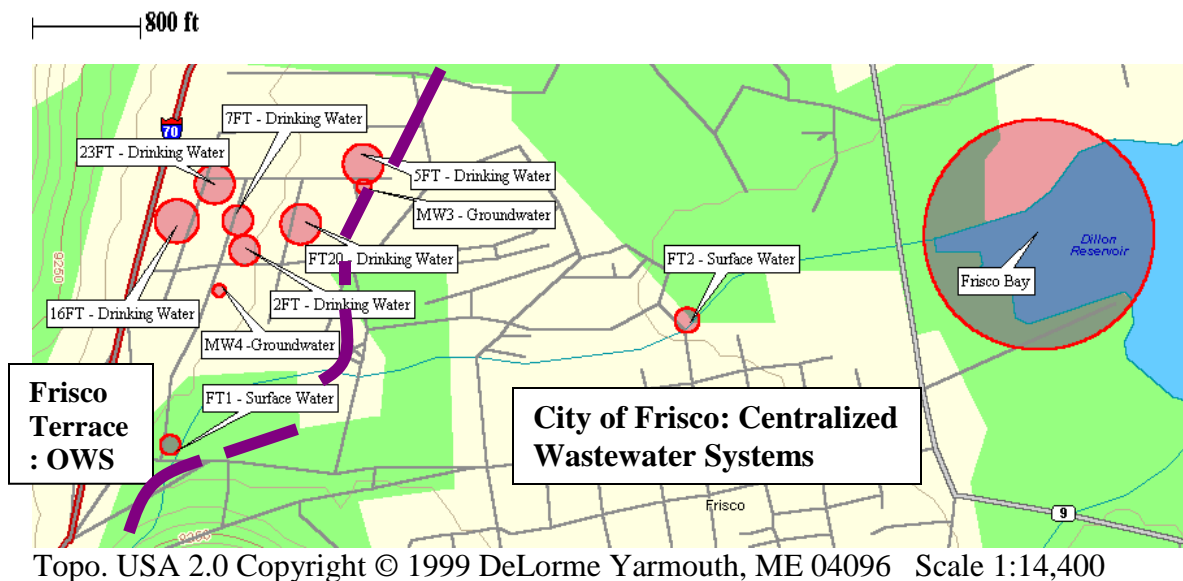


Figure 1-3: Frisco Terrace Site-specific Sampling Locations / Boundary between OWS systems and Centralized Sewer System

The second selected site (Figure 1-4) is the Blue River Estates (BRE), a residential development, comprised of 2200 acres of unincorporated land located up gradient on the Blue River (i.e. south) from Breckinridge. BRE consists of a number of small subdivisions along Pennsylvania Creek, a tributary to Blue River, which were initiated in the mid-1960s, with active development continuing today.

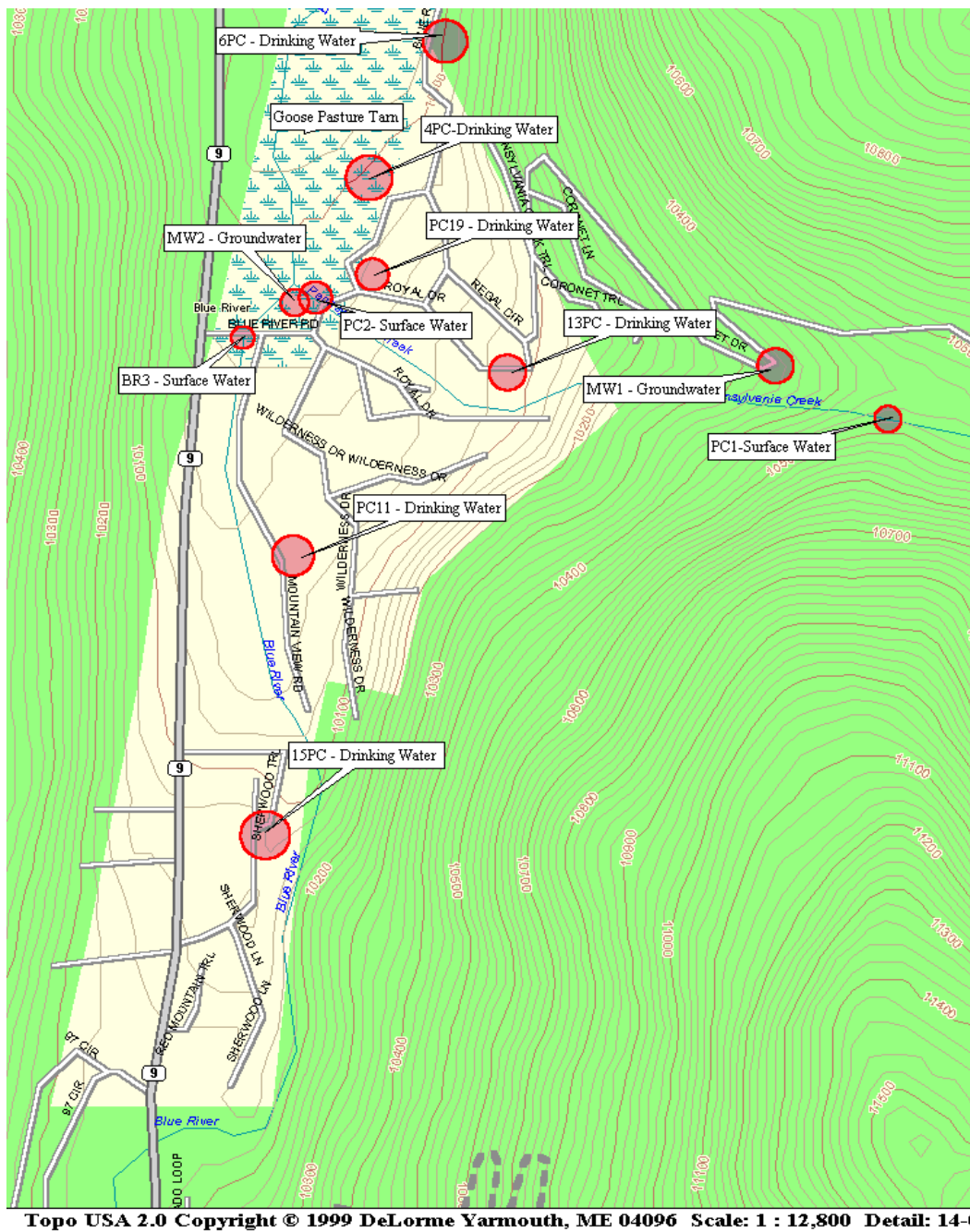


Figure 1-4: Blue River Estates Site-specific Sampling Locations

Neighborhoods consist generally of ½ acre parcels which are served by private wells and on-site systems. BRE exhibits elevation changes that range from the edge of the developed area near the continental divide and the background monitoring well MW1 at approximately 10,277 ft amsl, down to the flood plain at the confluence of Pennsylvania Creek and the Blue River, (the location of MW2) at 9980 ft amsl.

CHAPTER 2: LITERATURE REVIEW

The vast majority of the drinking-water wells in Frisco Terrace and Blue River Estates are located in the unconfined aquifers of sands and gravel with trace or limited amounts of clay's and silts. For porous media such as these, there are a few parameter values which must be determined to better understand the hydrology of this area. These values include: *Hydraulic Conductivity*; defined as a coefficient of proportionality describing the rate at which water can move through a permeable medium (Fetter, 2001), and *Transmissivity*, defined as the rate at which water of a prevailing kinematic velocity is transmitted through a unit width of the aquifer under a unit hydraulic gradient (Fetter, 2001). Both these values can be derived from various calculations found in the literature.

For example: Transmissivity can be derived solely from well log information utilizing the following equation to estimate aquifer transmissivity (T) in square feet per day:

$$T = 1140 (SY / \Delta h)^{0.67} \quad (\text{Razack and Huntley, 1991}) \quad (2-1)$$

where: T = Transmissivity in square feet / day, SY = sustained yield in gpm,
 Δh = drawdown in feet

This equation is empirical and was developed to estimate transmissivity from specific capacity data in a large and heterogeneous alluvial aquifer. Other more detailed expressions are available (Fetter, 2001), but these require estimates of the specific yield, which are not available through well log evaluations alone. This derivation will allow for a first estimate of T for Blue River Estates and Frisco Terrace. Hydraulic Conductivity Estimates (K values) can be made using the equation:

$$\mathbf{T=Kb, \text{ or } K=T/b} \text{ (e.g., Fetter, 2001),} \quad \mathbf{(2-2)}$$

where: T = Transmissivity from the equation above, and b = the aquifer thickness

This equation derives K values in the 10^{-3} cm/s range consistent with published data for coarse glacial material (Fetter 2001) or sandy outwash (Bradbury and Rothschild 1985).

When only the textural classification is known, simple class PTF (pedo-transfer functions) can be used to provide average hydraulic properties for each soil textural class (Carsel and Parrish, 1998; Wosten et al, 1995). When the actual particle size distribution is known, PTFs that predict continuously changing hydraulic properties across the textural triangle can be used (Schaap, Leij and Genuchten 1998). This data was collected from monitoring well installation soil samples tested at the University of Wisconsin Plant and Soil Science Center.

There has been a significant quantity of work completed on the subject of determining which constituents should and can be effectively monitored during water quality sampling to best indicate potential water quality impacts from on-site systems, and potential for eutrophication of water bodies due to increased nutrient content in natural systems. Some of the key references for these parameters included USGS texts, (Hem, 1985), USEPA MCL documentations and others. Some of the water quality constituents that can indicate contamination from on-site systems include boron, nitrate, phosphate, fecal coliform bacteria and total organic carbon. All are possible products of consumption of commercial products or human waste that would be disposed of in an on-site system. Boron is a potentially good indicator of on-site influence because: (1) natural background concentrations are relatively low, (2) boron does not undergo a biological removal during treatment, and (3) boron is not significantly sorbed in the subsurface. Boron concentrations in the Colorado Front Range typically range from less

than 10 µg/L to 40 µg/L. Elevated Boron concentrations can indicate human influence. Anthropogenic sources of boron include non-chlorine bleaches and fruit.

If we assume that onsite indicators are similar from home to home, it is possible to infer that the constituents seen indicating impact in the following Canadian research may be indicators of impact for our sites as well. Distinct plumes of on-site system impacted groundwater at two single family homes located on shallow unconfined sand aquifers in Ontario showed elevated levels of Cl⁻, NO₃⁻, Na⁺, Ca⁺, K⁺, alkalinity, and dissolved organic carbons and depressed levels of pH and Dissolved Oxygen. (Robertson, Cherry and Sudicky, 1991). These indicator parameters should be included in this characterization.

Nutrient analysis is the measurement of different forms of nitrogen and phosphorous in water. Nutrients are a concern in surface water because of eutrophication. In drinking-water, excess nutrients are a human health concern: the maximum contaminant level in finished drinking-water is 10 milligrams per liter mg/L (USEPA 1994). Nitrate can be useful as a tracking tool for on-site contamination because large concentrations can be contributed by human waste, and nitrate is mobile in water. Nitrogen measured within the on-site (septic tank) system itself is found in the form of ammonia rather than nitrate, nitrification occurs after the waste has been discharged to the soil. To measure impact concentrations in the waste itself, one must measure ammonia, but to measure impact in the system after discharge to the soil, one must measure total nitrogen or another nitrogen parameter other than ammonia.

Phosphorous, is a common ingredient in detergents and cleaners, so it can also be an indicator of on-site contamination. Phosphorous can be readily removed in the subsurface by sorption and precipitation (USGS Open File Report 00-214, August 2000).

Several sub-projects and theses have been generated for the Environmental Protection Agency (EPA) from this overall project entitled: Quantifying Site Scale Processes and Watershed-Scale Cumulative Effects of Decentralized Wastewater Systems. The thesis work most directly related to this research was written by Jennifer Guelfo Bagdol in 2003 (Guelfo, 2003). Guelfo's thesis evaluating surface water quality in Lake Dillon Watershed Summit County Colorado is the sister document to this research which evaluates the groundwater in the same area. Guelfo (2003) evaluated the surface waters of Blue River Estates and Frisco Terrace in a year long sampling program, analyzing for similar constituents as were evaluated in the groundwater sampling program. Surface water sampling was initiated in September of 2001, prior to initiation of groundwater sampling in February 2002, and lasted until September 2002. From February through September 2002, surface water and groundwater sampling schedules overlapped. These surface water and groundwater data allow for the fingerprinting of the waters, and will provide the basis for the comparison between the groundwater and surface water in this system. Defining the potential for interaction between surface water and groundwater in the area is integral to evaluating possible fate and transport of contaminants in the groundwater within this system. The data sets for the surface water used in this research, are included in chapter 6.

Another thesis written as part of this larger project was by Shiloh Kirkland (2001). This thesis is the preliminary work for this project, and it defines some of the expected generalized parameters commonly used in modeling watersheds and performing overall analyses of this type. Kirkland (2001) supplies key interpretive information for this project such as expected phosphorous concentrations in on-site effluent and expected constituents in potential contamination from (STE) septic tank effluent. Proceeding from this preliminary set of data, Guelfo (2003) and Smith (this document) individuated the parameters to a more site-specific set of values, better reflecting site-specific conditions found in Summit County, Colorado. The thesis by Lemonds (2003), collected and

combined information from Kirkland (2001), Guelfo (2003) and Smith (this document) and compiled an assessment evaluation of watershed modeling programs for use in defining operations of the natural systems with in the Lake Dillon watershed.

Some field specific professional knowledge such as flow dynamics and general subsurface hydrogeology must be comprehended in order to discuss the hydraulics and overall systems in this watershed. Toward that end, a variety of general hydrology textbooks were referenced, including (Fetter, 2001), (Driscoll, 1986), (Hem, 1997) and (Kresic, 1997). (Fetter, 2001) and (Driscoll, 1986), provided fundamentals such as an understanding of terms such as hydraulic transmissivity, hydraulic conductivity and specific yield, and helped to construct the basis for many concepts and ideas with in this thesis. A sound understanding of basic engineering hydrogeology is key to proper evaluation of the data sets in this thesis. Some integral concepts used in this paper which apply specifically to this work include: well construction, groundwater hydraulics, sampling techniques, and estimations of hydraulic conductivity and transmissivity in these aquifers. Kresic, (1997), provided specific equations for actual applied type problems for typical, realistic, available data. Hem, (1985), provided key conceptual explanations of the geochemistry of natural water systems, not only including information on sources and chemistry of nitrogen and phosphorous in waters, but also defining the significance of properties and constituents reported in water analysis. Hem's study addressed most of the constituents evaluated in the groundwater characterization of Frisco Terrace and the Blue River Estates portion of Summit County, Colorado. Hem also discussed the mechanics behind the pH and Specific Conductance measurements made on the water samples.

Identification of the general hydraulic properties of an aquifer is necessary to better understand groundwater flow and pollutant transport characteristics of the groundwater system, thereby allowing for construction of watershed-scale groundwater

and pollutant transport models. Finally, in watersheds where the potential pollution of surface-water bodies from OWS effluent is of concern, identifying the potential for groundwater surface water interaction is paramount. In the Blue River watershed, the eutrophication of Lake Dillon with nutrients such as nitrogen (N) and phosphorus (P) is an ongoing problem. In particular, other researchers have identified OWS as a potential cause of P pollution (Lewis et al., 1984). These issues are addressed in this preliminary characterization of the groundwater system in the Blue River watershed.

CHAPTER 3: EVALUATION OF EXISTING DATA: GEOLOGIC AND TOPOGRAPHIC MAPS, SOIL SURVEYS, AND WELL LOGS

3.1 Introduction

There are many sources of existing information that can be potentially helpful when initiating a watershed evaluation. These include but are not limited to: topographic maps, geologic maps and cross sections, soil surveys, state engineer records, and investigations performed by other commercial or research institutions within the area in question. Existing data is desirable in any preliminary work, because costly field investigations have already been completed, and information that may help plan additional studies more efficiently or accurately may be derived from these works. Evaluation of existing works may also help limit additional costly repetitions of previous investigations. Also communities with limited investigative budgets that may not accommodate field investigations can still find and utilize site specific information regarding their specific watersheds.

3.2 Methods

The information available with in each form of existing data is quite varied from type to type. Typically useable data is found as a subset within a larger grouping of generally applicable information (i.e. within the set of all of the states engineering logs). So initially a sorting process must be undertaken to disseminate which data is specifically useful for the investigation and characterization at the area of concern. This sorting could

be computerized (as with the large Colorado State Engineers Office (CSEO) data base) or manual (as would be expected when sorting through stacks of potentially applicable maps for a general area).

3.2.1 Topographic / Geologic Maps

Various geologic maps were consulted for this work, including: the geologic “Map of the Leadville 1°x2° Quadrangle, Northwestern Colorado,” and the more detailed geological map the “USGS Frisco Quadrangle.” These maps indicate that the bedrock in the areas of Frisco Terrace and Blue River Estates are comprised predominantly of sandstones, shale, carbonates, diorites and gneisses of varying ages. (Tweeto et al., 1978) These bedrocks are overlain in both FT and BRE by glacial deposits.

The Blue River Watershed is bounded by the Williams Fork Mountains on the East and the Gore Range to the West. On the eastern slope of the Blue River Watershed, near Blue River Estates, the Pennsylvania Creek watershed runs through an area where bedrock is comprised of the Minturn and Belden Formations. Drinking-water well installation logs and monitoring-well records for this area indicate that the depths of unconsolidated overburden extend roughly 60 feet below ground surface. The origin of the sandy glacial material is likely the original bedrock. The Minturn formation is comprised of Pre-Cambrian rocks including: sandstones, grit, conglomerate and shale, and scattered beds of reefs of carbonate rocks. This unit is greater than 6000 feet thick and thins to the east. The Belden Formation is composed of black shale, carbonate rocks and sandstone with a maximum depositional thickness of 900 feet. This Precambrian rock is intruded by Larimide Intrusives from the Eocene, Paleocene, and Upper Cretaceous age (40-72 million years old). These intrusive rocks are comprised of: quartz monzonite, granodiorite and quartz diorite porphyries in stocks sills or dikes. Along the

river corridor, these rocks are overlain by young glacial drift made up of unsorted bouldery glacial deposits (till) and associated sand and gravel deposits. The bedrock beneath the glacial till and alluvial sands of the Blue River is also Minturn and Belden Formations with the Larimide Intrusive rocks outcropping sporadically. This lithology continues up the western slope of the Blue River Watershed and turns almost predominantly into heavily faulted Biotitic Gneiss and Migmatites (still Precambrian aged rocks) containing minor layered hornblende gneiss and calcsilicate rocks. Parent materials of these rocks were mainly greywacke and shale.

The bedrock around Frisco, the study area adjacent to Dillon Reservoir, is mapped as various quaternary deposits, primarily “Young Glacial Drift (Bull Lake Glaciations or Younger).” This glacial material is comprised of unsorted bouldery glacial deposits (till) and associated sands and gravel deposits. It appears that this glacial drift in the area of Frisco Terrace overlays an area where Precambrian Gneisses (Biotitic Gneisses and Hornblende Gneisses) contact the Upper Cretaceous aged Pierre Shale, Dakota and Morrison Formations.

3.2.2 Soil Surveys

The soil survey of Summit County, Colorado was performed by the Soil Conservation Service and the USDA in 1980. The southern Summit County area consists primarily of areas defined as: steep mountain uplands and glacial drift. The soils mapped in the area of Frisco Terrace where our monitoring wells were installed are comprised of “Grenadier gravelly loam with a 0-6% slope.” The Soils of Blue River Estates are comprised also of Grenadier soils, but they are differentiated into two additional subunits (different from the FT soils) based on the grade of their slopes (i.e. 6-15% or 15-55% grade respectively). Grenadier soils are described generally as deep, well drained, and moderately permeable. They are strongly acidic, medium textured, soils. They have a

brown, gravelly loam surface layer, a strong brown (based on Munsell Soil Color Chart designations) gravelly sandy clay loam subsoil and a brown very cobbly loam substratum. The subsoil and substratum contain more than 35 percent rock fragments by volume (Miles, Fletcher-USDA, 1980). The woodland management and productivity assessment portion of the soil survey, includes severe erosion hazards and equipment limitations, moderate seedling mortality, a slight wind throw hazard, and plant competition issues for these Grenadier soils. Shallow excavations and building sites in these areas have severe limitations due to large stones (boulders in the subsurface overburden). The installation of septic tank absorption fields in these Grenadier soils also is reported to have “severe limitations” for effective installation, due to the presence of large stones in the soils and the steep slope of the soil grade.

Table 3-1 Soil Survey Descriptive Words (Miles, Fletcher-USDA, 1980)

Descriptive Terminology used in the USDA Soil Survey	What it means specifically
Very (as in Very Cobbly)	35%-85% rock fragments compose soil by volume
Medium (as in medium water capacity)	Infiltration Rates of 0.6 – 6 inches per hour
Medium (surface water runoff)	Has moderate permeability infiltration rates
Moderate permeability	Infiltration rates of 0.6 – 6 inches per hour
Deep	More than 2 feet of soil depth – prior to top of rock
Strong (brown)	Munsell Soil Color Chart: soil color designation
Loam	Soil material that is 7-27 % clay, 28-50% silt and <52% sand

These soils are classified by the unified system as gravelly loam from 0-6 inches; gravelly loam, gravelly sandy loam, clay loam from 6 inches to 19 inches; and very cobbly, sandy loam, very stony loam from 19-60 inches depth. Permeability rates are from 0.6-2.0 inches/hour from 0-19 inches of depth and 2.0-6.0 inches/hour from a depth 19-60 inches of depth. The pH of these soils ranges from 4.8-5.5 s.u.

Grenadier gravelly loam with 0-6% slopes are found in Frisco Terrace. These soils are specifically defined as deep, well drained, nearly level to gently sloping soil. These soils were formed in glacial drift derived from a variety of rocks. Permeability is moderate and the available water capacity is medium. Surface runoff is medium. The hazard of wind and water erosion is slight.

Grenadier gravelly loam with 6-15% slopes are found in the Blue River Estates area of MW2, and are defined as deep well drained moderately sloping to strongly sloping soil on glacial fans. This soil formed in glacial drift, and it is derived from a variety of rocks. Permeability is moderate and the available water capacity is medium. Surface runoff is medium. The hazard of water erosion is moderate.

Grenadier gravelly loam soils on the 15-55% slopes are found near the location of MW1. This soil is defined as deep, well drained, moderately steep to steep slopes and ridges. The soil formed in glacial drift derived from a variety of rocks. Permeability is moderate and the available water capacity is medium.

The “moderate” permeability definitions are given as infiltration rates of 0.6-2 inches to 2-6 inches per hour and the generalized soil composition in this area is defined as glacial till. These general water capacity availability values and general pH information taken directly from these soil surveys can be plugged in to modeling parameters to condense the range of generalized parameters in the model defaults.

3.2.3 CSEO Well Logs

One low cost, preliminary method used for this watershed-scale groundwater characterization was the analyses of the available Colorado State Engineer's Office (CSEO) well logs. The CSEO, like many state administrators, maintains databases that are computer-searchable in a variety of ways, including: keyword, general location, county, town, or specific well installation permit identification number. Well logs are viewable free of charge, and the general public can spend as much time as they like sorting through the records on publicly available computers during modified working hours. It is suggested that office availability times be verified prior to arriving at the Engineers office to review records. Once particular locations of interest are identified within the watershed (in this case FT and BRE), the corresponding well records can be printed out in hard copy and taken from the CSEO (for a per-page cost) to be used as needed. CSM researchers associated with this study have reviewed more than 5000 well logs for this and other watershed studies. It is important to note that while these logs are a good source of information, it is often quite difficult to specify exact locations of the wells due to the referencing of the well locations through quarter-quarter sections designations rather than detailed specific digital geo-referencing points. While there is typically a more specific address of the well owner included on the logs, often the address is for the current mailing address of the owner during the well construction, not the actual location of the well itself.

Table 3-2 lists some of the useful information typically found on well logs, along with a semi-quantitative judgment on the frequency of recording for each type of information. The data reviewed for this particular project spanned over 50 years of records, dependent upon the time period for which development occurred in each particular area of concern. While this information is not always considered to be highly accurate, it provides an excellent first-estimate of the groundwater hydrology. In many

cases these logs supply the only data on the groundwater system that will be available for a watershed-scale study.

Initial evaluation of the well logs for BRE and FT, Summit County, Colorado refuted an initial hypothesis of this project, which stated that many of these drinking-water wells were likely set in fractured bedrock. Assessment of the logs immediately showed that nearly all the drinking-water wells in the developed areas of BRE and FT are installed in medium to coarse-grained sandy overburden to depths averaging 80 feet below ground surface.

The CSEO logs request that the driller collect detailed information. However, all the requested information is rarely recorded. A subsurface lithologic description of a well log, for example, may be “very detailed,” describing grain sizes, colors, weathering of materials at specific depths, lithologic names for encountered bedrock, and the fracture intensity, however, the majority of logs have only very general information recorded. A characteristic description may include “0-90 feet bgs (below ground surface) FILL” or “0-10’ bgs soil, 10-70’ bgs sand, 70-90’ bgs rock”. Entire sections of the well logs are frequently left blank, providing no information to the user at all. While highly detailed descriptions are ideal, they are found in less than 5% of the reviewed well logs. Nonetheless, this information can be very informative to the groundwater hydrogeologist. If a well is set in 70 feet of “fill,” and top of water is found at 20 feet bgs, then one can determine that the aquifer is comprised of a porous-media that is at least 50 feet thick, and the top of bedrock must be at least below 70 feet below ground surface.

Two hundred seventy eight (278) individual well logs for residences with in the BRE area, and 87 logs for wells in the FT portion of Summit County, Colorado, were acquired from the CSEO. The logs were reviewed and evaluated, identifying physical well characteristics such as:

- “Quarter-Quarter Section” Locations
- Well Depths
- Soil Lithology
- Rock Type
- Depth to Static Water
- Borehole Diameter
- Drilling Type
- Sustainable Pumping Rates
- Pump Test Lengths and Results

By utilizing this information, a description of the subsurface lithology, aquifer composition material, and the location within the aquifer wherein the drinking-water wells have historically been installed was derived. The majority of the development in Summit County, Colorado has been within the glacially carved valleys of the mountain ranges, which are filled with glacially derived sandy alluvium defined in the majority of the well logs as “till”. The “till” description is found frequently throughout all the drilling logs completed by a variety of different drilling companies and multiple drillers, from 1960 through present, and it seems to be an accurate assessment of the general subsurface media wherein the wells are installed. A glacial till is, by definition, comprised of “a mixture of clay, silt, sand, gravel and boulders ranging widely in size and shape.” (Bates and Jackson 1984) Based on the drilling logs, it appears that the till in our study areas is primarily coarse-grained sand with cobbles and boulders. This till description is also consistent with visual assessments of the soils’ lithology of the local road cuts, construction derived excavation piles, and the naturally occurring stream cuts or other observation points found near our areas of interest.

Table 3-2. Available Information from Typical CSEO Drilling Logs

Parameters Potentially Available on Colorado State Engineer Drilling Log Records	Degree of Frequency that Information is Available on Drilling Log Records
Drilling Methods (i.e. rig type)	Always
Quarter Quarter Section Location	Often
Specific GIS or Survey Location Information	Rarely
Well Permit or ID number	Always
Well Owner at Time of Permit Issue	Often
Well Owner at Current Time	Occasionally
Total Well Depth	Always
Well Drilling Completion Date	Often
Casing Sizes and Depths	Occasionally
Perforated Casing Size and Depth	Occasionally
Grouting Materials	Occasionally
Grouting Intervals	Occasionally
Pump Test Date	Often
Static Water Level Prior to Pump Test	Often
Length of Pump Test	Rarely
Sustained Yield	Often
Final Water Level after Pumping	Rarely
Hole Diameter	Often
Depth to Rock (if applicable)	Often
General Lithology Descriptions (i.e. fill, sand, rock, soil)	Often
Specific Lithologic Descriptions (i.e. med. gr. Brown quartz sand, limestone, granite, coal veins, etc.	Rarely

Always = recorded 90%-100% of the time

Often = recorded 65%-90% of the time

Occasionally = recorded 40%-65% of the time

Rarely = recorded <40% of the time

With no discernable watershed-scale confining units observed or recorded to depths up to 200 feet below ground surface, the groundwater and surface water at this site has the potential to be connected. This is a markedly different situation than many of the high alpine mountain watersheds in this region, where fractured rock aquifers are common or where groundwater and surface water are often not connected. In BRE and

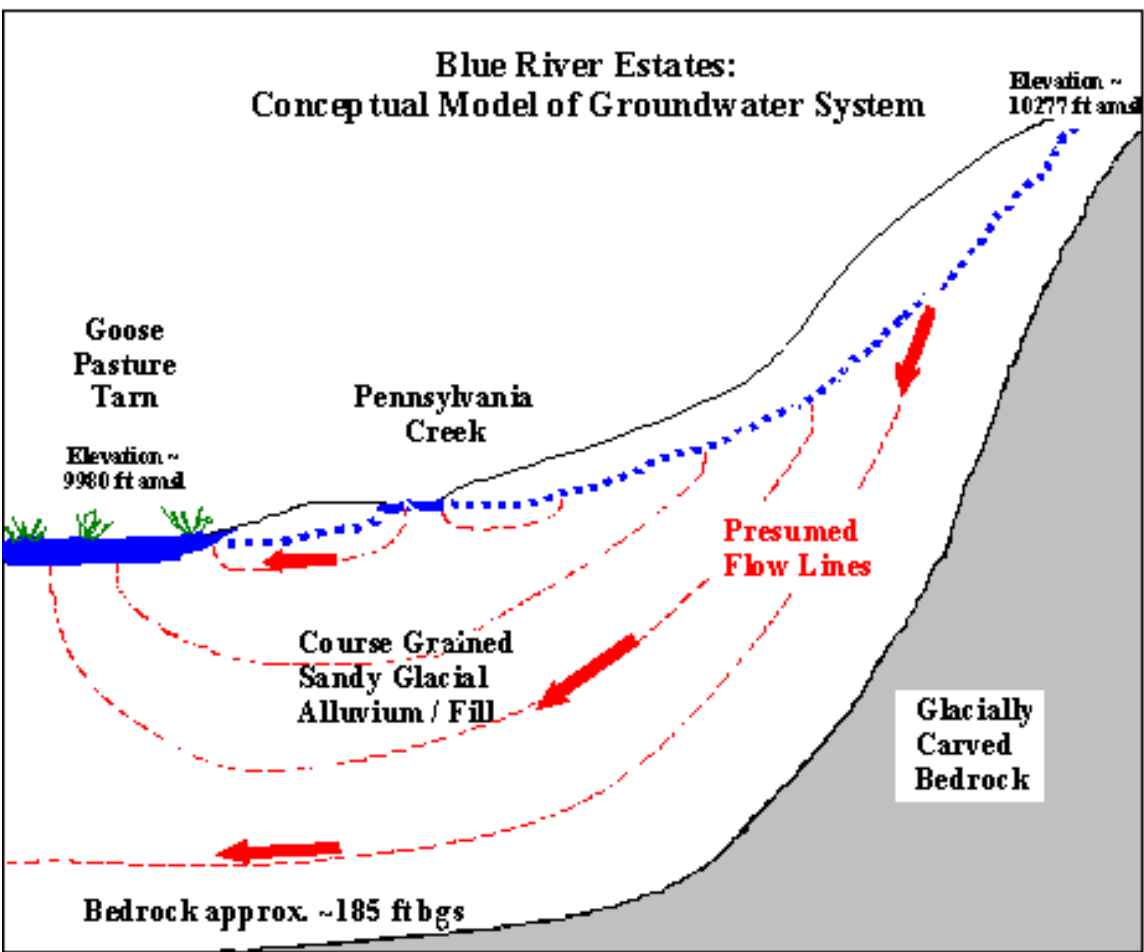
FT it appears that both the septic systems and drinking-water wells in our study areas are installed with in the porous materials that were defined above, so it is feasible that OWS pollutants could potentially enter streams via a groundwater pathway if conditions were susceptible.

3.3 Results and Discussion

Compilation of the existing data available at low cost for BRE and FT in Summit County Colorado facilitated the creation of the following conceptual models of the subsurface with in our areas of interest. Figure 3-1 addresses groundwater flow in the varied elevations of Blue River Estates and Figure 3-2 addresses the flow regime expected at Frisco Terrace.

Table 3-3: Well and Water Level Depths (bgs - below ground surface) for FT and BRE.

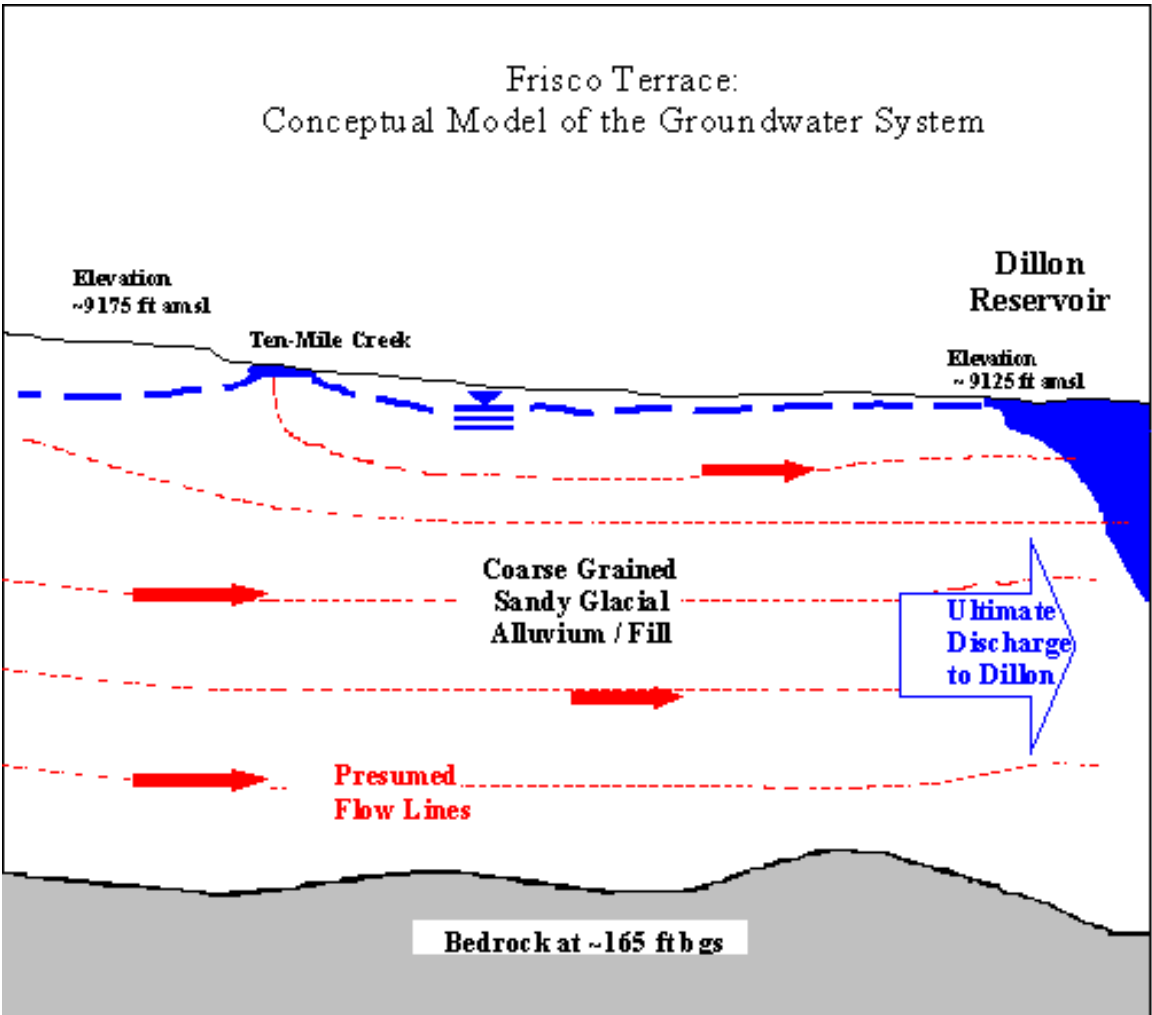
	Frisco Terrace (bgs)	Blue River Estates (bgs)
Average Well Depth	83 feet (25 meters)	94 feet (28.5 meters)
Std. Dev. of Well Depth	74 feet (22.5 meters)	60 feet (18 meters)
Geometric Mean for Well Depth	67 feet (20.5 meters)	76 feet (23 meters)
Well Depth Ranges	22 – 310 feet (7-95 meters)	27.6–520ft (8.4-158.5 m)
Avg. Depth to Water	38 feet (11.5 meters)	49 feet (15 meters)
Std. Dev of Water Depth	35 feet (10.5 meters)	36 feet (11 meters)
Geometric Mean of Water Depth	29 feet (8.9 meters)	37 feet (11 meters)
Water Depth Ranges	9 – 160 feet (3-49 meters)	4 – 170 feet (1-52 meters)



Notes: Not to Scale.

- Bedrock Assumed Impermeable.
- Depth to Water is 15-30 feet bgs.
- Bedrock outcrops periodically at top of mountain divide, and is recorded sporadically at depths up to 185 ft bgs in CSEO well logs.
- Glacial till overburden is course grained sandy material with no identifiable aquitards to inhibit flow.

Figure 3-1: Cross Sectional Conceptual Model of the Groundwater System at BRE



Notes: Not to Scale

- Bedrock Assumed Impermeable
- Depth to water is approximately 15-35 feet bgs.
- Glacial till overburden is coarse grained sandy material with no identifiable aquitards to inhibit flow

Figure 3-2: Cross Sectional Conceptual Model of the Groundwater System at FT

Figure 3-3 summarizes water levels (based on static depths to water measured after drilling) and the number of wells installed from the CSEO well logs over the past 40 years. It is evident from statistical analysis of the available well logs and the review of Figure 3-1 below, that average depth to water in FT and BRE have increased (i.e. depth to water levels from the ground surface, in this watershed at both locations have deepened) as more wells are installed.

Further analysis would have to be compiled to confidently state whether BRE's groundwater levels are dropping within this system. It does appear that well depths have increased in FT, which may be due to a decrease of groundwater levels within this portion of the aquifer. It is likely that the well depths increased in part because homeowners are drilling deeper wells to have more water storage in their well designs. Well installation rates at FT have been relatively stable at approximately 20 wells per decade in the FT area.

In the past 15 years, the water table elevations at these two study areas have stabilized, and have even apparently increased slightly at BRE. The reasons for this are unclear, because one might expect continuing water table declines with continued growth. There is no consistent trend in the precipitation record (Lemonds, 2003) that can explain these increases. Figure 3-3 shows that the number of wells installed per year has remained relatively constant. Thus, the relatively constant water level depth may occur because the groundwater system has reached steady state with respect to pumping of wells, recharge from precipitation and influx from septic tank effluent, and additional discharges to surface water.

The close proximity of Lake Dillon to the FT subdivision also likely helps regulate the water levels in this area by acting as a source when needed to equilibrate the

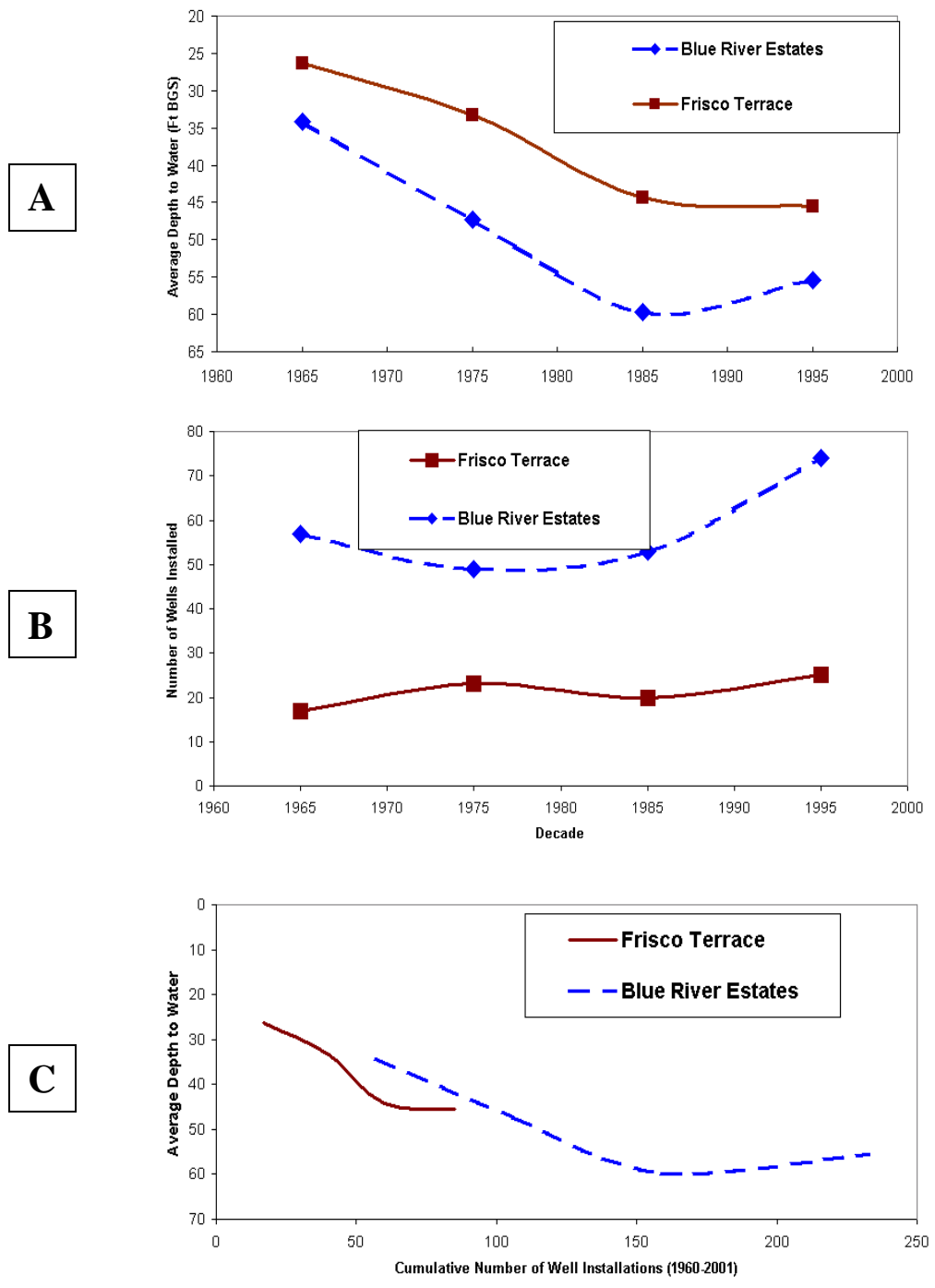


Figure 3-3. CSEO data for (a) Average water level by decade since 1960, (b) Number of wells installed by decade, (c) Cumulative number of wells installed vs. depth to water. BGS = below ground surface.

potentiometric surface of the water table. At BRE, the number of wells installed has increased significantly while the water table levels have increased slightly.

One potential reason for this is that the homes built in the BRE area in the past 20 years are generally much farther away from the stream system and from each other as they are built on larger lots. Thus, the influence of growth on the water table in this area is not as concentrated in the last few decades at BRE as it was during the first 20 years of development.

3.2.4 Sustained Yield from the CSEO Well Log Pump Tests

Nearly all well logs have some form of pump test information on them. The values given in these logs are presumed to be sustainable pumping rates that have reached equilibrium. It is important to note that it is very rare to have a recorded water level corresponding to the drawdown of the depth to water after pumping rate. To quantify transmissivity of the aquifer from these data, some basic assumptions must be made. The first assumption is that the recorded pumping rate reflects a sustained rate of recharge from the formation after water is removed from storage in the well bore itself. The second assumption is that when drawdown is recorded as “all” or “total”, the total drawdown corresponds relatively closely to the total borehole depth minus the static water level (defining the height of the water column above the bottom of the borehole). It is important to remember that pump tests during well installation, not pump installation, often do not involve a pump at all, but are a qualitative test, executed by blasting air down the drill string and while evacuating the water from the borehole. There are other associated documents called pump test records which are occasionally filed in conjunction with the drilling logs at CSEO, and those provide information about the type of pump installed for use at the residence and its manufactured pumping rate capacities, as well as the depth at which the pump is installed. These pump installation records can

definitely be helpful if samples or analysis are to be preformed based on operating conditions. Pump information was not uniformly found recorded in conjunction with the drilling log/ well installation CSEO records for these areas of concern over the course of this research. In most cases, well bore storage is not a significant issue when interpreting these results, as the time it would take to empty the well assuming no recharge from the formation is small (< 20%) compared to the duration of the pumping test. Thus we can assume that the majority of the described discharge is formation water recharge to the hole, which makes the assumptions above reasonable for a first estimate of hydraulic properties. This allows aquifer transmissivity (T) to be estimated as:

$$T = 1140 (SY / \Delta h)^{0.67} \quad (3-1)$$

where: T = Transmissivity in ft²/day, SY = sustained yield in ft²/day, Δh = drawdown in feet (Razack and Huntley, 1991). This equation is empirical and was developed to estimate transmissivity from specific capacity data in a large and heterogeneous alluvial aquifer. Other more detailed expressions are available (Fetter, 2001), but these require estimates of the specific yield, which are not available for these single well tests, as specific yield derivations are usually performed on a 2 well test. Equation 3-1 allows a first estimate of T for BRE and FT (Table 3-4).

Table 3-4. Transmissivity Estimated from Equation 3-1 and CSEO Well Logs

Site Location	Average Transmissivity	Std. Dev. Transmissivity	Geometric Mean of Transmissivity	Data Range
Blue River Estates (BRE)	773 ft ² /day (8.3 cm ² /sec)	497 ft ² /day (5.3 cm ² /sec)	647 ft ² /day (6.9 cm ² /sec)	153-2106 ft ² /day (1.6 – 22.6 cm ² /sec)
Frisco Terrace (FT)	585 ft ² /day (6.3 cm ² /sec)	395 ft ² /day (4.2 cm ² /sec)	416 ft ² /day (4.5 cm ² /sec)	41–1403 ft ² /day (0.44 – 15.1 cm ² /sec)

3.2.5 Hydraulic Conductivity (K) Estimates

Hydraulic conductivity (K) may be estimated using equation 3-2; if an aquifer thickness b, is assumed.

$$K = T / b \quad (3-2)$$

For these study areas, we assumed two cases for aquifer thickness. A thickness of 50' is a reasonable minimum aquifer thickness, which approximately corresponds to the distance between the average water level and the average well depth. For deeper wells the maximum aquifer thickness is taken to be the average depth to the bedrock. The results are shown in Table 3-5.

Table 3-5. Hydraulic Conductivity Estimates from CSEO Well Log Information

Site Location	Depth of aquifer Thickness	K (cm/sec) from Average T	K (cm/sec) from Geometric Mean of T
Blue River Estates	50' (1524cm)	5.4×10^{-3} cm/s	4.6×10^{-3} cm/s (0.54 ft/hr)
Blue River Estates	185' (5639 cm)	1.5×10^{-3} cm/s	1.2×10^{-3} cm/s (0.14 ft/hr)
Frisco Terrace	50' (1524 cm)	4.1×10^{-3} cm/s	2.9×10^{-3} cm/s (0.34 ft/hr)
Frisco Terrace	165' (5029 cm)	1.3×10^{-3} cm/s	8.9×10^{-4} cm/s (0.105 ft/hr)

The estimated K values are relatively well constrained to within half an order of magnitude. This is a significant improvement over an estimate of K based strictly on porous-media type, whereby K would vary over at least 4 orders of magnitude (Fetter, 2001). No historic pump test or slug test information is available in either of these two study areas for comparison to the estimates provided in Table 3-5. Two slug tests were conducted in MW1 and MW2 (Lemons and McCray, 2003). Measured K values in these wells ranged between 2×10^{-3} cm/sec and 8×10^{-3} cm/sec. The values listed in Table 3-5 are consistent with these measured slug test values. These calculated values

are consistent with K values expected in coarse glacial material. K values in the range of 10^{-3} cm/s are conducive to relatively fast transport times (in the range of 0.1 to 1 foot per hour or 2.4 to 24 feet per day). Thus, pollution of streams from known or suspected areas of contaminated groundwater, or spreading of pollution within groundwater systems, should be a concern.

CHAPTER 4: MONITORING WELL DATA AND ANALYSES: SOIL CHEMICAL AND PHYSICAL DATA, AND HYDRAULIC HEAD DATA

4.1 Introduction

In the fall of 2001, CSM personnel and a contracted environmental drilling company installed four monitoring well points at BRE and FT. These monitoring locations facilitated additional site-specific characterization using groundwater level and hydro-chemical information as well as soil chemical analysis and physical data. These monitoring points provided anytime access to the aquifer and made it possible to obtain temporal data through monthly sampling. Groundwater sampling and evaluation will be discussed further in chapter 5 with the stream-water quality analysis. This chapter will discuss the chemical results of the soils analysis and the physical trends of water levels and hydraulic head information of the groundwater in the monitoring wells in comparison of the associated nearby surface water systems.

Standard operating procedures (SOPs) and ASTM guidance were followed by CSM faculty and their contractors during well installation operations. In November of 2001, initial installation of monitoring wells was performed, facilitating temporal sampling of the aquifer beginning in February of 2002.

4.2 Installation of Four Monitoring Wells

Four monitoring wells (constructed of 1 inch internal diameter (PVC) Poly-Vinyl Chloride materials) were installed to collect site-specific groundwater information (i.e.

groundwater chemistry, soil-chemical analyses, and water levels), (Figure 1-3). Three locations were dual wells, with each piezometer screened at different depths within the borehole. One location (MW4) housed a single monitoring well point. Two monitoring-well locations were positioned within Blue River Estates, (MW1 is located up gradient of the development and MW2 is located down gradient near the development at the confluence of the Blue River and Pennsylvania Creek). The other two monitoring well locations were installed within Frisco Terrace, (MW4 is located in the SW portion of FT, and MW3 was installed in the NE edge of the development). See Figure 1-2 for general locations.

Details for each monitoring well are given below:

- MW-1 is installed as a “background site” which is considered to be un-impacted by development. It is located at the edge of BRE at the highest elevation in this study, at the edge of the development. The MW1 location housed a nested well pair, but only the lower well was screened within the water column over the time frame of this research. A follow up sampling event in June of 2003 presented conditions in which water was found for the first time in the upper wells of both MW1 and MW2 in BRE. This is possibly due to the increased precipitation and resultant snowmelt of the 2003 season. Drought conditions were experienced within the study area during 2001 and 2002, at the time of this research. For this thesis, only the lower well is reported, defined solely as MW1. MW1 is a total depth of 27 feet bgs, with a 2.5 feet screen zone located flush with the bottom of the well.
- MW-2 is located within BRE near the confluence of Blue River and Pennsylvania Creek. This well is also a nested well pair, and over the February 2002 – April 2003 research season, only the lower piezometer (at the total depth 37 feet bgs, with 2.5 foot screen zone) was located in the water

column for sample collection. The upper piezometer was found to be within the water column in June 2003, as addressed above. For this research analysis, only the lower piezometer data is represented, and is referred to as MW2 throughout the following groundwater data results.

- Two locations in Frisco Terrance (MW-3 and MW-4) border a highly populated area along Ten Mile Creek near the exit of the creek into the Dillon Reservoir.
 - MW3 consistently provided water to be collected from both the “shallow and deep” nested piezometers at this location year round. Thus, MW3 water-level measurements and groundwater samples in this research are designated MW-3U (upper – total depth 20 feet bgs, 5 foot screen zone) and MW-3L (lower – total depth 30 feet below ground surface, 2.5 foot screen), to differentiate between the two monitoring depths at this location.
 - MW4 is a single piezometer, installed well within the water column at a depth of 40 feet below ground surface. A 5 feet long screen zone is located at the bottom portion of the well.

A small mobile auger drilling apparatus was used to create these boreholes and complete these well installations. The borings ranged in depth from 30 to 40 feet below ground surface. Monitoring well construction logs are included in this document as Appendix A. Installation of these monitoring points allowed for the collection of more specific detailed information for a few representative locations within this watershed. Installing enough wells to specifically characterize the entire watershed on this scale would be cost prohibitive, thus selecting a minimum of sites, which can be used as reference for the entire watershed, is key prior to beginning these installations.

Combining these detailed site-specific information sets with the generalized information derived from the CSEO well logs and sporadic drinking-water sampling events however, is useful for overall watershed characterization.

4.3 SOIL -CHEMICAL DATA

Soil Chemistry was analyzed as part of this project prior to the beginning of this thesis research. The laboratory results for soil chemistry are reported in this document, but are only briefly interpreted. Soil samples were collected during monitoring well installations in the fall of 2001 and were evaluated in laboratories at both the Colorado School of Mines and the University of Wisconsin Soil and Plant Analysis Lab, for a variety of physical attribute and chemical evaluations.

4.3.1 Methods

Soil chemistry analysis (like the hydrometer analysis) was performed at the University of Wisconsin, Soil and Plant Analysis Lab in the fall of 2001. The soil-chemical parameters measured included: soil organic matter (O.M. %), cation exchange capacity (CEC), and analysis of the following chemical constituents: phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), ammonia nitrogen (NH₄-N), nitrate-nitrogen (NO₃-N), and total nitrogen (N). Soil solids (soil solution values + solids constituents) were also evaluated, and results were reported in mg/kg or wt%. The results reported here for soil chemistry, can be assumed to be total soil values.

Samples for analysis came from three (3) discrete depths at all four (4) monitoring well locations. The soil sampling intervals are addressed in detail in Table 4-2, but generally were collected from around the 2-2.5 ft, 6 ft and 11 ft bgs zones.

Corresponding laboratory methods and sample-collection technique guidance for the drilling activities are addressed in the References section of this thesis. Soil chemistry results are presented in Table 4-4, and are interpreted in the text that follows.

4.3.2 Results

Following are the results for soil analyses performed on the samples collected during monitoring well installations in Fall 2001.

4.3.2.1 Soil pH

The soil pH versus depth for each monitoring point is illustrated in Figure 4-4. The soil pH is consistently more acidic at the surface, becoming more basic with depth. It is generally expected that soils in these watersheds would be more acidic near the surface because of the pine and evergreen detritus. Infiltration of rain and snowmelt and the dissolution of minerals in the soil and rock dilutes the acidity. In contrast, the surface sample from MW-1 (the background well) is considerably more basic than MW-2, MW-3, or MW-4. This may be because MW-1 is located in a road cut, meters away from any organic material such as near by trees or pine needles. Overall, MW-1 soils are more basic than the other well samples with the exception of the deep sample from MW-2 also in BRE.

Table 4-4: Soil Chemistry (chemical concentrations are in ppm)

Local	Depth (cm bgs)	Depth (ft bgs)	PH	O.M. %	P	K	Ca	Mg	NH₄- N	NO₃-N	Total N	CEC meq/ 100g
MW01	75	2.5	7.7	0.2	7	97	1410	130	3.77	1.13	86.77	8.4
	180	6	7.8	0.1	7	106	1260	110	3.90	0.67	58.96	9.3
	330	11	8.0	0.1	7	77	730	90	2.70	0.41	33.38	4.6
MW02	60	2	6.4	1.0	16	91	1010	70	4.16	0.86	578.6	5.9
	180	6	7.1	0.7	14	102	1180	70	3.60	0.31	319.4	6.7
	300	10	8.2	0.2	8	113	960	50	0.65	0.35	92.87	5.5
MW03	60	2	6.3	0.6	15	80	430	60	4.95	0.21	232.4	2.8
	180	6	6.8	0.2	11	52	450	60	2.55	0.16	91.28	2.9
	300	10	7.1	0.2	15	147	1320	210	.49	0.17	49.22	8.7
MW04	60	2	6.7	0.4	22	145	400	50	0.10	0.35	97.61	2.8
	180	6	7.3	0.1	10	230	160	20	0.10	0.07	25.66	1.2
	300	10	7.2	0.2	16	121	330	50	0.10	0.16	43.87	2.4

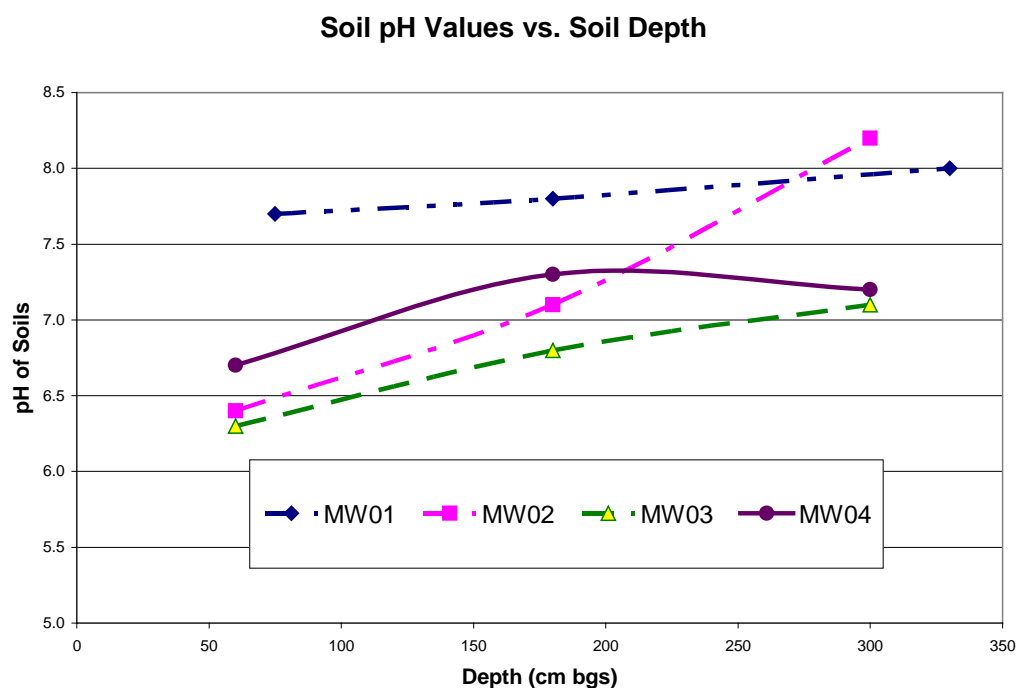


Figure 4-3: Soil pH vs. Soil Depth

The soils from the deeper sampling zones, further up gradient in the watershed (BRE MW1 and MW2) have more basic soils than the samples from down gradient in the watershed (FT). A possible explanation for this trend is that as surface water runoff increases at the mouth of the watershed, it incorporates more anthropogenic effects into the water (which generally cause more acidic pH). This is potentially due to the fact that there are more significant developed areas in this area of concern, near the mouth of the watershed at the less topographically severe downstream locations.

4.3.2.2 Percent Organic Matter (%OM)

As we might expect, the levels of organic material (OM) present in these soil cores are consistently higher at the ground surface, decreasing with depth into the soil column. This is intuitive, due to the increased organic detritus (leaves and grasses or other common organic materials) found typically on the surface of the soil. The highest percentage of organic material was found in the flood plain location of BRE at the soil boring for MW-2. There is no apparent trend with respect to location or elevation in the watershed. Rather the OM percentages are probably most dependent on the nature of the ground surface at the well location. Specifically, MW2 has the most abundant plant growth and correlates with the highest OM percentages. MW3 and MW4 have similar growth surfaces with less plant growth than seen in MW2 and depict similar OM percentage trends. MW1 has essentially no plant growth at the ground surface and correlates to the lowest OM percentage trend in this study.

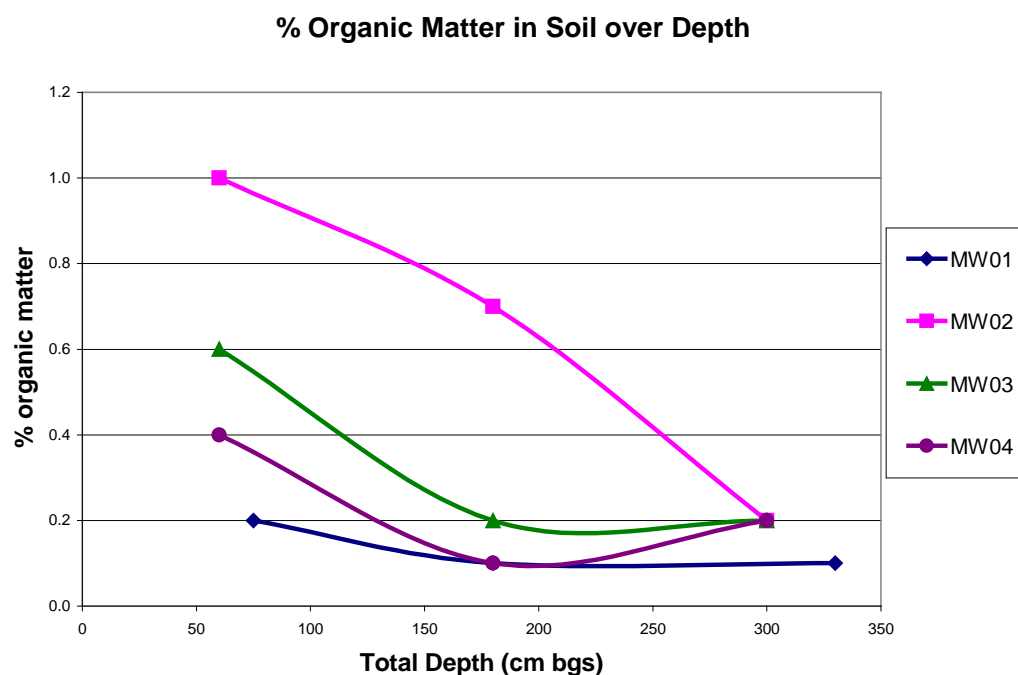


Figure 4-6: Percent Organic Matter in Soil over Depth

4.3.2.3 Soil Nitrogen

Total nitrogen (TN), is the measurement of ammonia, nitrate/nitrite and organic forms of nitrogen (Figure 4-5).

Nitrogen is present in soils from many sources including: the atmosphere, native soils, plants and animals, and from anthropogenic effects including wastewater effluent excretion from both wastewater treatment facilities and on-site waste water systems. The highest occurrence of total nitrogen (TN) in this analysis is found in the surface soils at location MW2. This soil core sample was collected at the MW2 boring which is situated in the flood plain portion of the junctions between the Pennsylvania Creek

tributary and the Blue River. This area is likely to have more organic material, including nitrogen, associated with the higher plant density, detritus, and microbial and small invertebrate populations associated with flood-plain communities. The relatively higher organic matter at this location (Table 4-4) supports this hypothesis. In all the samples TN decreases as borehole depth increases.

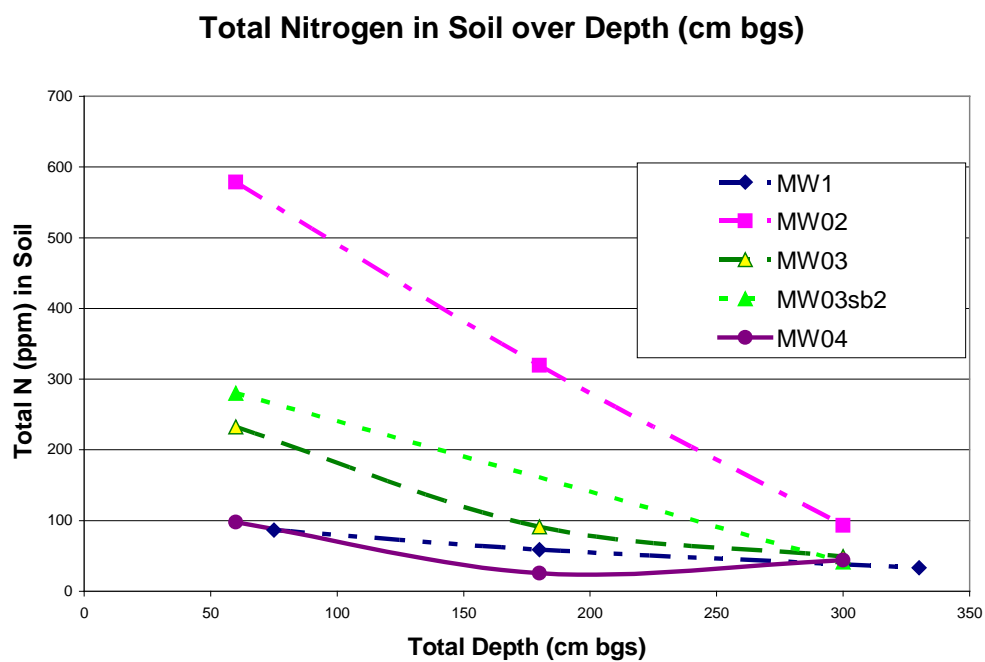


Figure 4-4: Total Nitrogen in Soil over Depth

4.3.2.4 Soil Phosphorous

Figure 4-6 depicts the soil phosphorus (P) concentrations in the monitoring well soil samples. MW-1, the background well, has a stable P concentration with depth, also MW1 surface soils are collected meters below the natural land surface (due to the road cut conditions found at this site). We can presume that this stable P concentration value may reflect the naturally occurring P found in the soils of this watershed. MW2 has an elevated level of P in the upper soil layers, probably from the increased organic matter (as explained in the previous paragraph). The P concentration at this location returns nearly to the “background level” at depth. Soils sampled from locations MW 3 and MW4 (FT) show similar trends. No apparent trends exist with respect to spatial location in the watershed for the near surface soils. However, at depth, the locations at higher elevations in the watershed exhibit lower P concentrations. This is similar to the trend exhibited by pH. The P concentrations in these soils are comparable to soil concentrations from sandy soils based on a literature search by Kirkland (2001).

Phosphorous is a rather common element in igneous rock. It is also fairly abundant in sediments, but concentrations present in solution in natural water are normally no more than a few tenths of a milligram per liter. Phosphorous is a component of sewage, as the element is essential in metabolism and it is always present in animal metabolic waste (Hem 1985). The soil concentrations shown in Figure 4-6 are up to 2 orders of magnitude higher than is typically present in natural waters, thus soil erosion may add considerable amounts of suspended phosphate to streams.

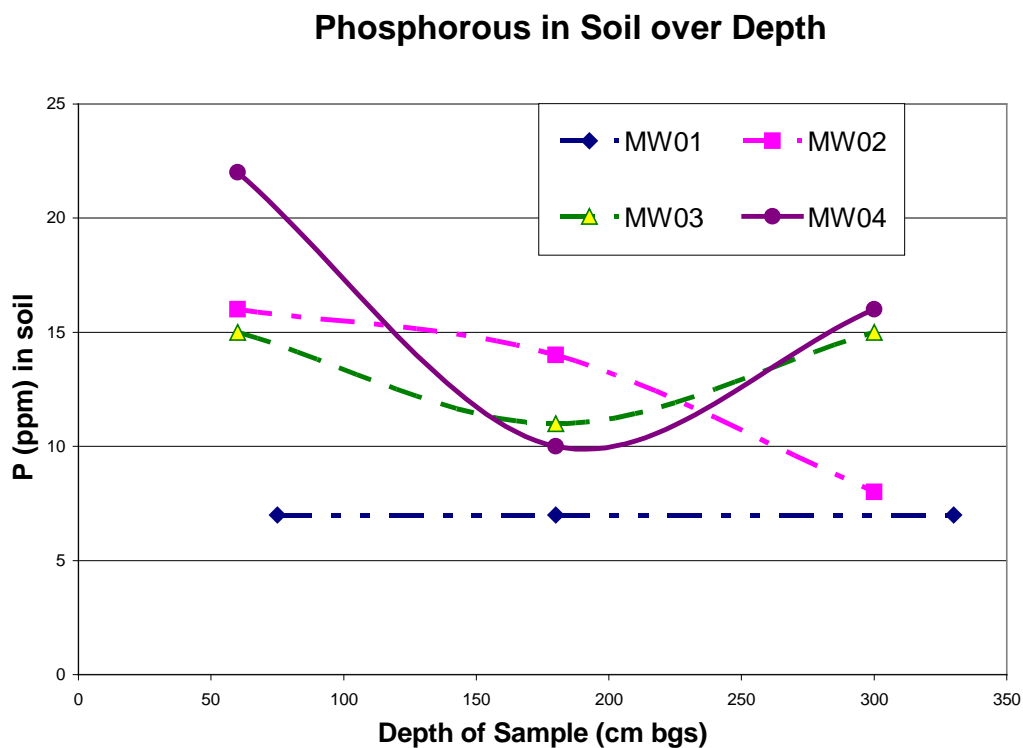


Figure 4-5: Phosphorous in Soil over Depth

4.3.2.5 Soil Calcium (Ca)

The bedrock that is the source of the glacial drift overburden in this watershed is described as Precambrian rocks as well as Pennsylvanian aged Minturn formation comprised of: sandstones, grit, conglomerate, shale, and scattered beds of reefs of carbonate rocks. It is also comprised of the Belden Formation, consisting of back shale, carbonate rocks and sandstone. Both of these prevalent rock formations have the potential to contribute a fair amount of calcium (Ca) to the soils.

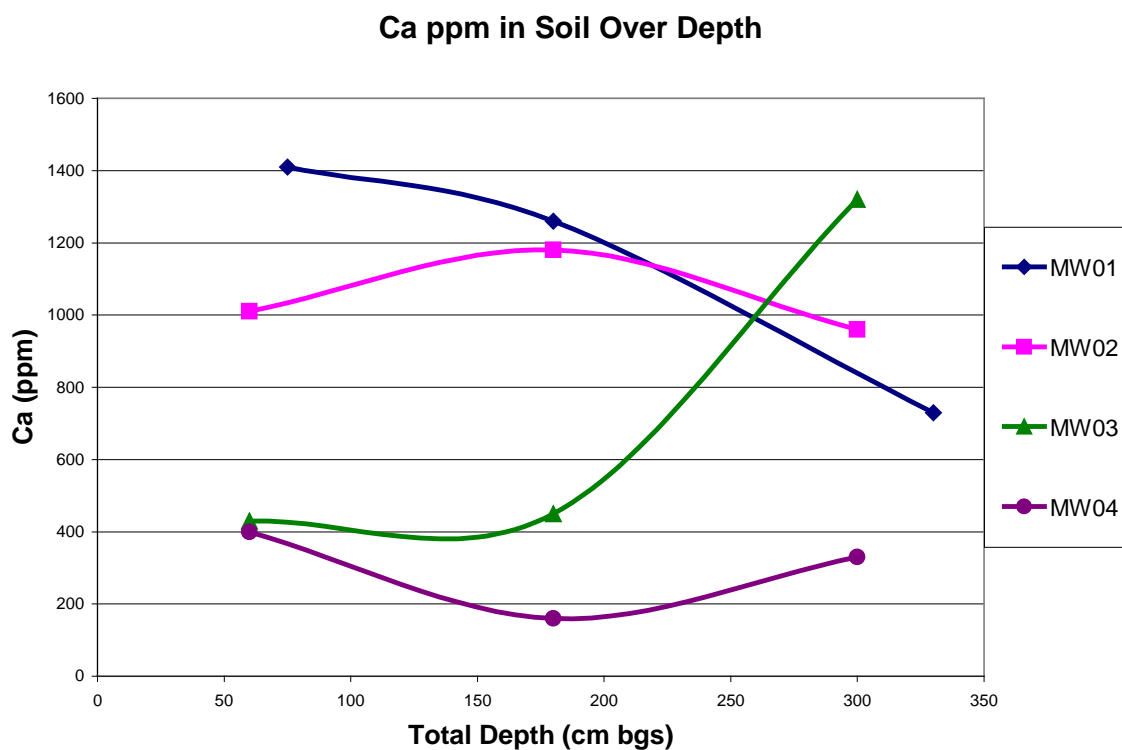


Figure 4-7: Calcium ppm in Soil over Depth

The calcium concentrations recorded in this soil data are presumed to be the naturally occurring calcium found in the original rock detritus derived from either the calcareous cement of the sedimentary rocks, the carbonate reef structures in these formations or as common constituents in the metamorphic or igneous rocks composing the bedrock in this area. In the surface soils, Ca concentrations at BRE are greater than at FT. However, no trends are apparent for the deeper soil samples.

4.3.2.6 Magnesium (Mg) in Soils

It is interesting that the trend lines from the Frisco Terrace well points (MW3 and MW4) depict similar proportional compositions of Magnesium (Mg) as Ca (above), reflecting a dip in the concentrations for MW4 at the ~180 cm bgs (7 feet bgs) soil sampling location, then an increase in concentration. MW3 reflects a consistent concentration reading, with a spike in value at 300 cm bgs (12 feet bgs). These concentrations are likely a result of natural soil sample compositions, as these constituents are both common elements and are essential in plant and animal nutrition. In igneous rocks magnesium is typically a major constituent of the dark colored “ferromagnesian” minerals. (Hem 1985) Mg concentrations are generally higher in the surface soils at BRE than at FT locations. Again no trends are apparent for the deeper soils.

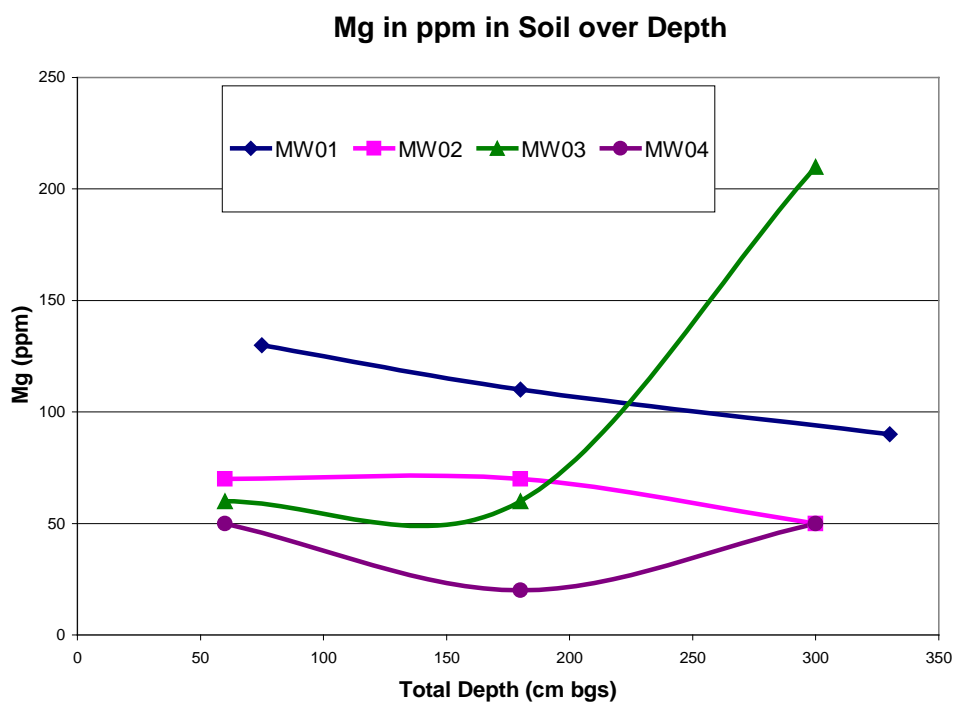


Figure 4-8: Magnesium ppm in Soil over Depth

4.3.2.7 Potassium (K) in soils

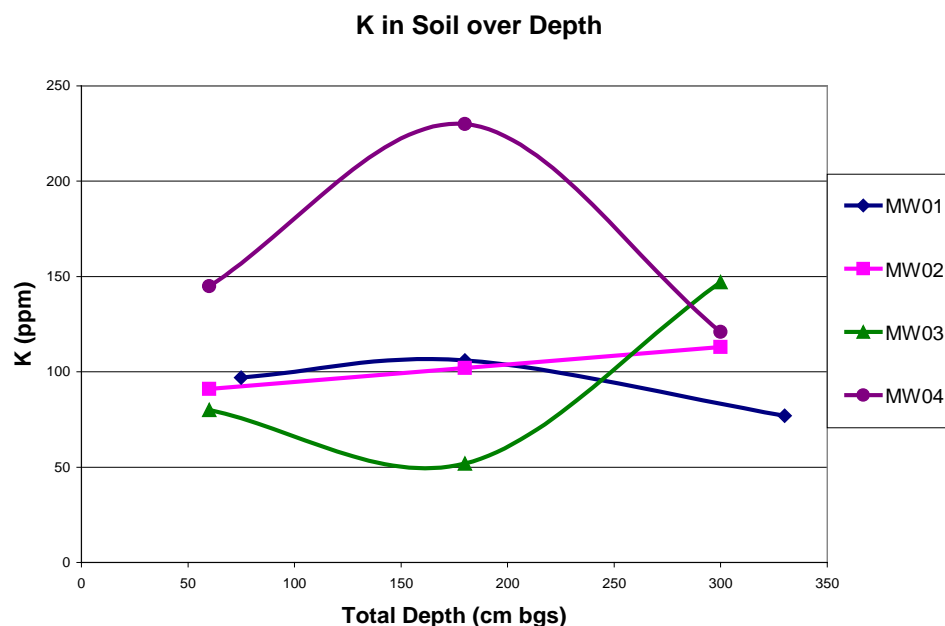


Figure 4-9: K in Soil over Depth

A common constituent of clay minerals, potassium (K) is likely seen in these sandy soils as pieces of potassium feldspar minerals left over from the breakdown of the original bedrock in the area as it was scoured and re-deposited by the glaciations that carved these valleys during both the historic and recent glaciations responsible for the overburden deposition in these mountains. MW4 has the greatest level of K in the soils with a mirrored concentration curve in the other FT well depicting the concentrations of K in the soils at this area. The 2 wells in BRE have statistically similar K compositions in their soils. No other trends related to the study area locations are noted.

4.3.3 Summary of Key Soil Nutrients

The soils examined in the cores collected during well installations can provide additional information to examiners with respect to what the composition of soils with in their specific watershed may look like chemically. What constituents are specific soils rich in and what chemical constituents are these soils potentially depleted in are key values, when modelers are inputting soil constituent parameters into computer models or programming default values for geochemical reaction equations such as those discussed by Lemonds 2003 and Kirkland 2001. The soils examined from this portion of Summit County, Colorado, along the Blue River Watershed defined numbers which came directly from the area of interest being investigated, not just from a nation wide generalized set of values that are defined as “typical of what we could find” in any given watershed.

The parameters defined from our analysis included: Surface soils pH's ranging from 6.3 to 8.0; organic matter percentages ranging from 0.2 to 1.0 percent in the total volume of the soil composition; phosphorous values ranging from 7 to 22 ppm; soil Potassium ranges from 52-230 ppm; calcium in soils ranging from 160 to 1410 ppm; magnesium from 20-210 ppm, and Total Nitrogen ranges from 26 to 579 ppm.

Some of the trends apparent in the data for the following analytes: nutrients, organic matter and pH, include the near surface soils (0-2.5 ft bgs sample aliquot) in all the wells, they have the highest OM and nutrient concentrations when compared to the two lower sampled sections of the soil cores (5-7 ft and 10-12 ft bgs). MW2 has the highest plant and detritus density at the ground surface. The lowest concentrations of OM, TN and P in the near-surface soils are found at MW1, probably because the ground surface at this well is located within a road cut, and is thus several meters below the nearest plant cover. OM, TN and P are higher and pH is lower at the MW3 location in Frisco Terrace, than at the MW4 location in Frisco Terrace, probably due to the fact that MW3 has a

denser plant covering at the surface than is found at MW4. For the sample aliquots collected from deeper in the soil cores, a similar trend as was seen in the surface soils is observed for TN and OM. A different trend is observed for pH and P in the deeper soils. At these deeper depths, P concentrations are higher and the pH is lower (more acidic) at Frisco Terrace than at Blue River Estates. This is opposite of what was seen in the surficial sample aliquot. These parameter values are similar within the distinct locations at each particular study area, but are quite different between the general study areas of Frisco Terrace and Blue River Estates. No apparent trends exist for the cation studies in these analyses.

4.4 Soil Physical Data

Physical characteristics of the soils collected during borehole installation were evaluated by hydrometer and sieve analysis, to determine grain size values of the soils within these representative portions of the watershed. Fluid movement rates will vary through differing media within the subsurface, dramatically affecting the transport times of chemical constituents moving within the watershed.

4.4.1 Hydrometer Data:

Hydrometer analysis was performed on samples collected during monitoring well installation (as discussed above). Impacting field conditions, such as sampling core barrel refusal due to interference from large subsurface cobbles and boulders, dictated sample collection depths, though they averaged a total depth of 11-12 feet bgs. Hydrometer analysis facilitates the segregation of the fines constituent in the soil aliquots to a total depth of the 12 ft bgs sample. Due to the differing characteristics and properties between silts and clays, defining what is present in the soil composition at the level of

septic effluent release in to the watershed system, is key to defining sorption capabilities of the soils.

4.4.1.1 Hydrometer Methods

Samples were sent to the University of Wisconsin, Soil and Plant Analysis Lab for soil-classification analysis (% sand, % silt and % clay using the hydrometer method).

4.4.1.2 Hydrometer Results (Data)

Table 4-1 below summarizes the results of the hydrometer analysis performed on a portion of the site specific soils collected during well installation operations at FT and BRE in Summit County Colorado.

The soils identified at MW-2, MW-3 MW-4 all appear to have a similar size distribution. The soils are comprised primarily of sand (72-88%), with significant amounts of silt (generally 13-19%), and a relatively small amount of clay (less than 5-9%). The composition of soils collected at MW-1 (the background well located at the highest sampling point in the watershed) are similar to the composition of soils found at the other well locations. There is slightly more silt and clay in the two upper depth samples at the monitoring well 1 location than is found at the rest of the sampled locations. The main constituent of all of the soil samples (~60%) is coarse-grained sand.

Table 4-1: Hydrometer Data

Focus Area	Location	Depth (cm bgs)	Depth (ft bgs)	% Sand	% Silt	% Clay
Blue River Estates	MW-1 (Background Well)	75	2.5	60	27	13
		180	6	63	23	14
		330	11	81	12	7
Blue River Estates	MW-2 (Blue River/ PennCk Flood Plain)	60	2	75	19	6
		180	6	73	19	8
		300	10	72	19	9
Frisco Terrace	MW-3	60	2	78	15	7
		180	6	80	14	6
		300	10	76	16	8
Frisco Terrace	MW-4	60	2	81	13	6
		180	6	88	7	5
		300	10	73	19	8

4.4.2 Particle Size Data: Sieve Analysis:

In addition to the soil hydrometer analysis reported above in Table 4-1, a soil-sieve analysis was performed on soil samples from the MW2 location in BRE and the MW4 location in FT.

Soil samples to be sieved were selected from the same sampled soil cores from well installations, and were based on the total quantity of soil remaining available for use, after the other analyses had been performed. The MW2 location provided Blue River Estates soils from depths of 2-3.5 feet (Sample A), 6-7 feet (Sample B) and 11-12 feet (Sample C) below ground surface. From Frisco Terrace, MW4 soil samples were chosen for sieve analysis providing soils taken from depths of 1.5-3.5 feet (Sample D), and 10-12 feet (Sample E) below ground surface.

4.4.2.1 Methods

Samples were weighed on a scale with accuracy to the nearest 0.01 grams, and were then inserted into the sieve/shaker mechanism at the #3 ½ sieve level. Sieve Sizes utilized were #3 ½, #7, #10, #14, #30, and #60 and were selected based on availability within the hydrogeology lab at CSM. These are not the sieves typically utilized during sieve analysis, yet they provided a sufficient data set to plot the sieve analysis curve, and derive the D₁₀ and D₆₀ values used in the published numerical modeling calculations discussed below. The ASTM D2487 (Unified Soil Classifications) guidance referenced typically for sieve analysis, defines “gravel” as that portion of the sample which is contained between the 3-3/4 inch sieve and the number 4 sieve (4.76 mm screen size). For this portion of the test, a slightly larger sieve (#3 ½) which corresponds to a 5.66 mm opening as well as a #10 sieve, which ASTM defines as the lower limit for course grained sands, was available. There was no #40 sieve (opening of 0.42mm) which is defined as the lower limit for the medium grained sands, but a #30 sieve with a 0.60 mm opening and a #60 sieve with a 0.25 mm opening were available. Both of these values were recorded and an estimated value for the #40 sieve can be extrapolated from the curve. The #60 sieve was the smallest screen size available for these sieve analyses. The differentiation between fine-grained sands, silts and clays is impossible to delineate with the sieve equipment available in this test, but can be correlated and determined from the hydrometer data shown in Table 4-1.

The sieves were secured in a vertical in line fashion with the largest sieve openings at the top of the stack, and the “dustpan” collecting that material that passed through the #60 sieve at the bottom, and shaking to facilitate soils migration was conducted for a minimum of 10 minutes. The partitioned samples were then removed from the individual sieves and weighed, and the resulting percent of material mass passing through each sieve was calculated and recorded and graphed.

Particle Size (Sieve) Data

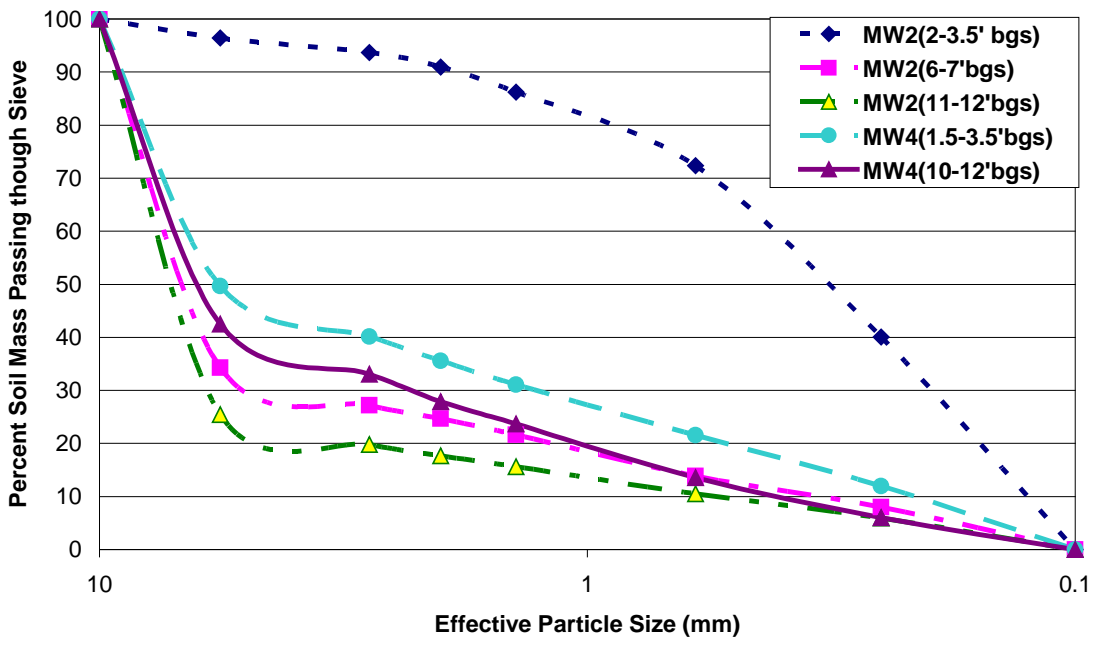


Figure 4-2: Particle Size (Sieve) Data

Table 4-2: Particle Size Data from MW2 and MW4 Sieved samples

Sieve Size #	sieve-mesh (mm)	(MW2 2.0-3.5 ft bgs)	(MW2 6-7ft bgs)	(MW2 11-12 ft bgs)	(MW4 1.5-3.5 ft bgs)	(MW4 10-12 ft bgs)
	10	100	100	100	100	100
#3 ½	5.66	96.43	34.25	25.47	49.63	42.47
#7	2.8	93.65	27.17	19.84	40.13	33.05
#10	2	90.93	24.65	17.7	35.6	27.89
#14	1.4	86.25	21.62	15.59	31.11	23.67
#30	0.6	72.38	13.87	10.53	21.57	13.53
#60	0.25	40.06	7.97	5.97	11.99	6.04
Dust	0.1	0	0	0	0	0

4.4.3 Discussion of Soil Physical Data and Hydraulic Conductivity.

Physical parameters of the sampled soils evaluated for this research, and an assessment of the associated hydraulic conductivity of these soils are described in detail below.

4.4.3.1 Soil Physical Data Discussion

Hydrometer analysis of the fine component in the soils found that soils identified at MW-2, MW-3 MW-4 all appear to have a similar size distribution. These fines in the soil samples are comprised primarily of sand (72-88%), with significant amounts of silt (generally 13-19%), and a relatively small amount of clay (less than 5-9%). The composition of soils collected at MW-1 (the background well located at the highest sampling point in the watershed) are similar to the composition of soils found at the other well locations. There is slightly more silt and clay in the two upper depth samples at the monitoring well 1 location than is found at the rest of the sampled locations. The main constituent of all of the soil samples (~60%) is coarse-grained sand.

Sieve analysis defined some key grain size statistics of the larger portion of the soil samples. D_{10} represents the effective particle size of the soil grains for which 90% (by mass) of grain sizes in the sample are larger than. The D_{60} value represents the effective particle size of the soil grains for which 60 percent of the mass is smaller. The D_{10} and D_{60} values were determined from the curves plotted in Figure 4-3.

For example for MW4 (1.5-3.5 feet bgs) in FT, 60 percent of the soils had a grain size diameter of 6.0mm or less, thus the D_{60} for that sample is 6.0mm.) The D_{10} is similar in concept, with the exception that it represents the grain size value for which the smallest

10 percent of the soils are found at or below. (Again for the MW4 (1.5-3.5 bgs) FT sample, the D_{10} value is 0.20 mm.)

Table 4-3: D_{10} and D_{60} values derived from Soil-Sieve Analysis.

Sample ID and depth interval	D_{10} (mm)	D_{60} (mm)
MW4 (1.5-3.5' bgs) FT	0.20	6.0
MW4 (10-12' bgs) FT	0.40	7.0
MW2 (2-3.5' bgs) BRE	0.15	0.4
MW2 (6-7' bgs) BRE	0.38	7.0
MW2 (11-12' bgs) BRE	0.60	8.0

4.4.3.2 Hydraulic Conductivity Estimates:

From the effective grain size diameter, several different methods can be used to estimate hydraulic conductivity (K). These equations are summarized in equation 3 a through 3c. Details about these equations are provided in the text by Kresic (1997).

$$K = (g/v)(6 \times 10^{-4} \log(500/U))D_{10}^2 \quad \text{Breyer Equation} \quad (3a)$$

$$K = (g/v)(6 \times 10^{-4}) (1 + 10(n-0.26))D_{10}^2 \quad \text{Modified Hazen Equation} \quad (3b)$$

$$K = (g/v)(6 \times 10^{-4}) n^3 (1-n)^2 D_{10}^2 \quad \text{Kozeny Equation} \quad (3c)$$

where $g = 9.807 \text{ m/s}^2$, v is kinematic viscosity ($1.14 \times 10^{-6} \text{ m}^2/\text{s}$ for groundwater at 15 degrees C), n is porosity, $U = D_{60}/D_{10}$ is the uniformity coefficient.

The Breyer equation is valid for poorly sorted grains, with $0.06 \text{ mm} < D_{10} < 0.6 \text{ mm}$, while the Hazen equation is valid for sediments with $0.1 \text{ mm} < D_{10} < 3 \text{ mm}$ (Kresic, 1997). No conditions were imposed for the validity of the Kozeny equation. All

equations were calculated for overall comparison purposes. In general, the D_{10} and D_{60} values obtained from the particle size analysis fall within these criteria for grain sizes. Table 4-3, presents estimated K values from each of the three methods, where the geometric mean of the K values estimated for each depth is used for the representative K.

The K values based on particle size are an order of magnitude larger than the values obtained from the K values estimated using the engineer's well logs (Table 3-5). All methods suggest the K values at both locations are approximately 10^{-2} cm/s, with K values at BRE being marginally higher than those at FT. The data from the CSEO logs is based on actual pumping tests, while the K values in Table 6 represent estimates based on soil properties from only 2 locations. However, the estimates shown in Tables 3-5 and 4-4 considerably reduce the uncertainty associated with estimating K values based only on sediment type because such estimates typically span at least four orders of magnitude (e.g., Fetter, 2001).

Table 4-4: Hydraulic Conductivity Estimates from Grain-Size Analysis

Site Location	Breyer 'K' (cm/sec)	Hazen K (cm/sec)	Kozeny K (cm/sec)	CSEO derived K Estimates
Blue River Estates	9.4×10^{-2}	7.6×10^{-2}	4.1×10^{-2}	5.4×10^{-3}
Frisco Terrace	5.5×10^{-2}	5.8×10^{-2}	3.1×10^{-2}	4.1×10^{-3}

The K values derived through the sieve analysis and hydrometer analysis provide estimates of K that are a full order of magnitude larger than the estimates derived from the CSEO well logs discussed in chapter 3. This discrepancy could create a scenario where residence times may be calculated at a longer time than may actually be seen in practice if only well logs are utilized for analysis.

4.5 Water Level and Hydraulic Head Data:

Water levels were collected from all four monitoring well locations consecutively during the fifteen (15) months of groundwater chemical sampling (which will be discussed in chapter 5).

4.5.1 Methods for water level and converting to head

Water levels were collected with an electronic water level indicator, lowering the measuring tape down the well until contact with water is made, and the depth is recorded from a marked reference point notched into the well casing. Water levels were recorded, and then referenced with elevation coordinates and defined as hydraulic head elevations. These hydraulic head points are then compared with the surveyed elevations of surface water stream levels and plotted to visually reflect spatial representations of water heights in the watershed system.

4.5.2 Results (Data)

The results of the water level analyses collected from February 2002 through April of 2003 are discussed below.

4.5.2.1 Water Levels

Figure 4-1 illustrates the water levels in each monitoring point collected from February 2002 to April 2003.

The water levels in our monitoring wells are considerably shallower than the water levels obtained from CSEO logs for the 1990s. This is probably due to a

combination of two reasons: (1) the monitoring wells were installed relatively near the streams, while the CSEO logs are averages for the entire developments; (2) drillers may not wait until the water table is completely rebounded after drilling to record the static water level. The static water level may reflect water elevations closer to the ground surface due to external pressures in the system, rather than reflecting the actual point of influx into the formation where first contact with groundwater was made during drilling, as is likely recorded by the driller during well installation operations.

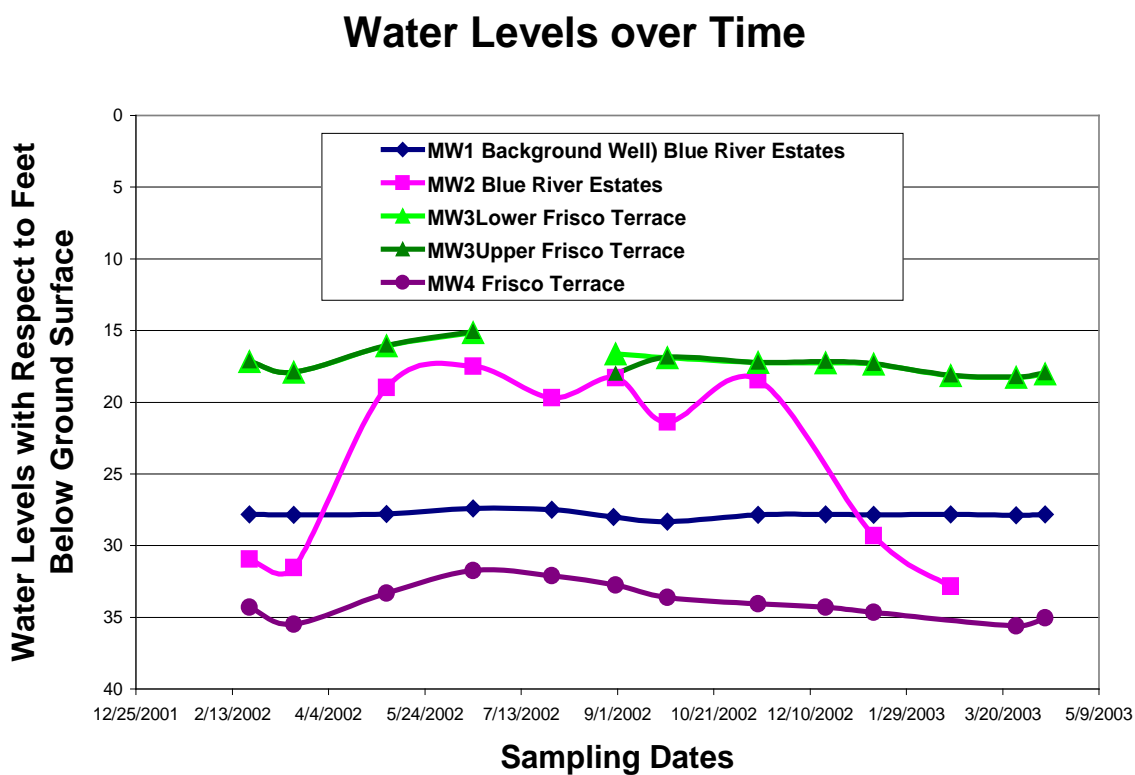


Figure 4-9: Monitoring Well Water Levels
(Please Note: These water levels are not reflective of water table elevation)

4.5.2.2 Hydraulic Head

Perhaps a more useful utilization of monitoring well water levels, is a plot of the hydraulic head (i.e. the relative elevations of the groundwater) in each well compared to the stream elevations (Figure 4-2a and 4.2b). Hydraulic head values were computed for groundwater from GPS measured elevations at the ground surface for the well, measured stick-up heights of the monitoring-well casing tops and measured depths to groundwater from the casing tops. GPS was performed utilizing a LEISA 6600 probe, and data was validated by a licensed surveyor.

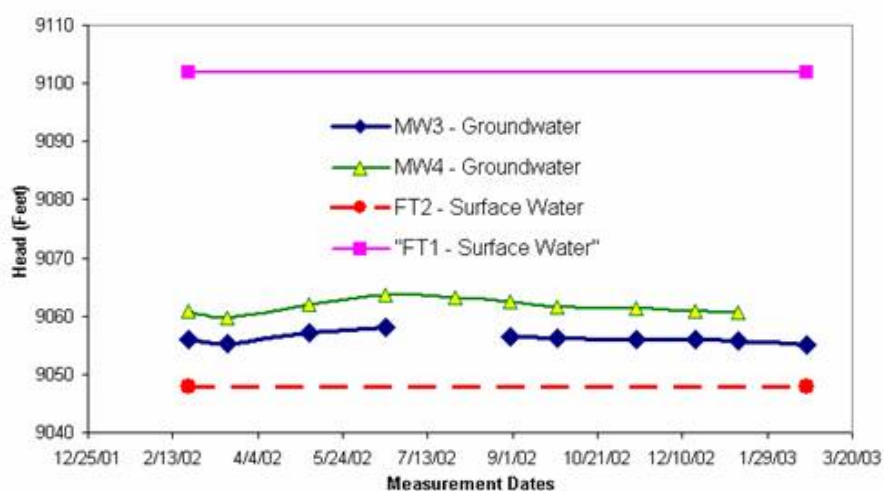


Figure 4-10a: Hydraulic head for groundwater and surface water at Frisco Terrace Elevation. Reference is mean sea level.

The potential error in this GPS elevation measurement is about ± 3 ft (1 m) due primarily to the uncertainty in the GPS measurement. The hydraulic head of the streams are measured from GPS elevations of the stream surface near the beginning of the study

and are assumed to remain constant as shown in Figure 4-3. The stream levels are known over time, and fluctuated by approximately a foot over the course of this study period.

Thus, the error in these values is about ± 4 ft (~ 1.3 m).

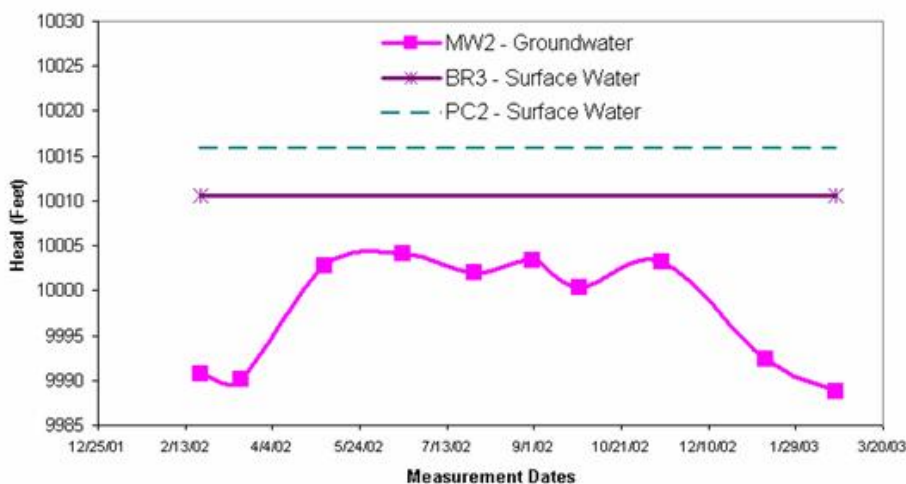


Figure 4-10b: Hydraulic head of groundwater and surface water, Blue River Estates

Note: For Figure 4-10b: The elevation reference is mean sea level. Average head at MW1 is 10291 ft (not shown).

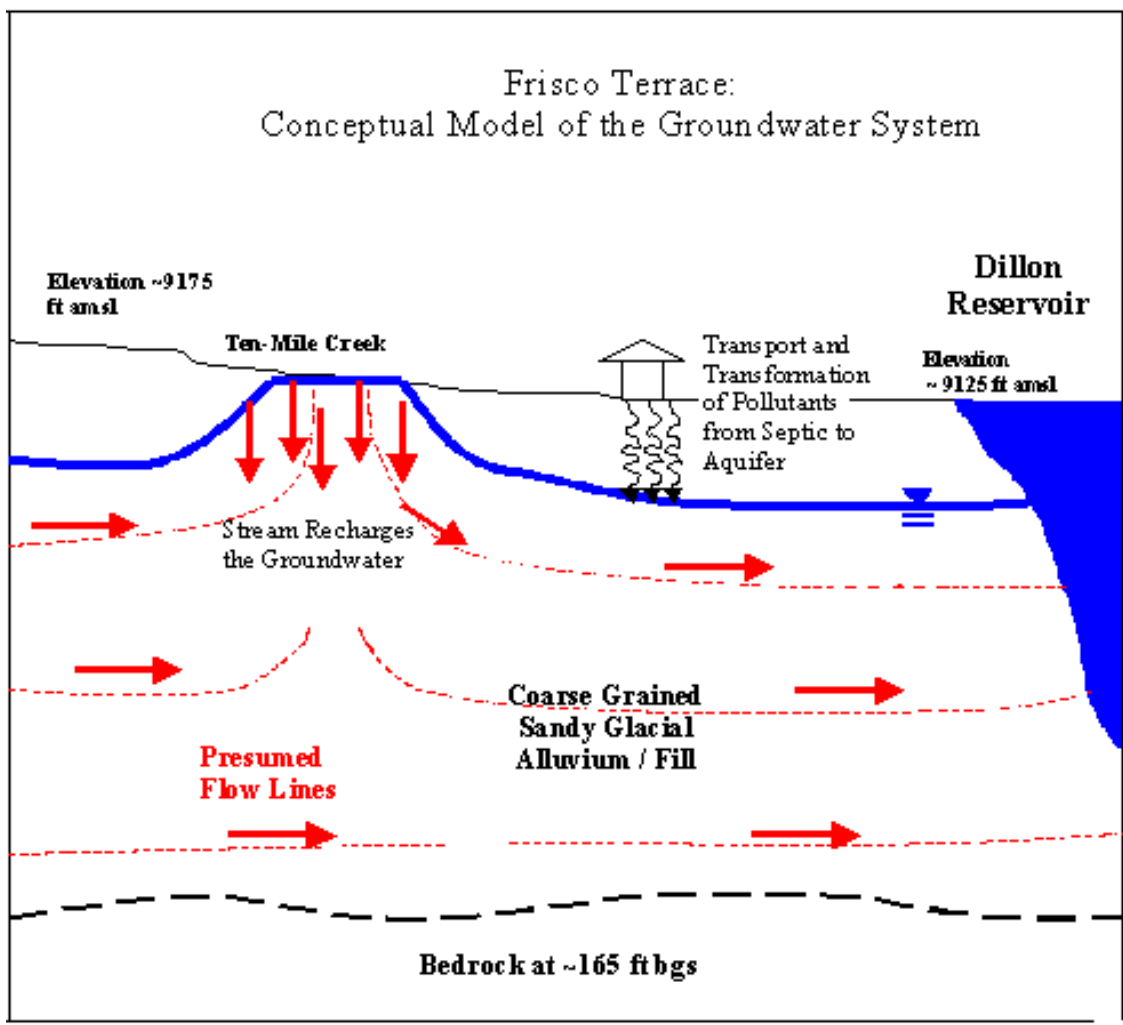
However, we believe the relative error between locations, all collected with the same GPS unit, is similar. Therefore these errors are considered appropriate for a watershed scale study. MW-3 is shown as only one value because the water levels and tops of casing elevations were essentially identical between the upper and lower piezometers as shown on Figure 4-2.

4.5.3 Discussion

Assessment of hydraulic head heights will allow us to determine where according to elevation, the water column falls spatially. If the streams in this watershed consistently feed the groundwater system, then direct OWS pollution of the nearby streams is not likely, because the OWS would also likely feed directly down into the groundwater system, thus passing through soils other treatment media in the process. In the Frisco Terrace focus area, flow patterns between surface waters and ground waters are complex because of the nearby lake, the close proximity of steep hills and mountains that facilitate local recharge and the city-setting where discontinuous pavement can also cause local recharge. Thus, additional monitoring wells would be required to ascertain specific flow paths. It is not clear whether the groundwater is discharging to the stream or vice-versa. We can; however, make a realistic assessment based on the data we have collected.

The monitoring wells in FT are in between stream-water surface water monitoring stations FT-1 (upstream) and FT-2 (downstream), although much closer to FT-1 (Figure 1-3). The head at surface water monitoring location FT-1 is significantly higher than the head in the monitoring wells. In addition, the head in MW-4 (closer to Ten-Mile Creek) is higher than the head in MW-3 (farther from the creek). This triangulation calculation suggests that the stream may be discharging to groundwater, which indicates that OWS pollution of the stream adjacent to the development is not likely, and thus the impact on this system is with in the groundwater, which is affected by soil and other environmental interactions prior to discharge to Dillon Reservoir. The stream chemical data discussed later in Chapter 6 supports this conclusion. The ultimate discharge of the groundwater system is the Frisco Bay at the inlet to Lake Dillon. However, under the current monitoring program, stream sampling near the development is not a useful method to assess OWS input from Frisco Terrace development into Lake Dillon. (See the generalized cross section / conceptual model for FT in Figure 4-10).

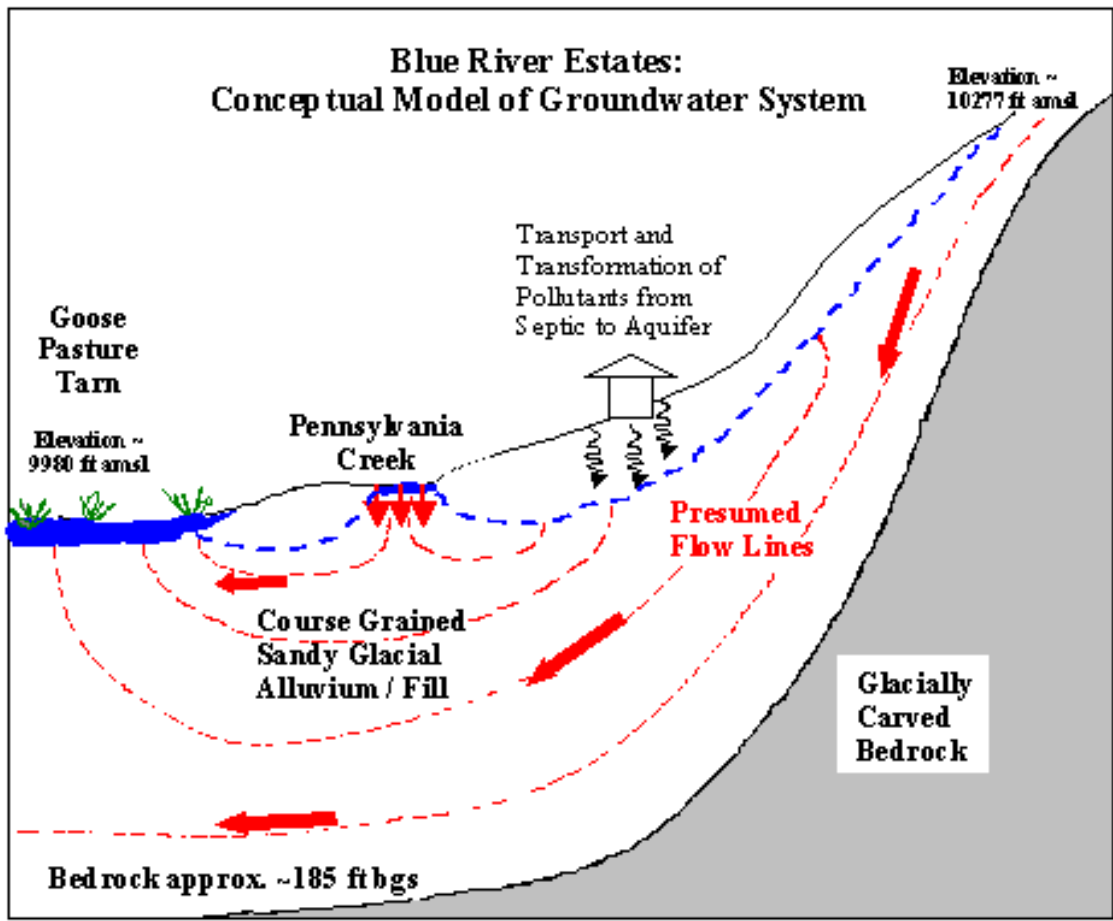
In the Blue River Estates focus area, the head of the MW-1 groundwater (shown in figure 4-12a) is at a much higher elevation than top of groundwater in MW-2. The head elevation in MW-2 is somewhat higher than the elevations of the nearby streams (Figure 4-11). Groundwater is currently flowing from higher elevations (MW-1 area) to lower elevations (MW2 area), towards Blue River and Pennsylvania Creek. Blue River and Pennsylvania Creek act to recharge the groundwater aquifer in this system. Blue River recharges the aquifer year round, and Pennsylvania Creek (a perennial stream) would recharge during periods of active flow in the stream channel. This conclusion is consistent with the discussion of the frozen-stream recharge effects on MW-2 water levels (recall Figure 4-1). The probable discharge location for the BRE groundwater (based on flow-direction analysis) is the wetlands in Goose Pasture Tarn several hundred meters south of MW-2. This is sensible because, in general geomorphic settings, groundwater discharge is the most likely source of a wetland.



Notes: Not to Scale

- Bedrock Assumed Impermeable
- Depth to water is approximately 15-35 feet bgs.
- Glacial till overburden is coarse grained sandy material with no identifiable aquitards to inhibit flow

Figure 4-10: Modified Cross Sectional Conceptual Model of the Ground Water System at FT



Notes: Not to Scale.

Figure 4-11: Modified Cross Sectional Conceptual Model of the Ground Water System at BRE

Thus, under current hydrologic conditions, wastewater-pollutants from OWS systems are not likely to enter the nearby streams, but rather enter the Blue River system via the groundwater after transport through the vadose zone, ultimately discharging in the Goose Pasture Tarn. It is at that point the septic system pollutants may become part of the surface water system (see Figure 4-11 for general cross section/conceptual model for BRE).

For both of the above scenarios, however, it is important to note that this analysis is based on monitoring conducted during a drought year; therefore, especially in the cases of MW3 and MW4, wetter years may result in groundwater discharging into nearby streams. Recently collected data during 2003 (a wetter than average year) indicate the same trends as above. However, it is not known how long it would take for “typical” hydrologic conditions to return after a several year drought as occurred from 1999-2002. Nonetheless, for both scenarios above, potential groundwater flow paths into surface-water bodies are longer than originally hypothesized, which would result in larger attenuation of pollutants due to soil sorption and other biochemical reactions.

At both sites it is possible that the groundwater table depression (below the level of the stream) is locally due to pumping of local drinking-water wells. However, the homes with wells also have septic systems that discharge treated wastewater back to the hydrologic system, which should moderate this phenomenon. Given the coarse grained nature of the sediments overlying the aquifers in these study areas; one might expect most of the discharged wastewater to eventually recharge the aquifer. It is possible that evapotranspiration (ET) may reduce the amount of wastewater recharge by a very small amount, due to the fact that in OWS systems wastewater is discharged a few feet below the ground surface. In any case, one important point of information gained from these data is that: for these points, in these conditions, it is unlikely that wastewater pollutants are immediately entering the surface water flow system leading to the Dillon Reservoir,

because the groundwater (the ultimate receptor for wastewater pollutants in the watershed) is not feeding the streams at these locations. Ultimate discharge after transport through the subsurface system may be the surface water system, but it is not immediate. (Again refer to the conceptual models Figures 3-1 and 3-2). In addition, recharged water from OWS systems (assuming an average depth of the OWS at 4 feet, and average water levels bgs in FT at 38 feet and in BRE at 49 feet (from the CSEO well logs referenced in table 3-2) and typical water depths in the monitoring wells at approximately 15-20 feet bgs) must travel through 15 to 45 feet (~ 4.5–14 meters) of the vadose zone (i.e. unsaturated soil media) prior to reaching the water table. This zone provides a substantial natural “treatment zone” of subsurface media (in this system course grained soils) for the OWS pollutants to move through prior to introduction to the surface water environment.

4.6 The Big Picture: Darcy / Transport Discussion

At Frisco Terrace, the groundwater potentiometric surface is relatively flat (based on elevation measurements in MW-3 and MW-4) and groundwater appears to be flowing away from the stream system. Of course, assessing groundwater direction utilizing so few head measurements is problematic. At BRE, groundwater appears to be flowing from higher elevations to lower elevations, and is therefore flowing in a northwesterly direction under Blue River and Pennsylvania Creek. The exact hydraulic-head gradients cannot be calculated because only two monitoring well groundwater points are available at each site and thus the true flow direction is not known. The water levels recorded in the CSEO records are unsuitable for these purposes due to decades of time lapse between the creation of these well installation logs.

CSEO records are useful for estimating average water depths as described in section 3.3.2, but they do not provide sufficient information for the construction of potentiometric surface maps. “They are not sufficient because the uncertainty in the well top elevations preclude converting the depth-to-water information in the CSEO logs to hydraulic head values with sufficient accuracy to estimate gradients at the scale of the study areas. This approach is likely to be satisfactory for constructing gradient maps at the scale of the entire watershed; however (Mudd et. al 2002).” By comparing Figures 1-3, 4-2a and 4-2b, one can estimate that the hydraulic gradient across BTE is on the order of 0.1 and the gradient across FT is on the order of 10^{-3} . The data above are also useful to estimate pollutant transport times. The groundwater velocities across the Blue River Estates development (the source of potential OWS pollutants) are relatively fast. The average hydraulic head difference between MW-1 (on the near up gradient side of the development) and MW-2 (down gradient of the development) is about 280 ft. The approximate distance between these along a flow path perpendicular to the hydraulic gradient is 2900 ft. This yields a large hydraulic gradient of about 0.1. Assuming a porosity of 0.3, using the K values estimated from the CSEO log analyses (Chapter 3), the approximate hydraulic gradient based on the monitoring wells, and applying Darcy’s Law, gives a groundwater velocity on the order of 10^{-3} cm/sec (~1000 ft/yr). Thus it would take groundwater about 1.5 years to travel from the center of the BRE development past MW-2. The gradient from MW-2 area to the wetlands is significantly less (about 0.01). This yields a travel time of 4 years. Total travel time of potential OWS contribution through the subsoil, which was input on the hillside with in the development, until discharge to the surface water at Goose Pasture Tarn is therefore about 6 years.

Contaminants may travel slower than the groundwater; however, due to sorption capacities onto soil or other reactions. Phosphorous (P) retardation factors, for example, are in the range of 10 to 100 for most soils (Kirkland, 2001). The best-case scenario would thus yield a P travel time for the same scenario addressed above of more than 400

years. It is also important to point out that soil P is in the range of 7-22 ppm in the top 12 feet of all the monitoring wells. Phosphorous concentrations in the surface waters could be in part a result of run off from these soils. Clearly, to get an accurate estimate of pollutant travel times, more monitoring wells must be installed: to more accurately determine the hydraulic gradient, to obtain a better statistical representation of K, and to provide analyses that would provide site-specific sorption parameters for the soils. Travel times at the FT study area would be significantly slower because of much smaller hydraulic gradients across the development to the likely discharge point into Lake Dillon. Travel time information of the groundwater in the subsurface is important when assessing potential impacts of wastewater pollutants, because the removal of many pollutants from groundwater, including organics, nitrogen, phosphorus, and bacteria or virus, may depend on the contact time between soil and pollutants before the pollutants reach a surface-water body, well, or spring.

CHAPTER 5: EVALUATION OF DERIVED DATA GROUNDWATER / DRINKING WATER SAMPLING

5.1 Introduction

Fifteen months of groundwater chemical data, from the four installed monitoring well locations, are discussed in this chapter. During the month of April 2003, a comparative analysis of drinking water wells in the vicinity of FT and BRE was also performed. These drinking water wells draw from the same aquifer as the monitoring wells installed by CSM for this characterization and should reflect similar water chemistries as the monitoring wells sampled for 15 months. Water quality parameters were evaluated on-site, utilizing a 660R YSI Water Quality Checker, including: temperature, salinity, specific conductivity, total dissolved solids (TDS), pH, and Dissolved Oxygen (DO). HACH© sample analysis by the sampling team in the laboratory evaluated samples for: ammonia, Chemical Oxygen Demand (COD), pH, alkalinity, solids and total dissolved solids. IC and ICP samples were analyzed at the Colorado School of Mines, providing cation and anion concentrations including: fluoride (F), chloride (Cl), nitrate (NO₃), phosphate (PO₄), sulfate (SO₄), silver (Ag), aluminum (Al), arsenic (As), boron (B), barium (Ba), beryllium (Be), calcium (Ca), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), iron (Fe), potassium (K), lithium (Li), magnesium (Mg), manganese (Mn), molybdenum (Mo), sodium (Na), nickel (Ni), phosphorus (P), sulfur (S), selenium (Se), tin (Sn), strontium (St), titanium (Ti), vanadium (V), zinc (Zn), scandium (Sc), and argon (Ar). The basic results are included in chapter 5 in both the form of original non-charge balanced data (which leaves all the derived sampling information) as well as the charge balanced data set (which has

removed incomplete data sets or uncharge balanced sample sets from the graph). The trends for these two comparative data sets are similar throughout the analysis.

5.2 Methods

The 1 inch inner diameter piezometer well points, made sample collection a challenge. The total depth of the boreholes measured between 20-40 feet bgs with corresponding elevations between 9,000 and 11,000 feet amsl. Typical peristaltic pump technologies were not effective in these areas due to an inability of the pump system to lift the water column to the heights required at these elevations. Bailing was the rational solution to this problem, but bailing only removed a limited amount of water from the water column since we were restricted to utilizing a bailer that would fit into the small-diameter piezometer. Waterra© makes a check-valve type, micro purge internal-pumping device that screws into the bottom of sampling tubing dedicated to each piezometer. For these monitoring wells, 3/8 inch polyvinyl tubing was utilized with a 3/8 inch Waterra micro-flow internal-pump system (See Figure 5-1).

This system can pump approximately a half a gallon per minute, and was an ideal choice for these small-diameter wells.

The micro-purge pumping system is operated by positioning it approximately 1 foot from the bottom of the well. The tubing is manipulated in approximately 1 foot up-and-down strokes within the well. This up-and-down motion allows water to enter the tubing on the down stroke, and on the up stroke the check valve closes keeping water in the tubing. By continuing this motion, the water travels up the tubing, facilitating a relatively quick purging / sampling rate of up to 1 gallon every 4-5 minutes (~0.2 to 0.25 gpm).



Figure 5-1: The Waterra pumping system utilized for groundwater removal

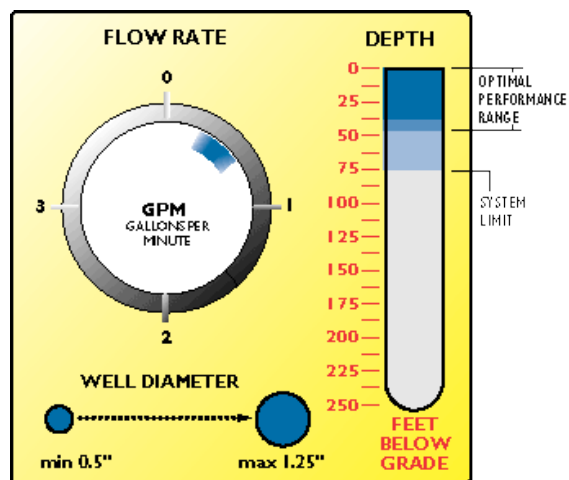


Image taken from the following website:

<http://www.waterra.com/pages/productpages/microflow.html>

Figure 5-2: Flow Rate Chart for the 3/8" Micro-Purge Internal-Pumping System

A minimum of 3 well casing volumes of water is removed (purged) from the well prior to sampling to ensure that fresh formation water is being collected rather than potentially stagnated water from the open well bore. Consecutive parameter readings on the YSI water quality checker must stabilize to within 10% prior to sampling. Dissolved Oxygen (DO) readings are not utilized for parameter evaluation, because the check-valve method of sampling introduces a tremendous amount of air to the collected sample and thus yields false high readings (most of the DO readings recorded during sampling equilibrated at over 100% DO, which is not possible). Groundwater sample containers were washed using a soapy non-phosphate wash, rinsed with potable water, acid rinsed, then DI rinsed, and finally were allowed to air dry. Sample containers included both poly-bottles and glass-bottles. IC samples were collected in the acid-washed glassware in an attempt to minimize precipitation of anions like P from the sample prior to analysis. Sample tubing and check valve adaptors are dedicated to the specific wells to minimize cross contamination during sampling operations. Samples were kept cool prior to analysis, during transport from the field collection site to the pilot laboratory at the Colorado School of Mines, and during storage in the laboratory refrigerators. The samples were kept after analysis until QA (Quality Assurance) procedures determined that the samples were no longer needed. Water analyses were evaluated initially for Sc and Ar concentrations which should have remained consistent throughout the suite of samples analyzed at the same time. In one instance all the data from an IC run came back orders of magnitude greater than would be expected, or had been seen previously, in all of the earlier sampling points. Closer evaluation of this data defined a problem with the sample analysis equipment. As a more intensive QA/QC check, cation and anion concentrations were charge balanced (discussed in chapter 6). Water should not have a charge, and if it does upon completion of this balance, it is likely due to error in either the IC or ICP analyses. There were also instances during this research, where samples just didn't get analyzed either through misplacement of the vials or through mechanical problems with the analyses equipment.

A routine collection of monthly groundwater samples was collected from five (5) of the seven (7) total piezometer points. Two (2) of the seven (7) piezometer points, MW1 Upper, and MW2 Upper, were consistently dry during sample collection visits. The groundwater sampling event was conducted for 15 months, from February 2002 through April 2003. Water sample analysis was performed using the analytical techniques summarized in Table 5-1 below

Table 5-1 Sample Analysis Techniques

Sample Analysis Type	Container Type	Container Size	Filtered with .45 micron filter	Holding time	Analysis Technician
IC Analysis	Acid Washed Glass	1.5 ml (split septa)	No	14 days	Dr. Dongping Dai
ICP Analysis	Plastic centrifuge vial	15 ml (10 ml sample)	Yes	30 days	Kathryn Summerville
Ammonia HACH	1 L poly	HACH vial	No	1 week	Heather Smith
COD HACH	1 L poly	HACH vial	No	1 week	Heather Smith
TDS	1 L poly	20 ml water	Yes	1 week	Heather Smith
Ph	1 L poly	50 ml aliquot	No	1 week	Heather Smith
Alkalinity	1 L poly	50 ml aliquot	No	1 week	Heather Smith

IC Analysis (for anions). IC samples were collected in clean acid-washed glass containers to minimize precipitation of P in the water sample.

ICP Analysis (for cations). ICP analysis was performed on water samples collected in poly containers. These groundwater samples were filtered using a .45 micron syringe type filter to remove excess turbidity and suspended solids. Samples were preserved with nitric acid to lower the pH of these samples to below 4.

HACH – Ammonia. “Low Range Ammonia” evaluations were performed utilizing the prescribed HACH methods from HACH METHOD 10023 for Low Range Ammonia (page 837). Spectrophotometer program #342 was run at range of 655nm.

HACH - Chemical Oxygen Demand (COD). Low Range COD analysis was performed utilizing prescribed HACH methodologies from HACH METHOD 8000 for Low Range (0-150mg/L) COD, pages 943-947, Spectrophotometer program #430 was run at the range of 420 nm.

Total Dissolved Solids. Total dissolved solids were analyzed by heating 20 ml of filtered solution at 150 degrees C in an oven for a minimum of 24 hours, until the liquid has evaporated, and only the solids remain. The weight difference between the initial weight of the pan, and the pan weight after the water is baked off is recorded and multiplied by 50 to get mg/L TDS

Ph and Alkalinity. PH is taken utilizing a bulb meter, which is calibrated prior to each usage utilizing a minimum of a 2 point calibration with 4.0 and 7.0 pH solutions. PH is allowed to stabilize and is then recorded prior to beginning the titration. A 1.6 molarity sulfuric acid titration solution was utilized to titrate 50 ml of sample to a 5.1 pH.

This quantity of drops of titration acid which were required to lower pH to the desired level was recorded. 5.1 is the titration limit for waste water and has been used as the standard reference point through out this project, but since this is groundwater and not pure wastewater titration continued beyond the 5.1 value till rapid reduction (quick drop off) of pH value occurred. Typically only a few more drops of acid was required to ensure the resulting location on the titration curve is near or on the “breaking point.” Titration values are multiplied by 2 to establish an alkalinity of CaCO₃ mg/L.

Fecal Coliform. Fecal Coliform analysis was performed by John Albert, graduate student at CSM. Fecal Coliform data is presented in the thesis (Albert 2003). The results of the fecal coliform analysis were non-detect or inconclusive in all the results from both FT and BRE.

5.3 Discussion and Results of Monitoring Well Derived Groundwater Analyses

The results of the groundwater quality evaluation can be grouped into four main units.

- Field Monitored Parameters, (i.e. water quality data collected in the field utilizing the YSI 660R Water Quality Meter)
- Nutrients
- Trace metals (IC/ICP data)
- Pilot Lab Analyses (TDS, Alkalinity, COD, ammonia, and pH)

5.3.1 Field Monitored Parameters Results

Water Temperatures Results. Groundwater temperatures were recorded during groundwater sampling starting in April 2002 through April 2003 (Figure 5-3). There is a

consistent trend in all the samples, which reflects the highest water temperatures recorded in June and July with a cooling trend through the winter. The temperatures recorded during the months of March and April 2003 suggest that groundwater is again warming, a trend seen during these months during the prior years analysis, and potentially suggesting input from surface water effects.

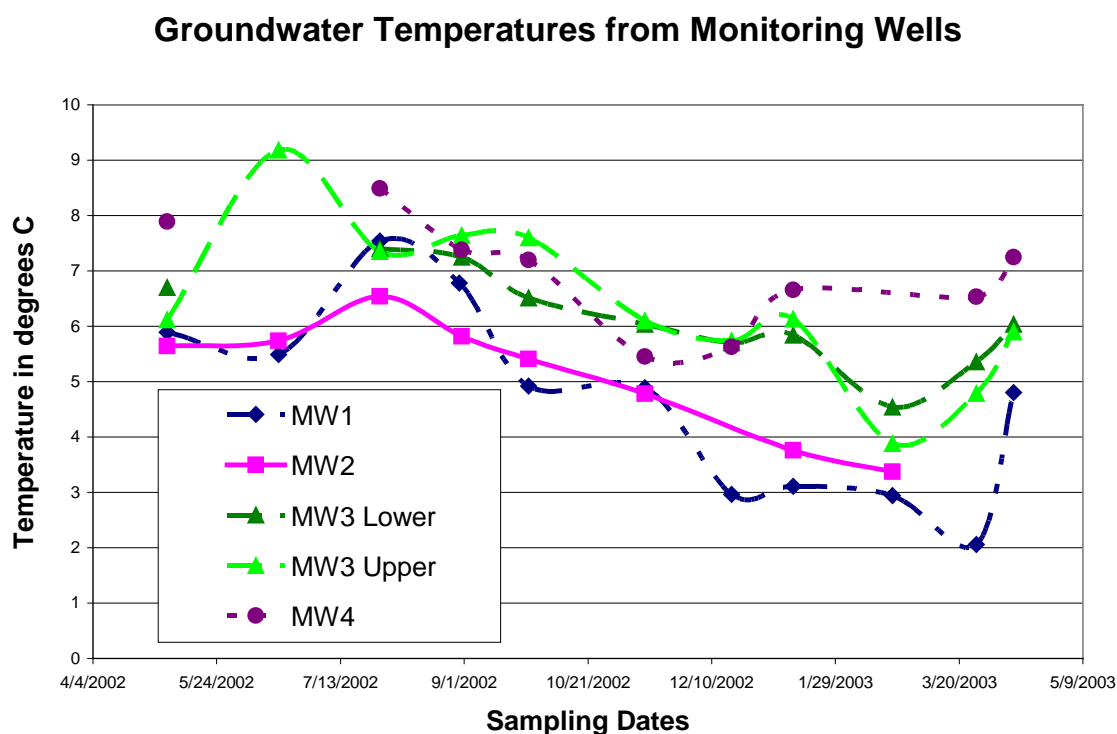


Figure 5-3: Groundwater Temperatures from Monitoring Wells

There is some degree of error introduced with the temperature readings due to the method of water retrieval. The pump system is relatively slow, and allows for contact with the atmospheric conditions by the majority of the water sample for a short time (less than 2 minutes during collection) prior to measurement. The Temperature reading was as a result collected as soon as it stabilized. It was consistently the first reading taken (out

of the T, DO, pH, Sal, Sp. Cond., suite of options displayed on the read out screen), and every attempt was made to minimize atmospheric impact on the sample quality.

pH Results. The pH of the groundwater found at these sites reflects the most “normal” values for natural waters between 7.8 and 8.5 in MW1, the background well, (Figure 5-4).

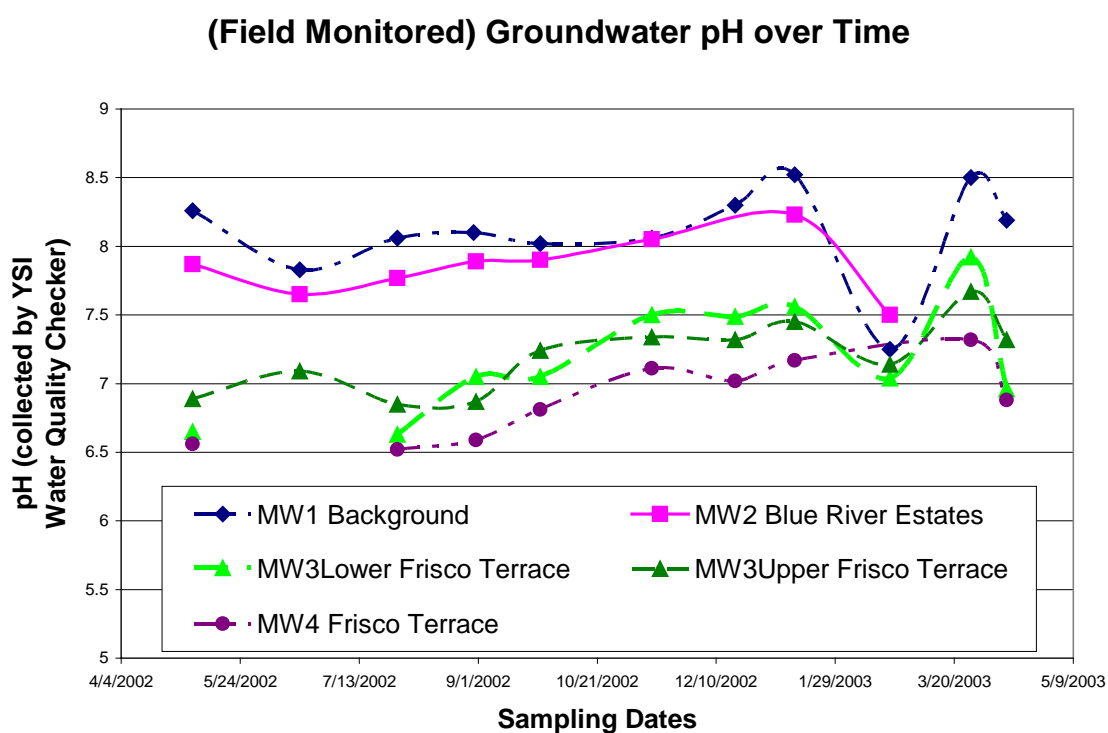


Figure 5-4: Field Monitored Groundwater pH over Time

PH ranged between 7.6 and 8.2 in MW2. The pH values from the FT area reflect pH values ranging between: 6.5 and 7.5. FT pH's are much more acidic than are seen at BRE site. Decreased pH levels trending down gradient from BRE to FT, may be a factor of impacts of the historic mining activities in the watershed.. The uniform decrease of

pH levels during the month of February 2003 is likely reflective of a calibration problem with the YSI meter during that month's sampling event.

Turbidity Results. The turbidity values recorded in the field depict the increase in turbidity as the monitoring well locations advance down gradient in the watershed. These turbidity values are similar to the Dissolved Solids Readings discussed in Section 5.1.4.2 TDS, alkalinity and COD.

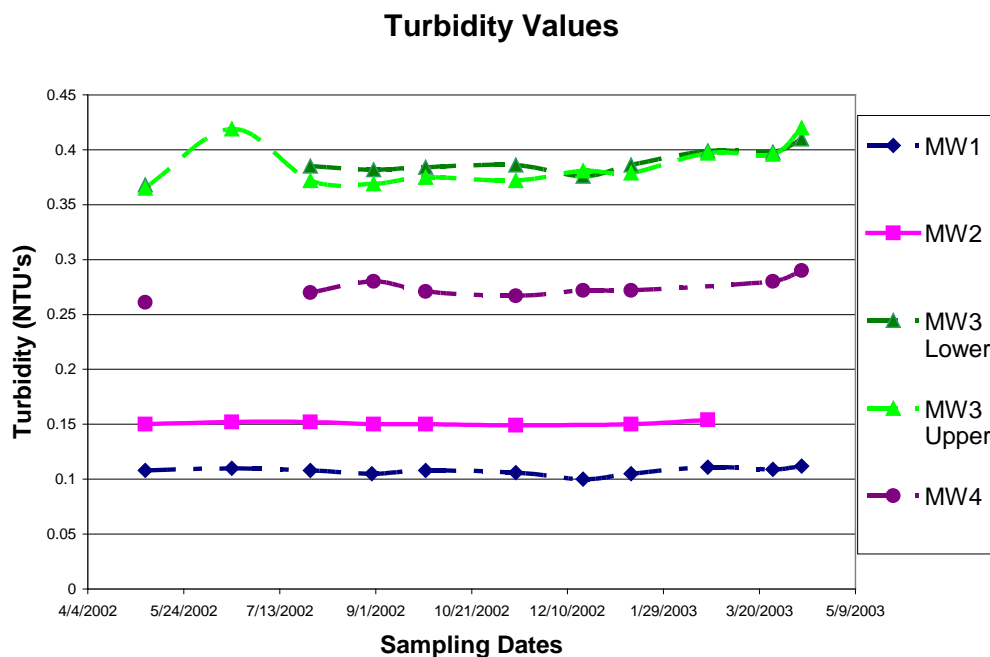


Figure 5-5: Turbidity Concentrations in Groundwater

Salinity Results. Salinity in groundwater increases down gradient in the water shed. The highest salinity results are in MW3 Upper and Lower with the results in MW3Lower slightly elevated above MW3Upper. Salinity concentrations range approximately 0.01 mg/L higher in MW3Lower than in the Upper well. MW4 concentrations are approximately 0.1 mg/L lower than MW3. MW2 has a salinity concentration that is consistently 0.11 mg/L and the background well MW1 has a consistent salinity of 0.08 mg/L, which is approximately 0.2 mg/L lower than MW4. The “Blank” water concentration was consistently 0 mg/L.

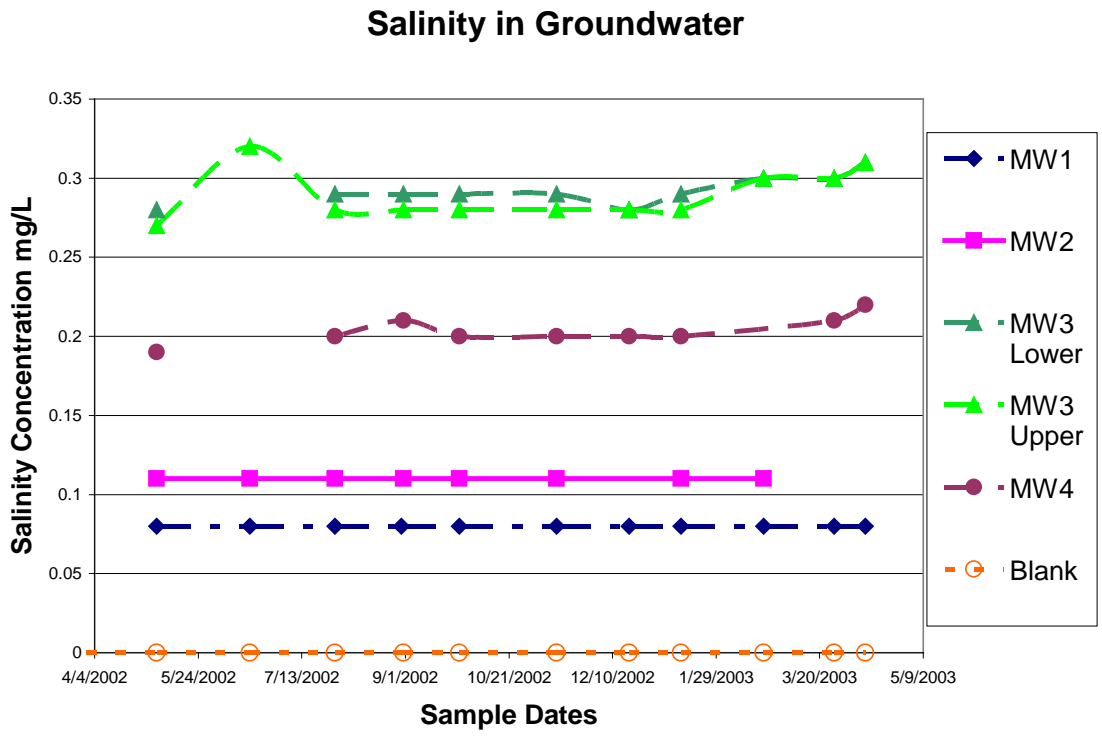


Figure 5-6: Salinity Concentrations in Groundwater

Specific Conductance Results. Specific conductance (Figure 5-7) measured a value indicative of the quantity of dissolved ions found in water. Specific conductance is usually proportional to the quantity of TDS in the water sample and thus depicts similar trends in the results as the graphs for turbidity and TDS (laboratory derived). The background well showed steady specific conductance values around 0.165 milli-siemens/centimeter (mS/cm). The highest specific conductance values were identified in MW3 in Frisco Terrace. There was no discernable statistical difference in the MW3 Lower and MW3 Upper results.

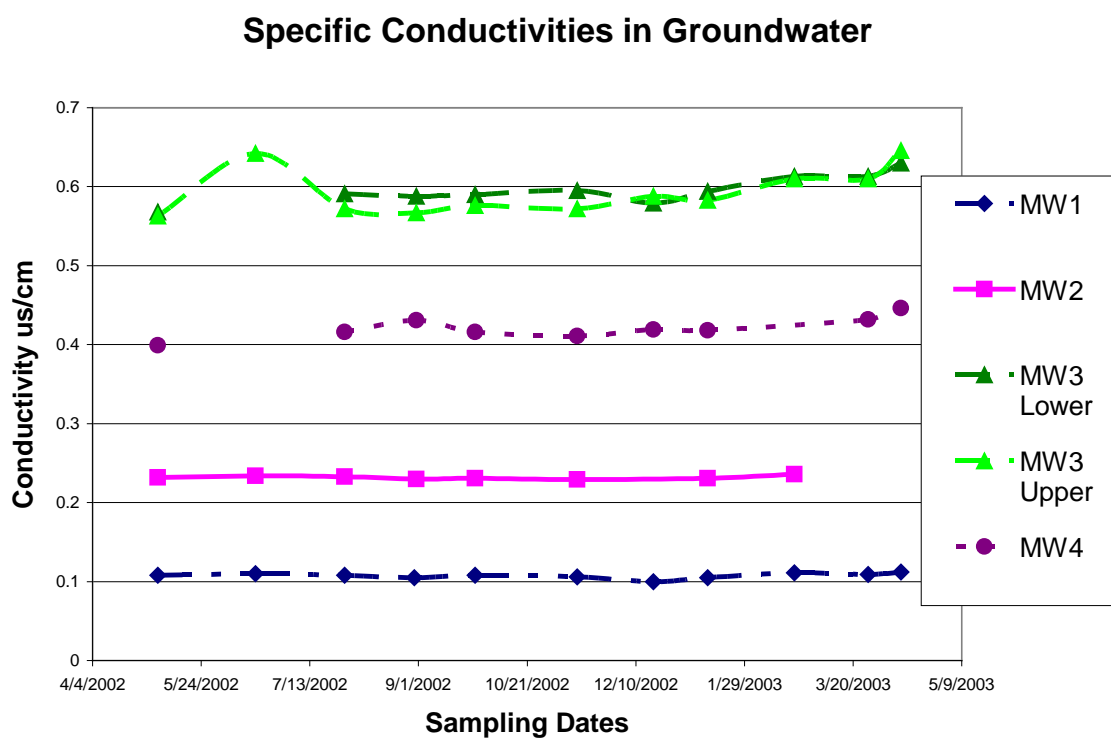


Figure 5-7: Specific Conductivities in Groundwater

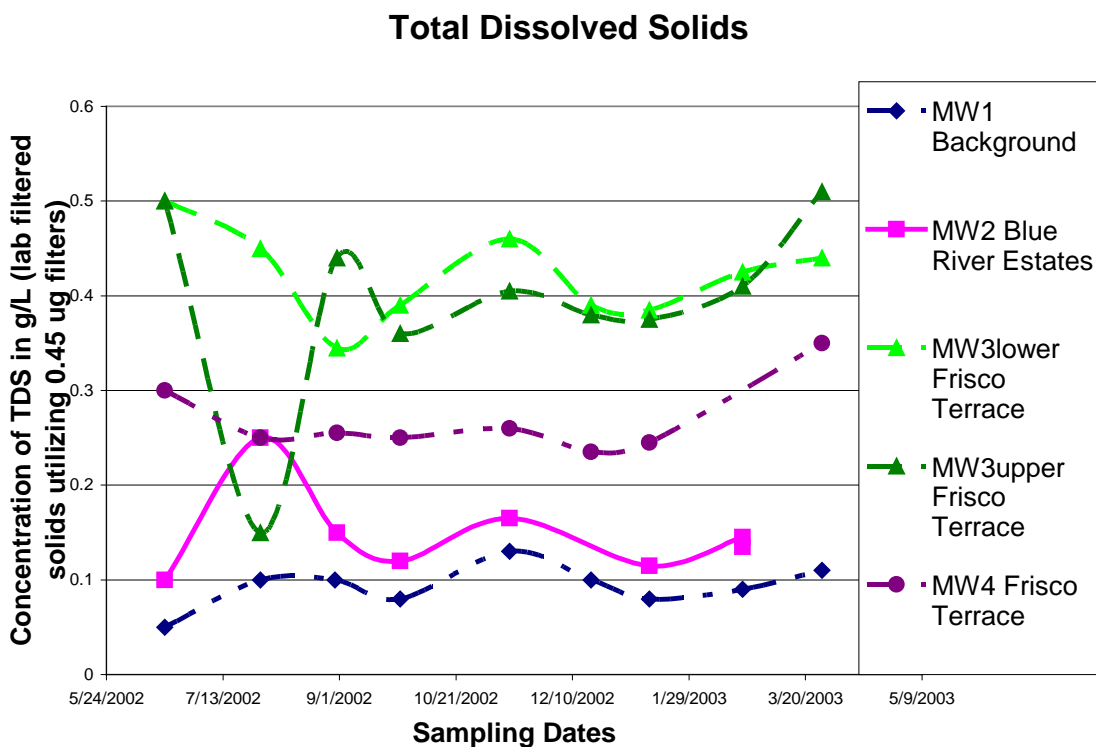
Both ranged from approximately 0.565-0.615 mS/cm. Conductivity values increased as the geographical location of the well points progressed further down the watershed, following a similar trend as many of the chemical parameters, particularly turbidity and TDS, which are closely related to conductivity.

Dissolved Oxygen Results. Dissolved oxygen readings, though potentially a good indicator of pollutants in the water column, are not reliable in this study due to the method of sample collection. Due to piezometer diameter limitations the water quality parameters are not measured in situ for this project. The Waterra© check valve pump, and the associated up and down manipulation of the valve with in the water column, has the capacity to introduce air into the sampling line with the water sample. The resulting DO readings were unnaturally high in most of the sampling results (over 100% in many instances), and will therefore not be evaluated in this research.

Total Dissolved Solids. It is evident that the total dissolved solids (TDS) concentrations in groundwater, show an increasing trend in severity, as the sampling points are geo-spatially located down gradient in the watershed. (Figure 5-8) The highest TDS concentrations are found in the FT sites, closest to the watershed outfall of the Lake Dillon Reservoir, while the lowest values are identified at the background well in BRE, MW1. This is a typical trend in groundwater as migration is made hydraulically down the watershed, potentially due to many factors including: natural increased weathering of formation materials during the “lifecycle” of the water in the system, cumulative anthropogenic effects at the discharge of the system, higher population and thus increased anthropogenic effects at the discharge, or most likely, a combination of these factors. Temporal effects on TDS, seem minimal in these wells, with only small

variations in concentration in October 2002, January 2003 and March/April 2003.

Overall concentrations do not fluctuate much, falling consistently within 0.1 mg/L of the previous data point for each well.



Total Dissolved Solids from the Laboratory Analysis in Groundwater over Time

Figure 5-8: Total Dissolved Solids in Groundwater

Groundwater Alkalinity Results. Groundwater alkalinity is measured by acid titration. Alkalinity is a measurement of the capacity of water to neutralize acids due to the bicarbonate, carbonate, hydroxide or other bases in the system. It is usually expressed (as it is here) in milligrams per liter of calcium carbonate equivalent. Eleven of the thirteen data-points for alkalinity from MW1 fall between 90 and 55 mg/L CaCO₃;

values roughly similar to the alkalinity found in MW2. MW4 ranges in concentration from 35-65 mg/L CaCO₃ and MW3's wells (both upper and lower) range between 20 and 50 mg/L CaCO₃ from titration. Though less severe a separation than is seen in other constituents of water quality in this research, there does still seem to be a separation between the BRE and FT data sets in this evaluation. See Figure 5-9.

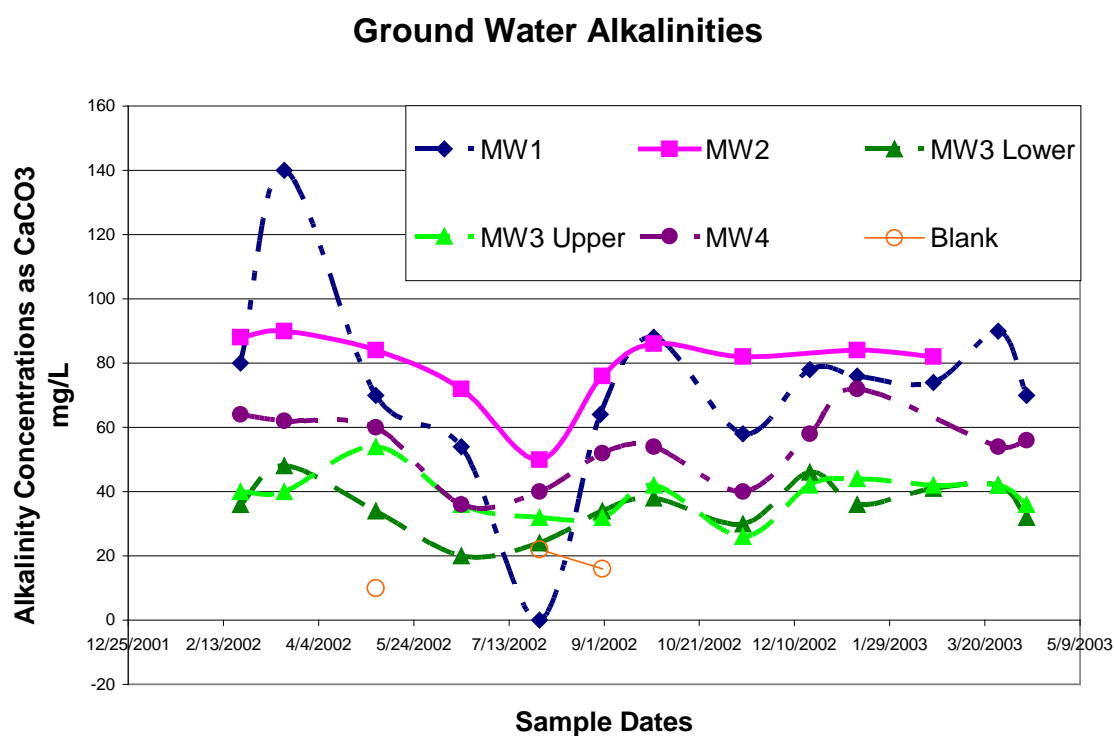


Figure 5-9: Alkalinity Concentrations in Groundwater

Chemical Oxygen Demand (COD) Results. Oxygen demand in groundwater was measured using a chemical oxygen demand (COD) test implementing a HACH analysis

system with a detection limit of 1 mg/L. Waters that are polluted may require a significant amount of oxygen to satisfy the demands of the constituents in the system. COD is one (relatively rapid) method of determining the oxygen requirements of a given system. COD results are useful in comparing the oxygen requirements of water quality at varying parts of a watershed. (Hem, 1985). The background well samples (MW1) and the blanks (QA data set) are consistently below detection limits with no elevated COD readings. In groundwater, the COD of the FT wells (MW3Upper, MW3Lower and MW4) are all consistently higher than the values found in either well at BRE.

Chemical Oxygen Demand (COD) in Ground Water

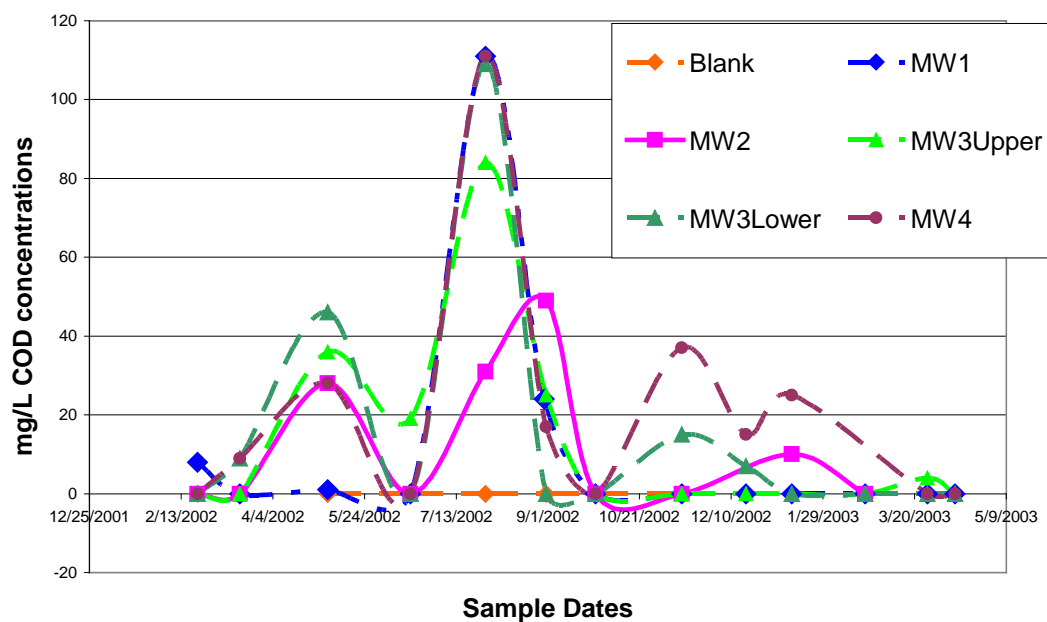


Figure 5-10: Chemical Oxygen Demand (COD) in Groundwater

Chemical Oxidation Demand (COD) was utilized for this project rather than Biological Oxygen Demand (BOD) to maintain consistency between the surface water analyses performed in this watershed and these groundwater analyses, and because the COD analysis will take into account the chemical oxidation demands on Oxygen in the system, such as aerobic degradation of minerals in a system that is not related to biological demands, where BOD will not.

The trends indicated in Figure 5-10 indicated a potential pollution source at the FT site that is most likely from septic systems. The effect is not seen at MW1 and thus the sources are not likely natural.

Note: Detection Limit for COD analysis is 1 mg/L.

5.3.2 Nutrient Results – Nitrate and Phosphorous

Nitrogen (N) and phosphorous (P) in groundwater were both measured during this study, as with the corresponding surface water characterization performed by (Guelfo 2003). Nutrients such as P and N can be found in high concentrations in wastewater and septic tank effluent. Potential sources of nitrate can be either natural (found in soil, rain, plants or animal excrement), atmospheric, or anthropogenic. It has been theorized that septic tanks are potentially contributing pollutants to the groundwater and ultimately to the surface water draining to the Dillon reservoir. If this hypothesis is true, we would expect to see impacts in the monitoring wells installed near the communities where on-site waste water systems are predominant (such as BRE and FT). The study communities were “bracketed” with one up gradient monitoring well and one down gradient monitoring well to monitor for potential groundwater impacts.

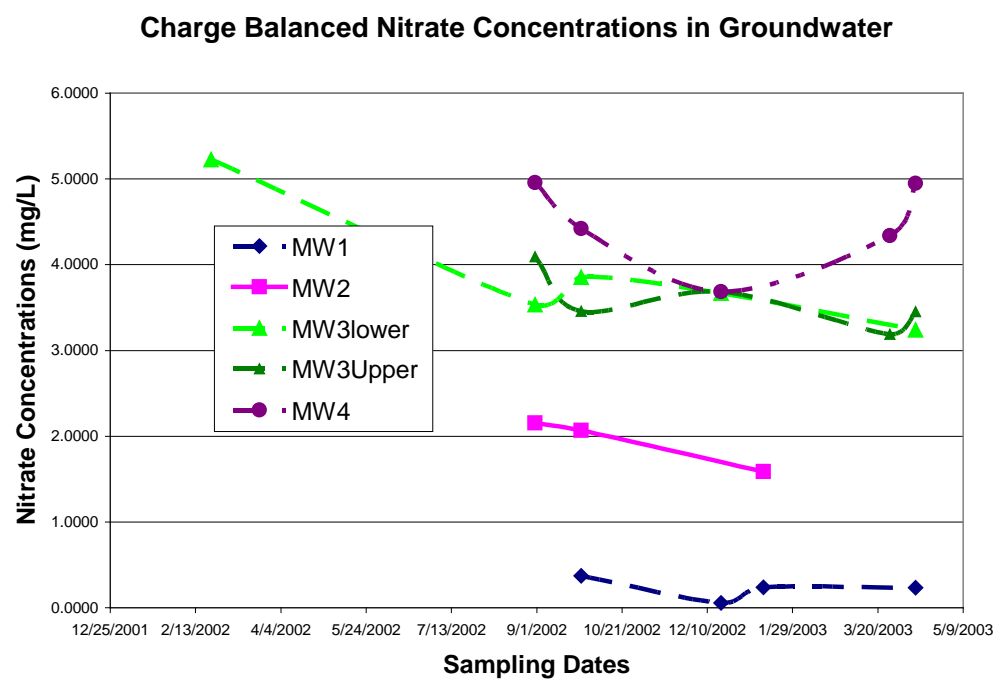
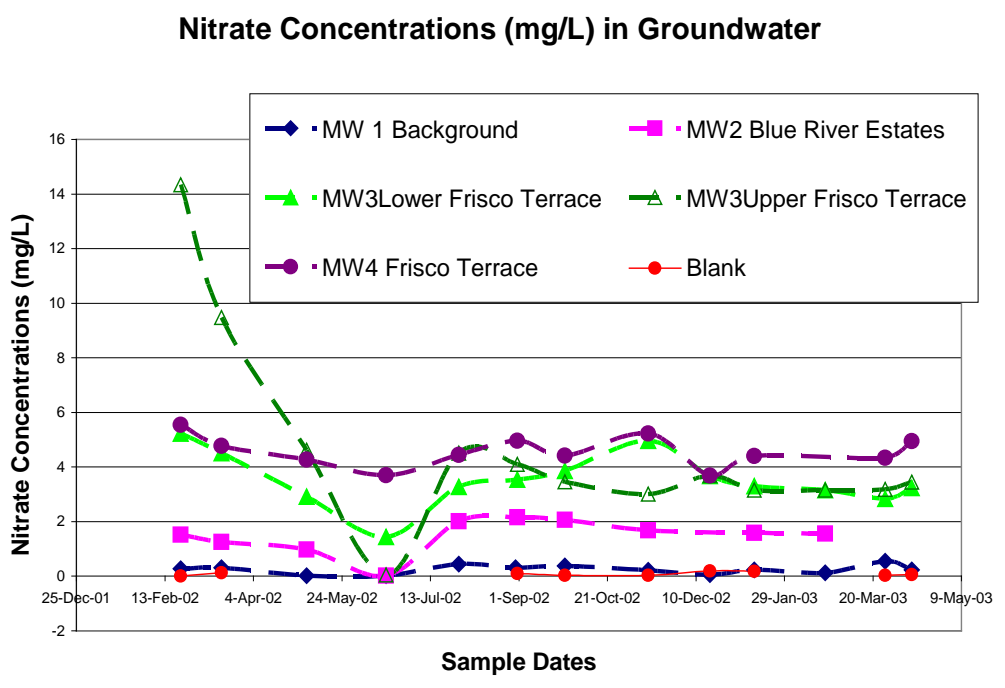


Figure 5-11: Nitrate Concentrations in Groundwater

Nitrate Results. Figure 5-11 depicts measured nitrate concentrations (mg-NO₃/L) over time. Nitrate concentrations again follow the trend of increasing concentrations with migration down the watershed. The anomalous decrease in nitrates in the upper well of MW3 from the uncharged balanced data set during June, as well as the two elevated values at the beginning of the MW3 Upper trend line (February and March 2002) can be explained by looking at data from the other charge balanced plot. The inconsistencies in the “un-charged balanced” data (upper) graph is likely a result of laboratory inconsistencies during analysis. The MCL (maximum contaminant level) for Nitrate defined by the EPA is 10 mg/L. The only groundwater results which exceeded that value during this study was the initial MW3 Upper well reading that was collected in February 2002.

Phosphate Results. Phosphate was analyzed utilizing the ion chromatograph (IC) (Figure 5-12).

During the months of October through December the phosphate values derived in the sampling blanks are higher than the concentration values seen in the actual groundwater samples. Thus, phosphate concentrations cannot be used for rigorous data analysis. Nonetheless, the results suggest that phosphate concentrations in groundwater in these sites are very small.

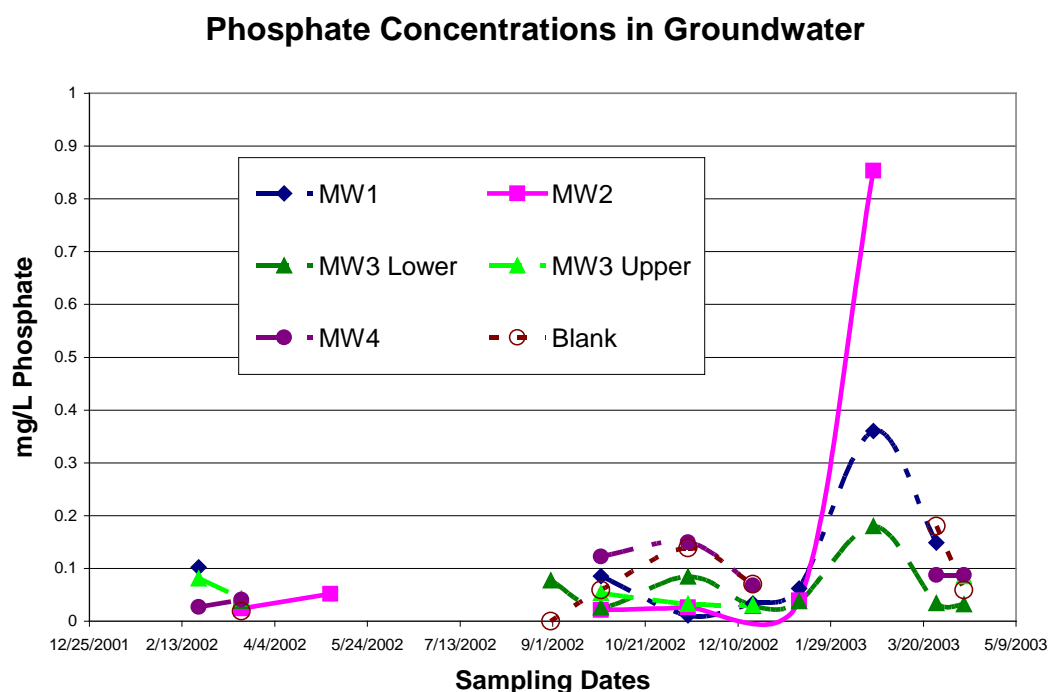


Figure 5-12: Phosphate Concentrations in Groundwater

Nutrient Data Summary. MW1 has provided the background data for these analyses. MW2's nitrate data also from BRE typically hovers around the data ranges established by the MW1 background site. The nitrate concentrations from FT are considerably higher than the background concentrations, but are still consistently lower than the EPA established MCL's (Maximum Contaminant Levels) of 10 mg/L. It is also important to note during analysis that nitrate impacts from septic (OWS) systems are most likely to be seen in fall and early winter, because those are the seasons where OWS makes up a greater percentage of the total groundwater recharge; as is seen in the water level plots. Periods of great surface water recharge from melt and precipitation would likely dilute the nitrate concentrations to a very small residual value in the system.

5.3.3 Anion Results

Chloride Results. Chloride concentrations depict a similar trend as other water quality parameters, with increasing concentrations of chloride as migration down the watershed occurs. Chloride is a relatively un-reactive element as it passes through the subsurface, not interacting much with the host formation, thus it is a good conservative tracer of potential anthropogenic impact on the system. Typical ranges of Cl^- in untreated wastewater are between 30 and 90 mg/L (Metcalf and Eddy 2003) but are generally lower in STE (septic tank effluent).

Average concentrations of chloride from the precipitation monitored in this area, are typically in the range of 0.20 mg/L (Drever 1982). Anthropogenic sources of Cl^- include foods, salts, preservative, water softeners, road salts, etc.

Figure 5-13 illustrates the chloride data. Clearly these concentrations indicate an anthropogenic input at all wells except MW1 (background well), with particular impact at MW4. The increase in chloride concentrations in FT cannot be explained solely by the addition of road salts near the wells in the winter as has been suggested, because these relatively consistently elevated levels of Cl^- in the FT samples, are seen through out the year. In addition, MW2 in BRE is far from a paved road and is less likely to be impacted by road salting activities yet it also shows heightened Cl^- concentrations. It seems that impacts other than road salting activities are in effect with in this watershed. The road adjacent to MW-1 is an unpaved road and is plowed but not salted, thus it can be presumed for this research, that the background well (MW1) represents the natural Cl^- concentration in groundwater for this watershed.

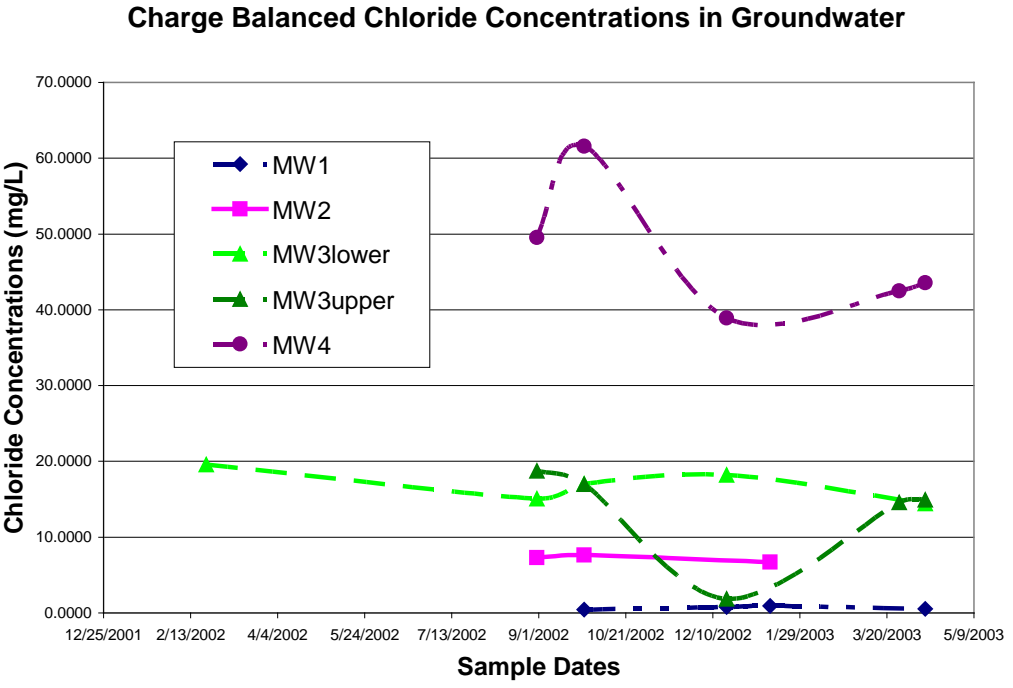
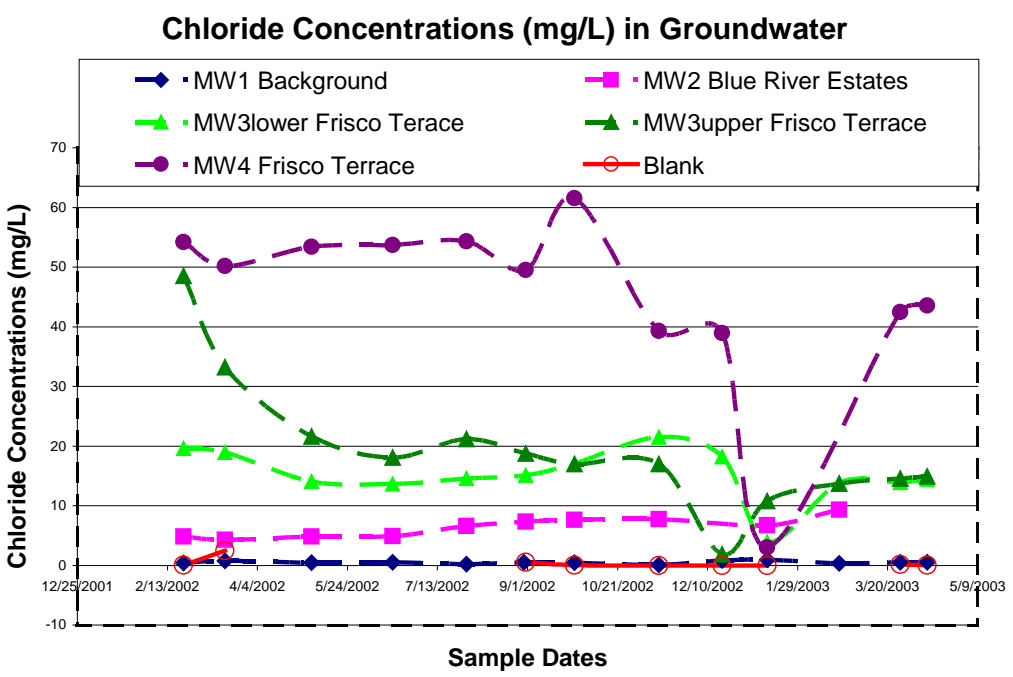


Figure 5-13: Chloride Concentrations in Groundwater

Sulfate Results. Sulfur is widely distributed in reduced form in both igneous and sediment rocks as metallic sulfides. Concentrations of these sulfides commonly constitute ores of economic importance (Hem, 1985). Figure 5-14 depicts sulfate concentrations in groundwater. The common occurrence of mining operations in the mountains of the Dillon Reservoir may account for the elevated sulfate concentrations in FT compared to background concentrations seen at MW1. Sulfate is also a wastewater component. Sulfur is required in the synthesis of proteins and so is subsequently released when those proteins degrade (Metcalf and Eddy, 2003). The dips in the trends of sulfate concentrations are similar to the dips seen with Chloride concentration values.

These similar graphs and trends, indicates that wastewater may be a possible source for both the Cl and the sulfate, as sulfate is not present in road salt and Cl⁻ is not a common mining contaminant. The fingerprint analysis discussed in chapter 6 suggests that mining activities may play a factor in the impacts in the FT study area. MW1, the background location in the upper reaches of Pennsylvania creek, is unaffected by the anthropogenic impacts of residential development, but it is also not impacted locally by high intensity mining activities. Sulfate concentrations from MW1 range in concentrations from 2.0-2.9 mg/L, following the trends of the blanks analyzed consecutively. MW2, further down gradient in the watershed at the confluence of the Blue River, has concentrations of sulfates in the range of 9-13 mg/L. Frisco Terrace sulfate concentrations are significantly higher than those in BRE. MW4 provided sulfate concentration values in the range of 50-65 mg/L, and MW3 Upper and Lower, provided significantly higher sulfate values, ranging from 197-290 mg/L. The boring designated MW3 is physically located near what has been hypothesized as a mine tailings drainage pond. The higher sulfate readings at MW3 maybe reflective of this and other historic mining activities located up gradient in the watershed of Ten Mile Creek..

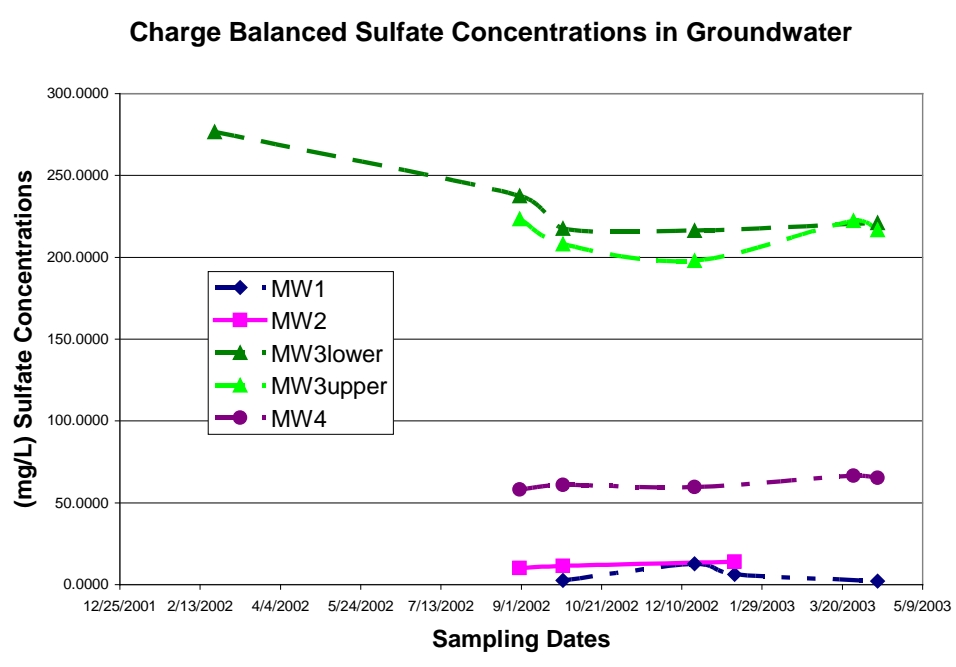
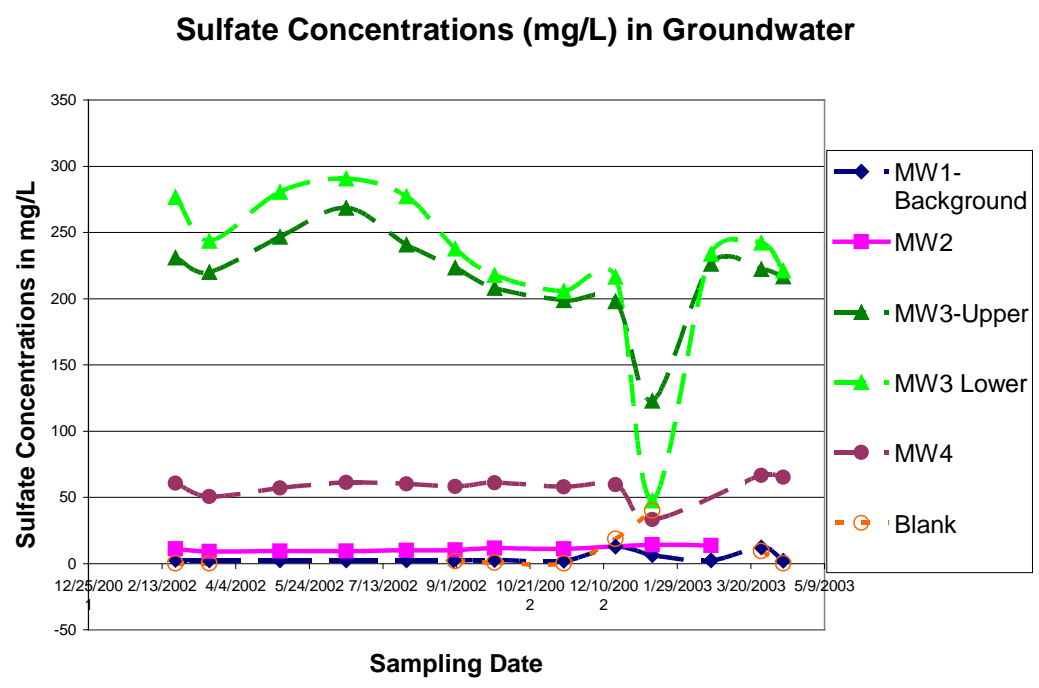


Figure 5-14: Sulfate Concentrations in Groundwater

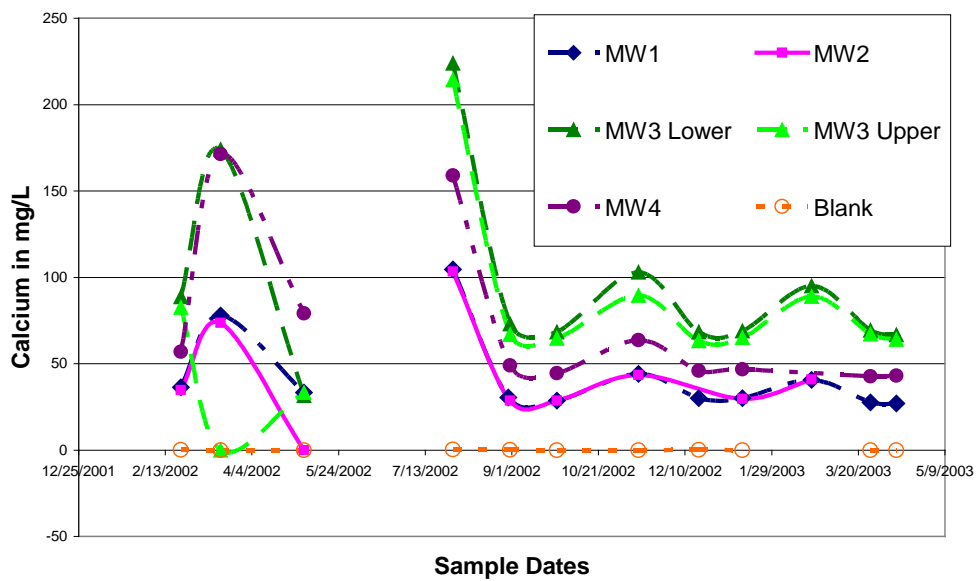
The EPA's MCL for sulfate is 250 mg/L. While MW1, MW2 and MW4 are not even close to this value, MW3 Upper and Lower trends consistently along this regulatory level, actually reporting higher than acceptable sulfate levels in water at 6 different times. These exceedences occur primarily in the spring and early summer (during periods of heightened snow melt and increased runoff in the watershed). The increase in sulfate during high runoff suggests the interface of waters with historic tailings or other high sulfate rock. Future work should involve monitoring these levels to minimize risk to drinking water wells in the area

5.3.4 Cation Results

Calcium Results. Calcium is the most abundant of the alkaline earth metals, and it is a major constituent of many common rock minerals. It is an essential element for plant and animal life forms and is a major component of the solutes in natural waters (Hem, 1985). Concentration ranges of Calcium in these sampled waters ranged from 0-223 mg/L, with higher Ca concentrations found in the Frisco Terrace portion of the watershed and lower concentrations found in the BRE portion of the watershed. These trends were consistent with the TDS values discussed earlier.

Mg Results. Magnesium concentration trends reflect similar results as seen in the TDS graph. Associated with calcium in common geochemical associations, Mg depicts similar trends as calcium.

Calcium Concentrations in Ground Water Over Time



Charge Balanced Calcium Concentrations in Groundwater

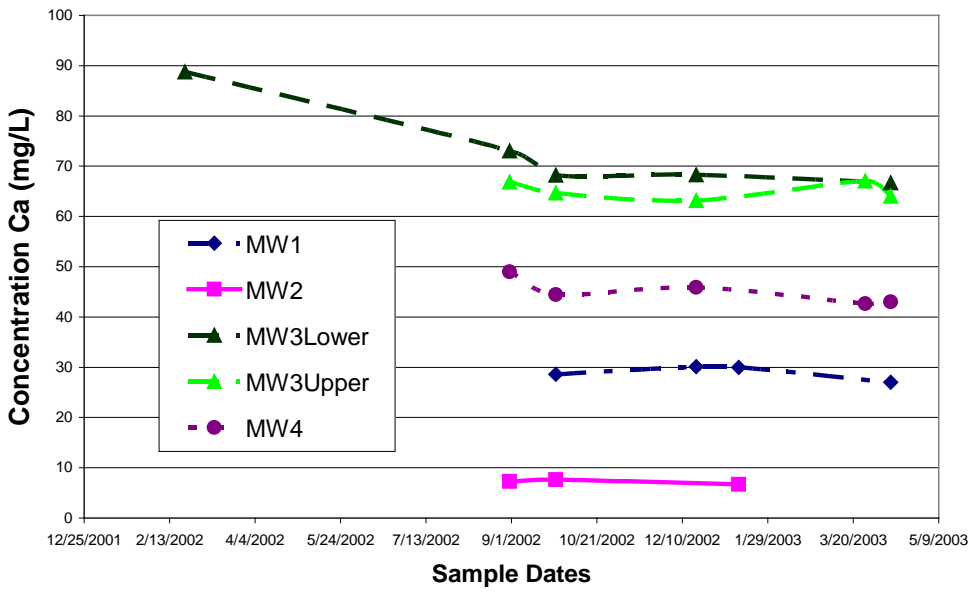


Figure 5-15: Calcium Concentrations in Groundwater

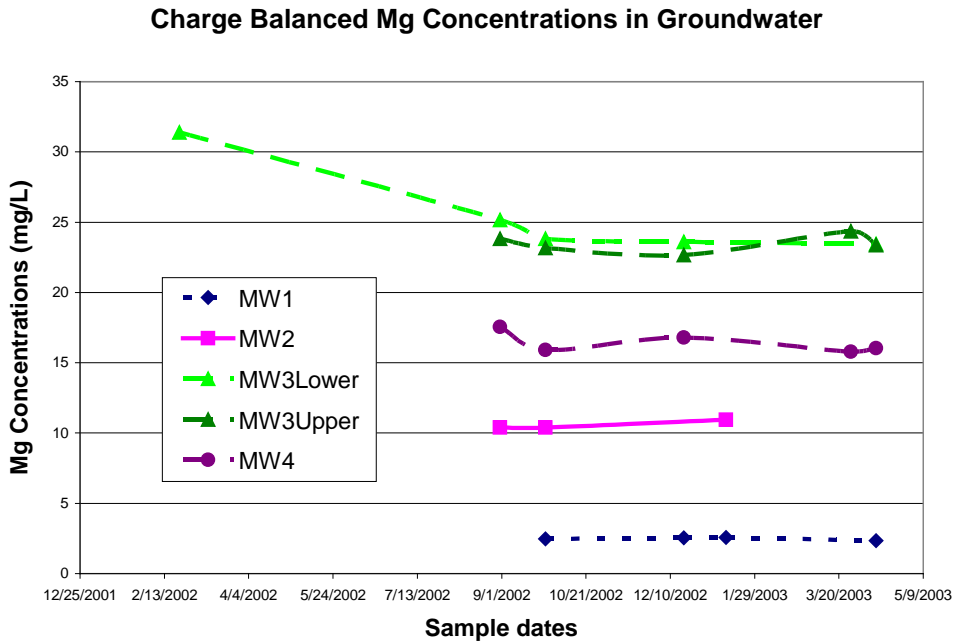
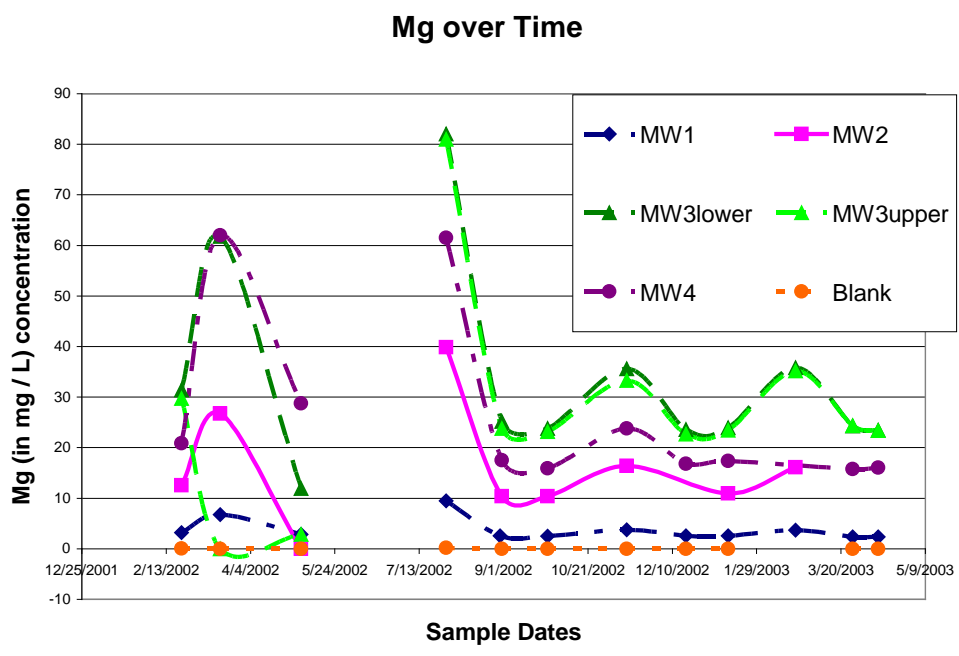


Figure 5-16: Magnesium Concentrations in Groundwater

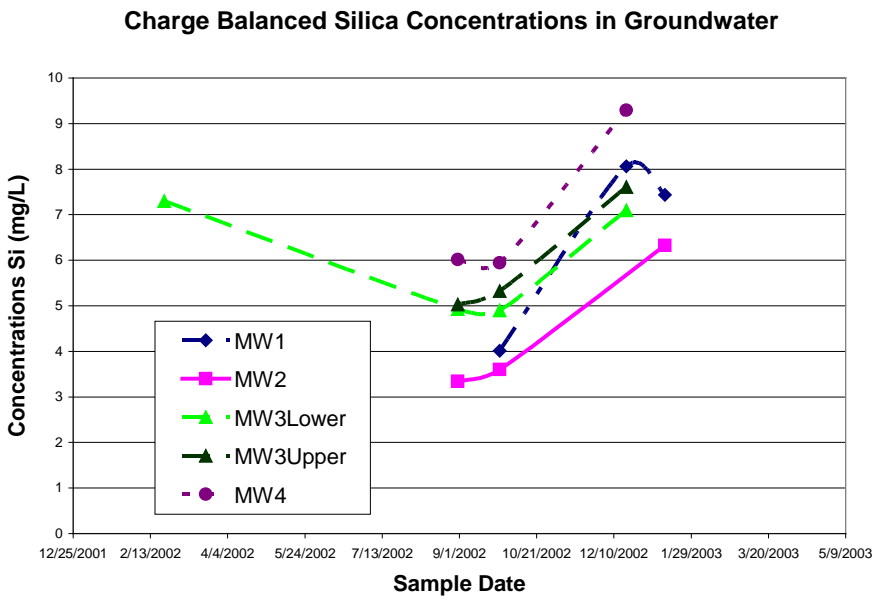
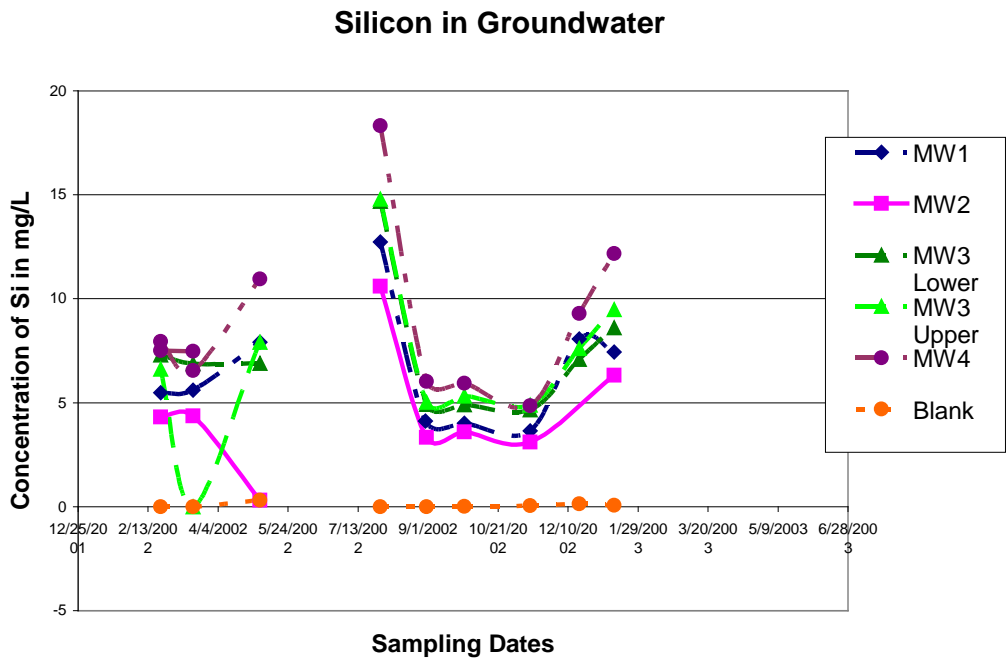


Figure 5-17: Silicon Concentrations in Groundwater

Silica Results. The element silicon is second only to oxygen in abundance in the Earth's crust. (Hem, 1985). Crystalline SiO_2 as quartz is a major constituent of many igneous rocks and is also the major constituent of sandstones. The trends of silica concentrations show no major differences in silica concentration in the groundwater samples. It does not appear that silicon concentrations in groundwater are important in this characterization analysis. The elevation of all of the concentrations in the July 2002 sampling set is similar in trend to the elevated Ca seen above in Figure 5-15 as well as in the Figure 5-16 with the Mg concentration trends. The increase of silica in groundwater during the summer months is likely due to increased flow volumes from snow melt and precipitation, and the resulting overall increase in weathering of the soils.

Potassium Results. Potassium concentrations in the groundwater samples charts as two distinct K concentrations groupings, again separating out FT and BRE. Frisco Terrace shows elevated levels of K ranging from 2.5 to 3.5 mg/L K. Blue River Estates concentrations are at 1 mg/L at the confluence of Pennsylvania Creek and Blue River at MW2 and at approximately 0.6 mg/L in the background well MW1. It appears that some impact is occurring down gradient in this watershed that elevates the K concentrations of these waters.

5.4 Drinking -Water Well Sampling and Analyses

Drinking-water wells in BRE and FT draw their waters from the same aquifer as the monitoring wells are installed with in.

5.4.1 Introduction

Sampling homes in Summit County's Frisco Terrace and Blue River Estates in April 2003 allowed for a comparison of the water quality parameters for which the monitoring wells samples were evaluated each month. Samples were collected from 6 homes in Frisco Terrace and 6 homes in Blue River Estates at the locations shown on Figures 5-23 and 5-24 for this single comparative sampling event. Care was taken to ensure good spatial distribution through the zones of interest.

5.4.2 Methods

Drinking water samples were collected when possible from outside faucets supplying water that was not treated by personal water treatment systems from within the home. Due to the very deep snow accumulation that still remained on the ground to depths of 6-8 feet during this April sampling event, it was occasionally necessary to collect the sample from an inside faucet. BRE in particular had inhibiting snow accumulation, making access to many outside faucets prohibitive. In instances of interior collection, no sample was taken if there was a personal treatment system being utilized in the home. Luckily, (with respect to this research), water softeners or purification systems are not common in BRE. Water was permitted to run for a few minutes to clear the lines, and facilitate the collection of a fresh sample. Samples were collected with the same methodology as the monitoring well samples, utilizing the 660R YSI meter to record water quality parameters and utilizing both glass and poly bottles for sample containment, chilling the waters during transport back CSM for analysis.

During this sampling event all the samples were collected on the same day, April 17, 2003. Both drinking water samples as well as monitoring well samples were

collected to facilitate comparisons among this data. Only one round of drinking water samples were collected, intended not for use as a characterization tool, but as a comparison with the groundwater to determine if results were similar. Ideally a correlation between the two sample types could be made and inferences with respect to drinking water quality could be made from the samples collected from the monitoring wells, which had been sampled monthly since February 2002 for this project.

Drinking-water sample analyses were performed in the same manner as the monitoring well groundwater samples addressed above. Laboratory analyses included IC, ICP and HACH analysis, while field parameters were collected on-site, using the YSI 600R Water Quality Checker. These analyses were utilized to “finger print” the water types from BRE and FT, and were subsequently used to compare additional groundwater data in the groundwater and surface water sample evaluations addressed above.

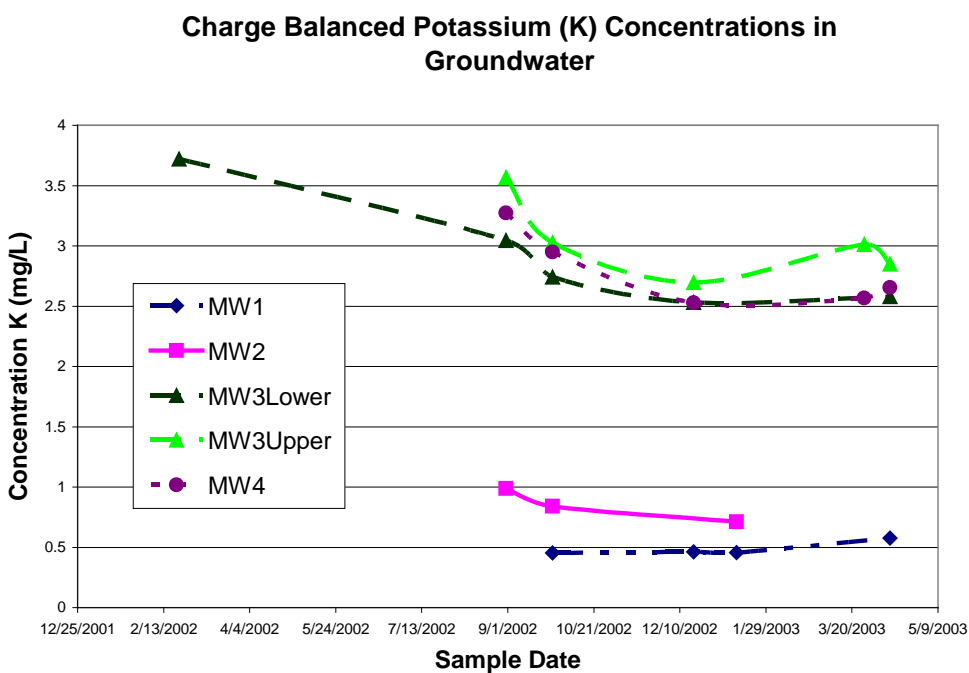
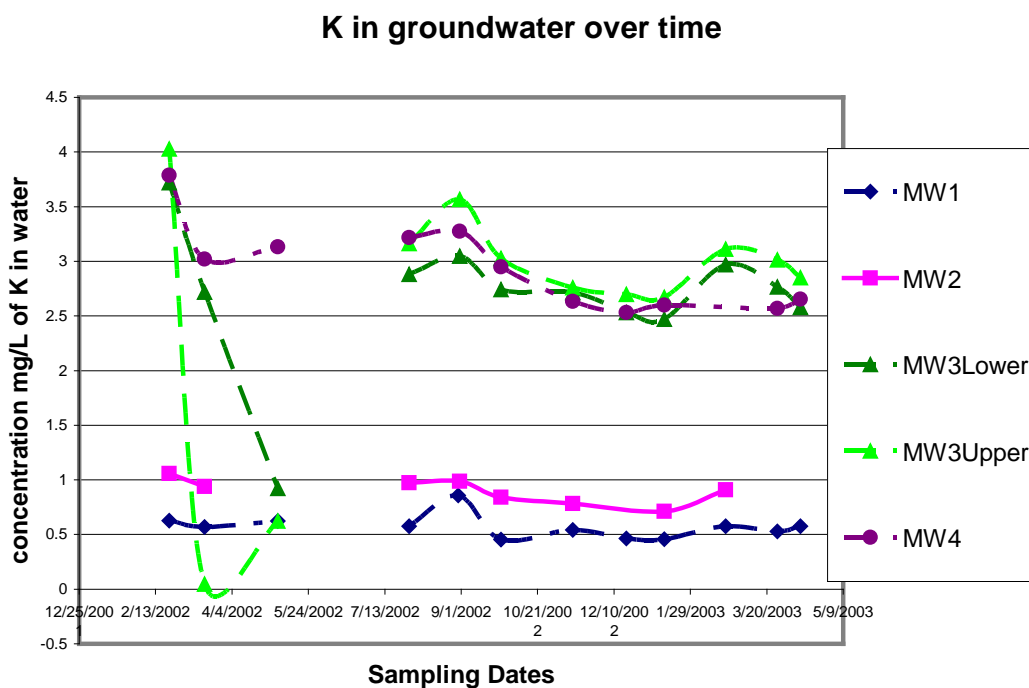


Figure 5-18: Potassium (K) Concentrations in Groundwater

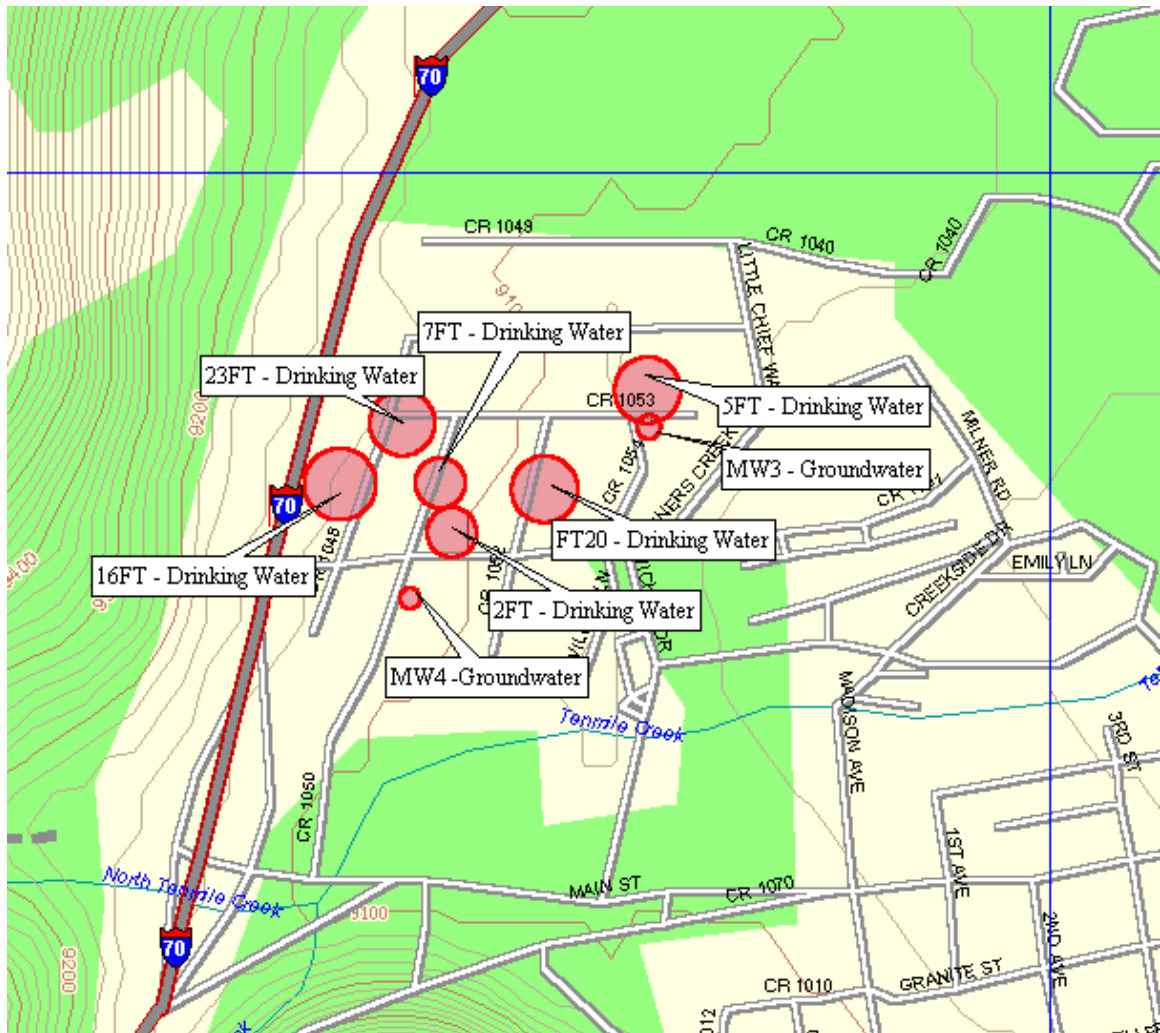


Figure 5-19: Frisco Terrace Basic Drinking-water Sample Locations

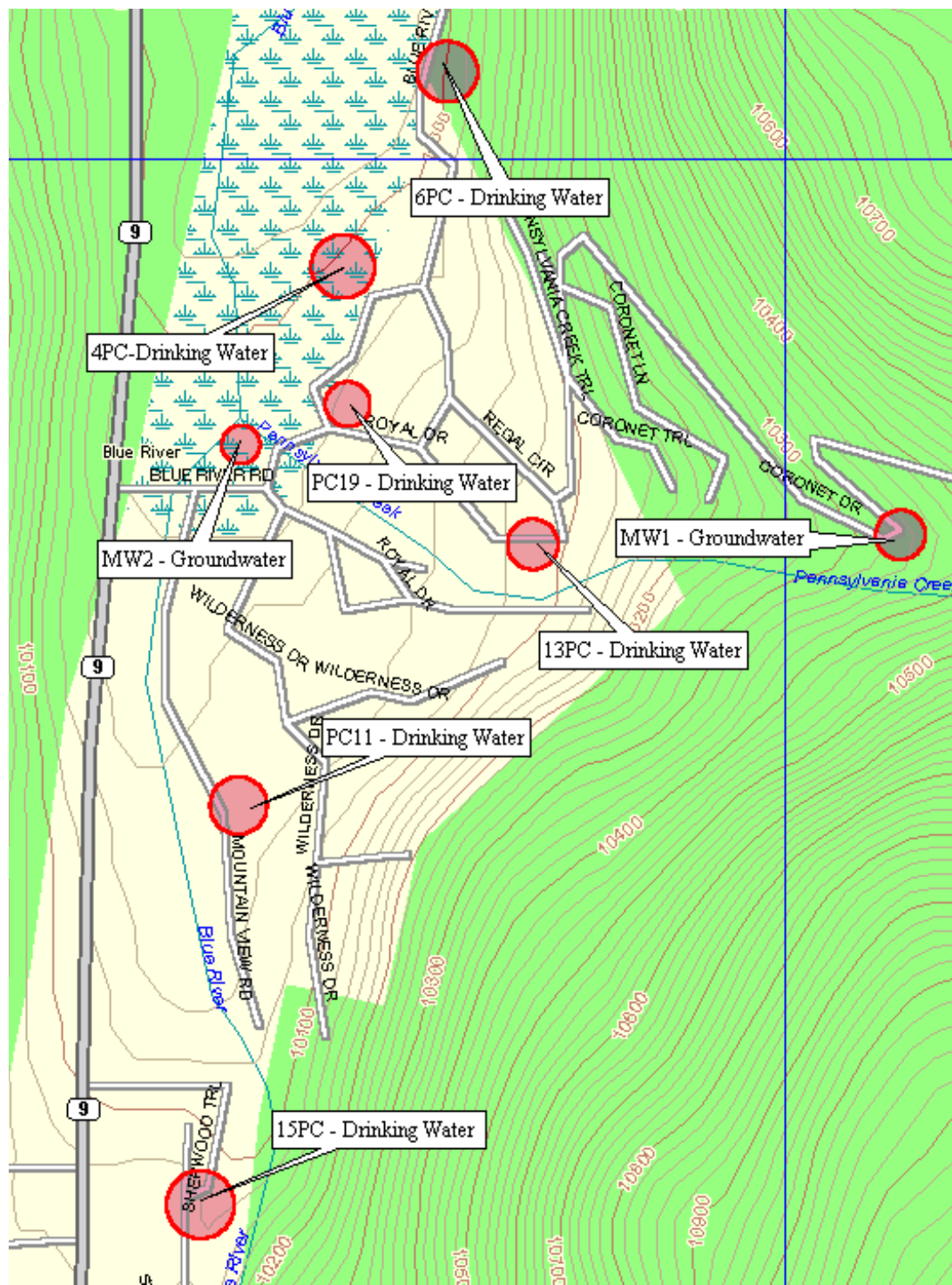


Figure 5-20: Blue River Estates Basic Drinking-water Sampling Locations

5.4.3 Discussion and Results for Drinking Water Analysis

The following plots depict constituent concentrations in drinking-water samples from the two areas of concern (Frisco Terrace and Blue River Estates). (Figures 5-25 and 5-26). The peaks seen with elevated concentrations of constituents are from right to left: Calcium (Ca), Potassium (K), Magnesium (Mg), Sodium (Na), and Sulfur (S).

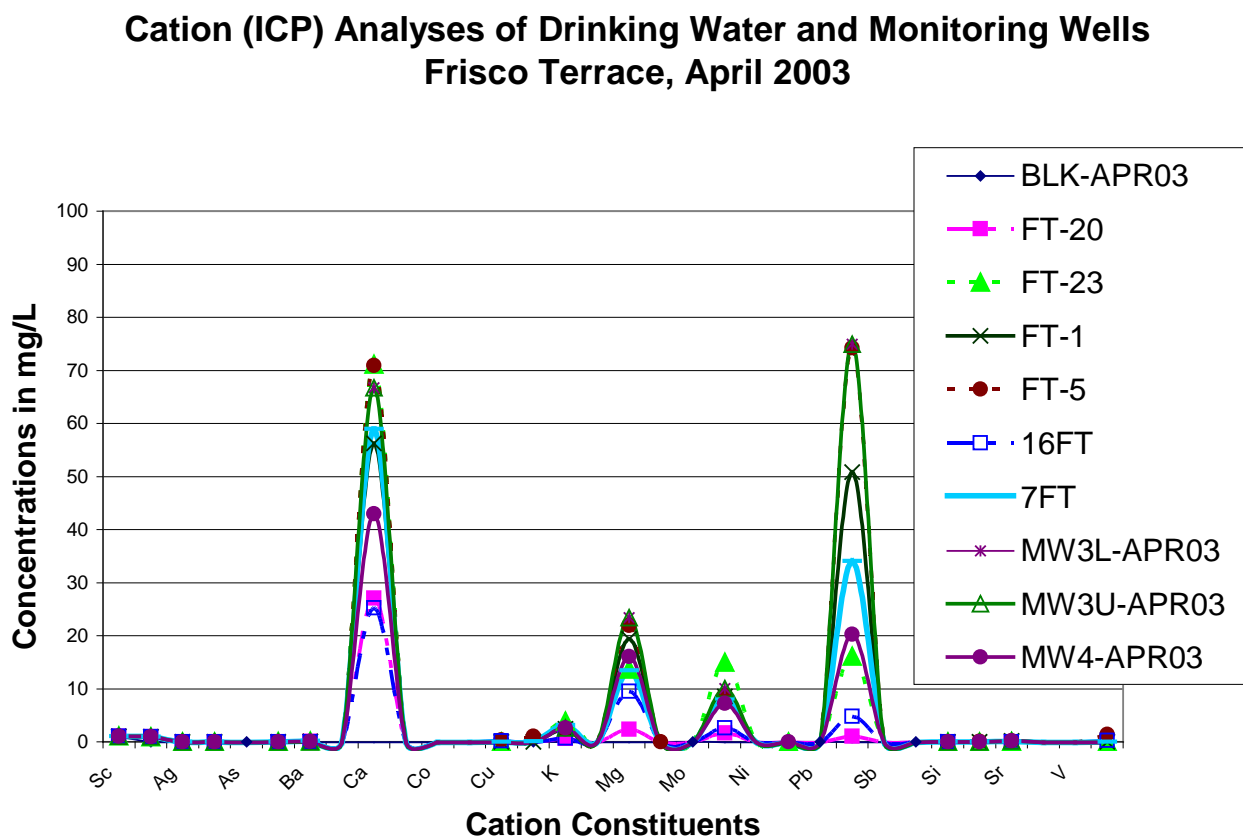


Figure 5-21: Cation (ICP) Analysis of FT Drinking water and Monitoring Wells

The cation values for the drinking-water samples from FT (Figure 5-21) included elevated concentrations of:

- Calcium (Ca). The values of Ca in the FT samples ranged from 25-70 mg/L Ca.
- Potassium (K). The concentration values of K in the drinking-water samples from FT range from 0-3.11 mg/L.
- Magnesium (Mg). All samples in this system displayed elevated levels of Mg ranging from 2.34 – 21.95 mg/L Mg.
- Sodium (Na). Concentrations of Na ranged between 2.34 and 15 mg/L Na.
- Sulfur (S) concentrations in FT drinking-water samples ranged from 1.08-74.3 mg/L S.

There appears to be no differentiation between the concentrations presented from the drinking water samples vs. the concentrations presented from the monitoring well samples.

- Fluoride, averaging 0.13mg/L, with a range of 0.009-0.92 mg/L. MCL is 4 mg/L. These samples are no where near that level.
- Phosphate, averaged 0.068 mg/L with a range of .035 to .107 mg/L. These trace levels are not a concern for general water quality regulatory limits.
- Nitrates averaged 6.39 mg/L ranging from 1.44 – 27.03 mg/L. With an EPA MCL regulatory limit of 10 mg/L the elevated nitrate value found in 23 FT is a concern and it was suggested that this home owner re-evaluate his water quality.
- Chloride averaged 38.8 mg/L with a range of .3-89 mg/L. The regulatory limit is a concentration of 250 mg/L. All these samples are with in required limits for concentration values.

Anion Analyses for Frisco Terrace Drinking Water and Groundwater Samples

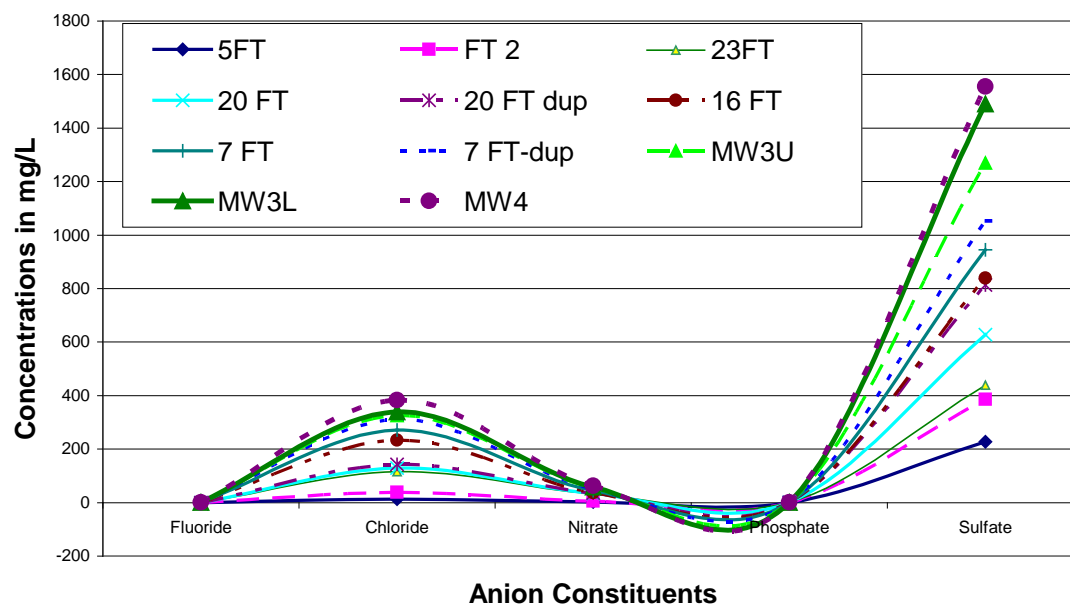


Figure 5-22: Anion (IC) Analysis of FT Drinking-Water and Monitoring Wells

The average concentrations of anion constituents of drinking-water in Frisco Terrace included:

- The Sulfates in FT averaged a concentration value of 131.58 mg/L with a range from 24.5 to 228. The EPA regulatory limit is 250 mg/L, so all the drinking-water samples fell within regulatory range for Sulfates.

There was again, no significant difference between the drinking water well constituent concentrations and the monitoring well concentrations for the anion analysis of April 2003.

The drinking-waters from BRE (i.e. along Pennsylvania Creek) are similar to the waters seen in Frisco Terrace with respect to which of the constituents depicted elevated concentrations in their water chemistries. Elevated results are seen in Ca, K, Mg, Na, and S. The values for sampling location #19PC are substantially higher for all the elevated constituent levels, than seen in the concentration values derived from the drinking-water samples taken from the surrounding homes on the same sampling day.

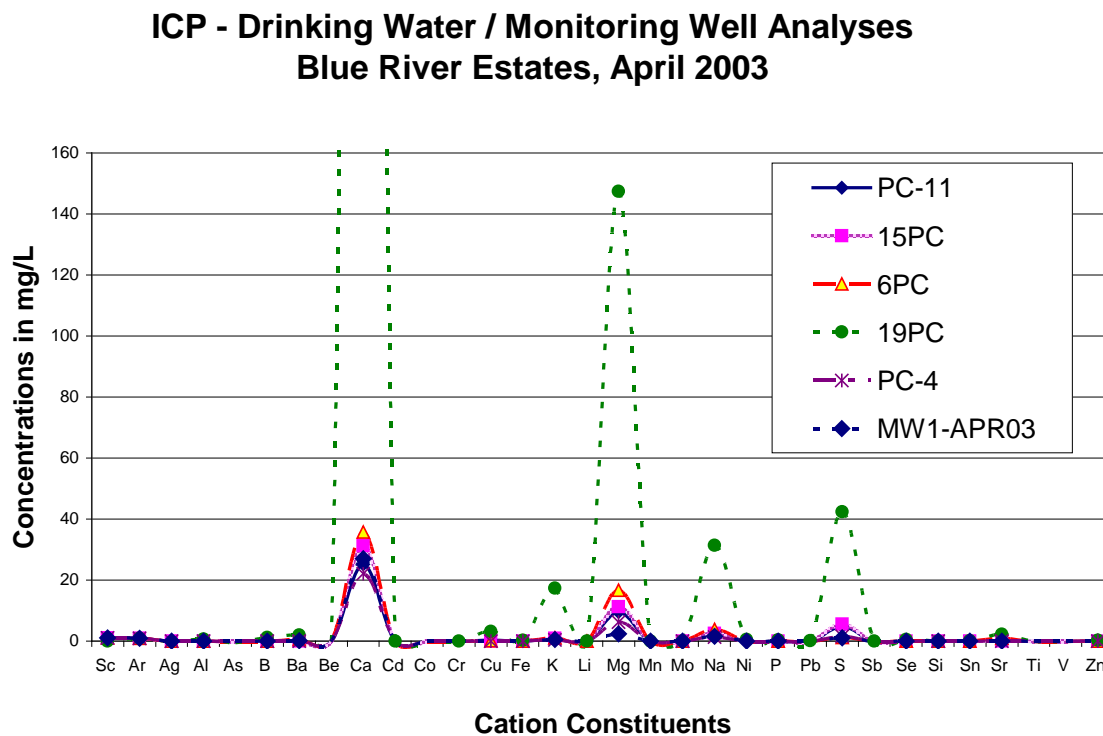


Figure 5-23: Cation (ICP) Analysis of BRE Drinking-Water / Monitoring Wells

The cation values for the drinking-water samples from BRE included elevated concentrations of:

- Calcium (Ca). All samples displayed elevated concentrations with all but 19PC falling within the range of 22-35 mg/L. Sample number 19PC depicted a value of 701 mg/L. While the EPA does not have a set MCL for Ca, this extremely high number should be investigated and re-sampled, as the value may be a result of a laboratory inconsistency or other anomaly.
- Potassium (K). Only 19PC depicts elevated levels of K at 17 mg/L.
- Magnesium (Mg). All samples in this system displayed elevated levels of Mg. With the exception of 19PC which had a concentration of 147 mg/L, the other samples ranged from 6 to 16 mg/L Mg.
- Sodium (Na). 19PC again displayed the highest concentrations for this sample set at 31 mg/L, while the other samples ranged between 1 and 2 mg/L Na.
- Sulfur (S). Sulfur is another constituent for which PC19 has the most elevated composition at 42 mg/L S. The other water samples range between 1-5 mg/L.

There does not appear to be a differentiation between the cation concentrations in the drinking water samples vs. the monitoring well samples with respect to concentrations of constituents. Monitoring well and drinking water wells plot along the same trend lines, (see Figures 5-22 for the cations and 5-23 for the anion comparisons).

The average concentrations of anion constituents in the drinking-water samples collected from the Blue River Estates, was consistently much lower in general than in Frisco Terrace.

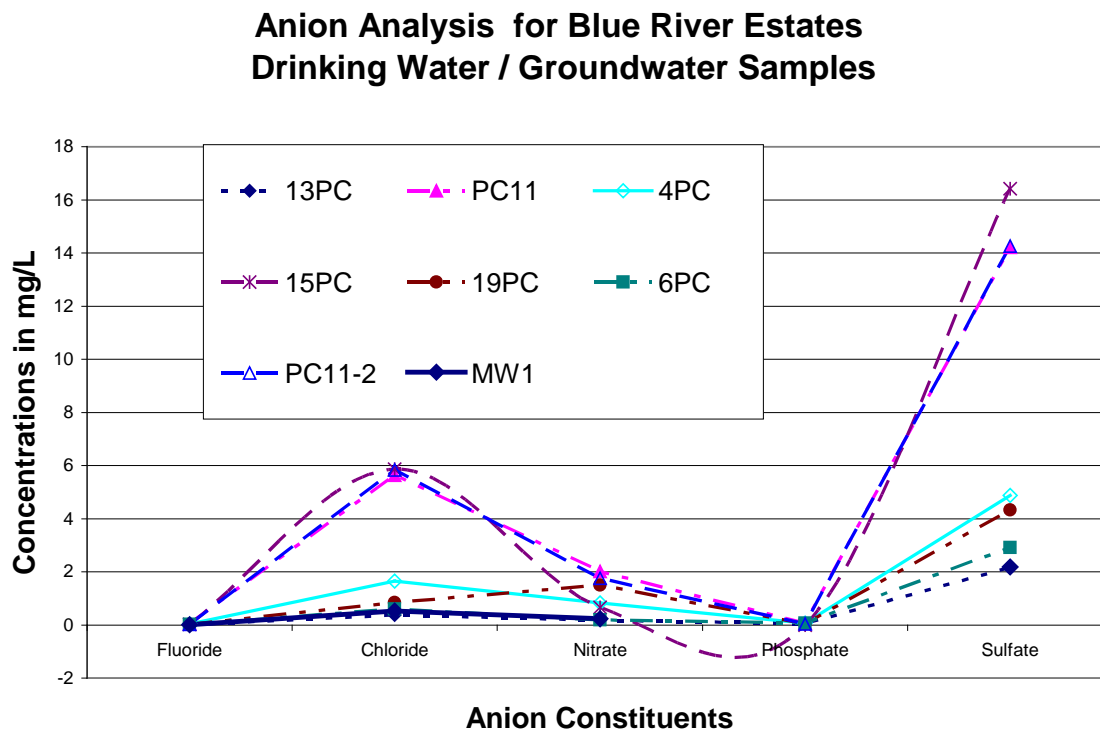


Figure 5-24: Anion Analysis of BRE Drinking-water and Monitoring Wells

These BRE values included:

- Fluoride, averaging 0.028 mg/L, with a range of 0.005-0.05 mg/L. MCL is 4 mg/L. These samples are well below that level.

- Phosphate, averaged 0.13 mg/L with a range of 0 to 0.6 mg/L. This is the only anion that was slightly higher at BRE. (FT averaged .068 mg/L). Regardless, these trace levels are not a concern for general water quality regulatory limits.
- Nitrates averaged 1.22 mg/L ranging from 0.177 – 2 mg/L. With an EPA MCL regulatory limit of 10 mg/L, there are no elevated nitrate values of concern in this suite of water samples from BRE.
- Chloride averaged 3.73g/L with a range of 0.37-5.8 mg/L. The regulatory limit is a much higher concentration of 250 mg/L.
- Sulfates averaged 10.19 mg/L with a range from 2.1 to 16.42 mg/L. The EPA regulatory limit is much higher at 250 mg/L.

There was no discernable difference between MW1 and the drinking water wells sampled during this April 2003 sampling event. MW2 was not sampled due to an inability to locate it under the multiple feet of snow accumulation in the open area where it is located.

5.4.4 April 2003 Groundwater Summary (Drinking Water & Monitoring Wells)

There does not appear to be any separation between the data derived in the drinking water wells in April 2003 versus the monitoring well data collected on the same date. The drinking water samples seem to fall closely around the monitoring well data with the exception of PC19 mentioned before as a potentially locally impacted anomaly in this data set. It appears that the monitoring well concentration values can be used as general water quality data for these sites of interest with little deviation from accuracy.

CHAPTER 6: GEOCHEMICAL MANIPULATION AND WATERSHED SCALE EVALUATION OF WATER CHEMISTRY.

6.1 Introduction

Water chemistry from both the groundwater analyses and the surface water analyses were combined in this manipulation. The first technique performed was a charge balance on all the available data. A charge balance is used to check validity of the analytical procedures and the data results. Once the charge balancing was completed, any water sample that met or was less than the $\pm 10\%$ of balancing, was used for further analysis. Additional analysis was performed using the PHREEQC geochemical modeling program. In this modeling assessment, the water quality parameters derived from sampling are first speciated and saturation indices are calculated. Using the saturation indices and the known mineralogy of the study area, inverse modeling was performed to try and identify the rock/water interactions responsible for the observed water chemistry. Then samples were compared from throughout the watershed.

Analysis of hydro-chemical data was made using Piper or Stiff diagrams, or by using a Scholler Plot. Whichever technique is utilized, the goal is still the same. To characterize the water chemistry in a fashion that allows for the visual representation of differences between concentrations of key components in the waters. It is expected that chemicals in surface water samples will be less concentrated than the groundwater due to lower contact time, but if the groundwater and surface water systems are connected, these connections should be revealed in the plots.

6.2 Water Chemistry Methods and Analysis

To charge-balance the water chemistry the main constituents comprising natural waters were converted from mass units to equivalents. The cations assessed included K, Na, Ca, and Mg values. The anions included alkalinity, sulfate, chloride, fluoride, nitrate, and phosphate values. A charge balance percentage was then derived using the formula:

$$\text{Charge Balance} = ((\text{Cations} - \text{Anions}) / (\text{Cations} + \text{Anions})) * 100. \quad (6-1)$$

Out of 75 complete groundwater sample sets (not including blanks), collected monthly from the monitoring wells in Summit County over the time period of February 2002 through April 2003, only 25 (33%) of the samples charge balanced to within + or - 10%. It is noted that samples from a given analytical suite, run at the same time, typically passed the charge balance test as a group. In contrast, the samples that did not pass the charge balancing evaluations were typically from the groups of samples that were analyzed at the same time as well. This indicates that equipment malfunction may explain the inconsistent charge balance results. The samples which passed the charge balancing quality assurance test consistently included collected in: February 2002, August 2002, September 2002, December 2002, January 2003, March 2003, and April 2003.

Scholler Plots were made by graphically representing the constituents of these 25 remaining groundwater sample sets. The initial Scholler plot of all 25 samples is included below in figure 6-1. It is clear that groundwater in this study falls into 3 distinct groupings. One group contains samples MW1 and MW2 from BRE, depicting water chemistry with moderate HCO_3 , but otherwise consistently very low anions. The second

group was comprised of groundwater from MW3 Upper and Lower. This water is markedly different from the other groupings due to the much higher levels of sulfate. The third group is comprised also of moderate HCO_3 values, but also contains moderate sulfates and chlorides. The cations in all of these water samples are generally similar with low K and Na and higher Ca and Mg.

6.3 Results and Discussion

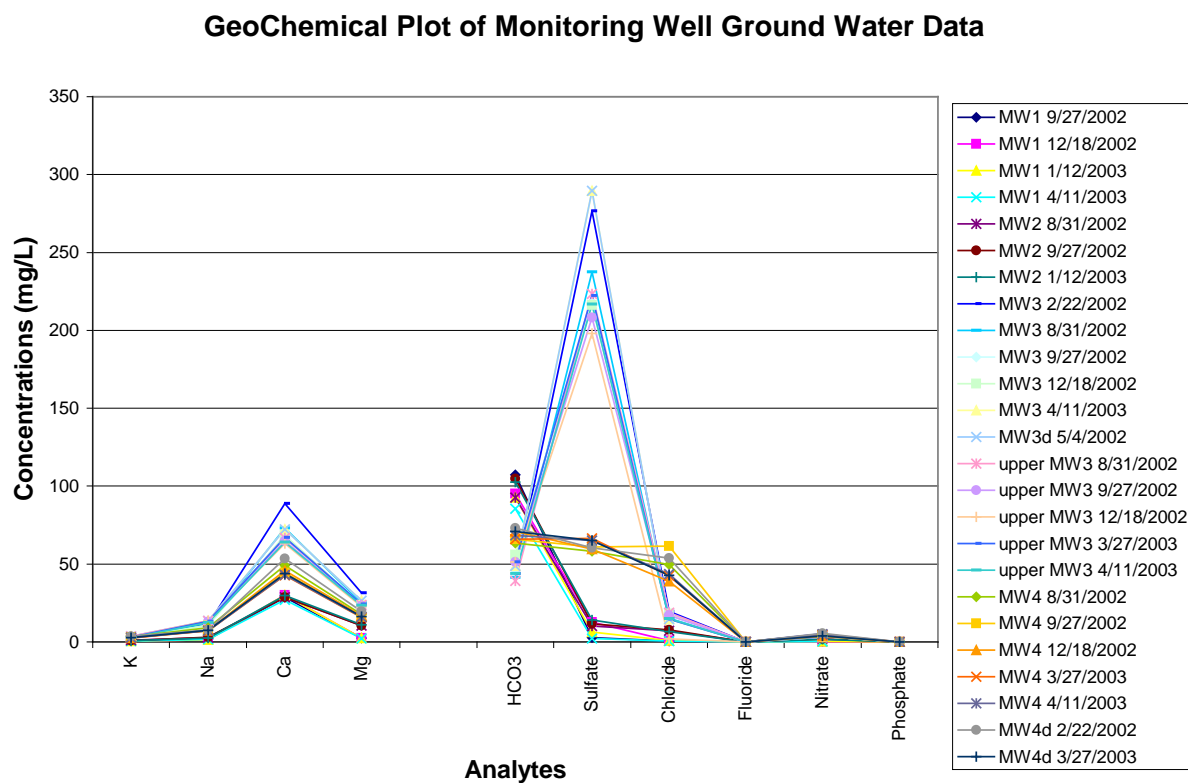


Figure 6-1: Geochemical Evaluation of the Monitoring Well Data

6.3.1 Surface Water and Groundwater Data Comparisons

The 25 groundwater samples defined above were added to 62 charge balanced surface water samples, derived from data collected by Guelfo 2003 at similar and additional sample locations in this watershed along the Blue River and its tributaries. (See Figure 6-2).

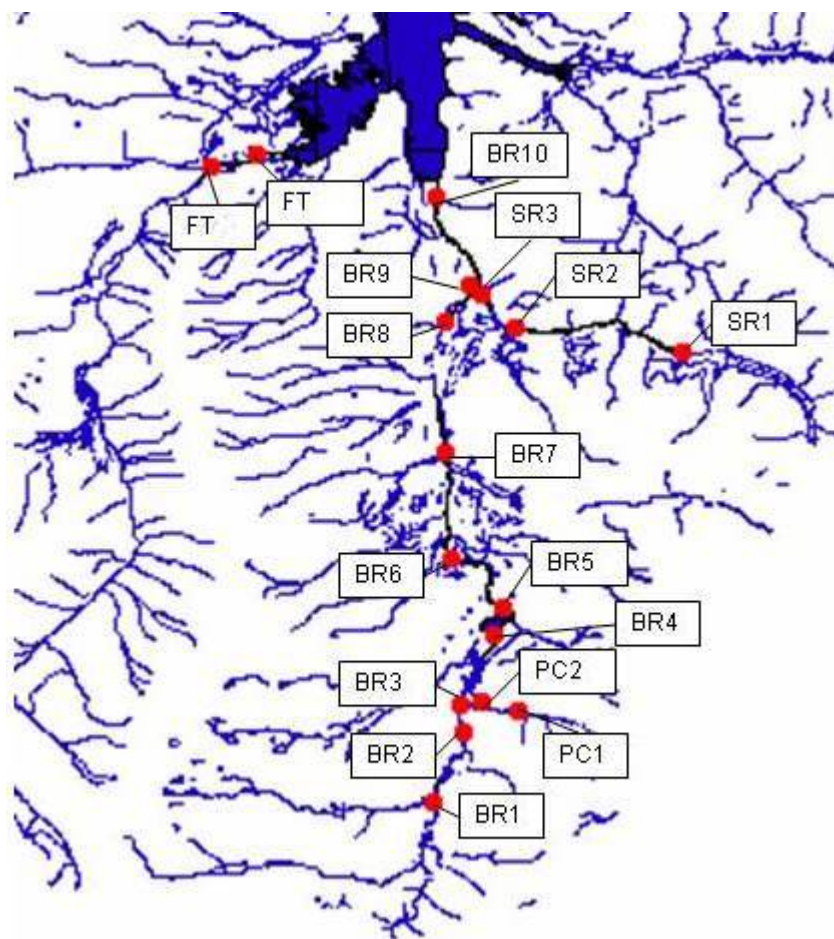


Figure 6-2: Surface Water Sampling Locations from (Guelfo 2003).

Guelfo's data originally was comprised of 155 samples. A total of 40% of the surface water samples originally collected for this project were able to be charge balanced. The results for the surface water reflect a trend similar to the groundwater data, (refer to Figure 6-3) where if one sample from an analysis suite (a group that was sent to the lab all together) passes charge balancing, then the majority of the other suite members did also. This again suggests that the source of these errors lie with in laboratory analytical procedures.

The 62 surface water samples in this group were collected along the Blue River drainage between September 2001 and August 2002 (Guelfo, 2003). There was a sampling overlap from February 2002 through August 2002, when both surface water and groundwater were being evaluated. A total of 24 charge balanced samples were collected during the time frame when both surface water and groundwater was being collected from Summit County. As was discussed in Chapter 5, temporal analysis of the datasets showed that the samples from the same location had very little monthly or even seasonal variations, but the samples did show significant spatial variations. Based on Na, K, Ca, Mg, HCO₃, SO₄, Cl, F and NO₃ data, all 87 of the surface water and the groundwater samples from (Guelfo, 2003) were plotted as was done above for the groundwater data alone. A larger version of this figure will be included in the appendices, but for rough evaluation it is also included here.

This plot shows six distinct groups of water. These groups were arbitrarily numbered 1 through 6. The full suite of data is listed in appendix D. The table in Appendix D is organized into the groupings addressed in the following text and lists the main constituents that were examined during the following geochemical evaluations. Table 6-1 addresses the statistical information of the groups, which were organized in appendix D

Table 6-1: Statistical Evaluation of the 6 Geochemical Groupings

		K	Na	Ca	Mg	HCO 3	SO4	Cl	F	NO3	P	TDS calc.
Group 1 n = 10 mean pH = 8.1	mean	0.41	1.6	25.7	2.3	84.8	3.5	0.62	0.02	0.14	0.05	119
	max	0.58	2.2	31.4	3.1	107.4	12.7	1.78	0.08	0.37	0.09	144
	min	0.28	1.3	20.2	1.9	58.6	1.5	0.28	0.01	0.02	0.02	84
	avedev	0.08	0.2	3.7	0.3	10.7	2.4	0.33	0.02	0.08	0.02	18
Group 2 n = 35 mean pH = 7.8	mean	0.90	3.40	24.34	6.65	75.36	15.39	5.88	0.05	0.49	0.03	131
	max	1.59	5.75	41.23	11.22	109.80	32.67	9.62	0.10	2.30	0.07	199
	min	0.58	2.07	18.69	4.31	48.80	7.81	3.33	0.01	0.03	0.01	97
	avedev	-0.21	-0.77	-3.25	-1.36	-12.12	-4.44	-1.62	-0.02	-0.49	-0.02	-16
Group 3 n = 3 mean pH = 8.2	mean	0.98	2.4	26.4	4.4	48.0	37.7	2.49	0.05	0.08		122
	max	1.02	2.6	29.8	4.5	52.5	45.1	2.77	0.05	0.11		137
	min	0.96	2.2	23.3	4.3	40.3	31.6	2.35	0.05	0.05		106
	avedev	-0.03	-0.1	-2.3	-0.1	-5.2	-4.9	-0.19	0.00	-0.02		-11
Group 4 n = 7 mean pH = 7.6	mean	0.85	2.1	19.6	4.0	64.3	17.3	0.66	0.06	0.06		109
	max	1.44	4.0	44.1	9.6	141.5	31.8	1.86	0.12	0.17		235
	min	0.44	0.8	10.3	1.9	30.5	13.0	0.27	0.01	0.00		57
	avedev	-0.18	-0.6	-7.0	-1.6	-24.4	-4.2	-0.38	-0.03	-0.04		-37
Group 5 n = 26 mean pH = 7.4	mean	7.44	11.9	128.7	17.4	53.3	320.6	14.17	1.01	2.34	0.04	571
	max	21.78	19.4	451.6	31.4	85.4	932.5	48.56	3.29	14.34	0.09	1505
	min	2.53	6.6	63.2	5.5	39.0	174.3	1.84	0.01	0.22	0.00	337
	avedev	-4.61	-2.5	70.36	-8.3	-8.5	-139.4	-5.85	-0.87	-2.06	-0.03	-224
Group 6 n = 8 mean pH = 6.7	mean	3.02	7.7	47.4	17.4	69.5	62.1	48.4	0.02	4.69	0.09	260
	max	3.79	9.2	57.0	20.9	78.1	66.5	61.6	0.06	5.63	0.14	288
	min	2.53	7.2	42.7	15.8	63.4	58.2	38.9	0.01	3.68	0.03	246
	avedev	-0.41	-0.5	-4.3	-1.5	-3.66	-2.63	-6.43	-0.02	-0.58	-0.03	-12

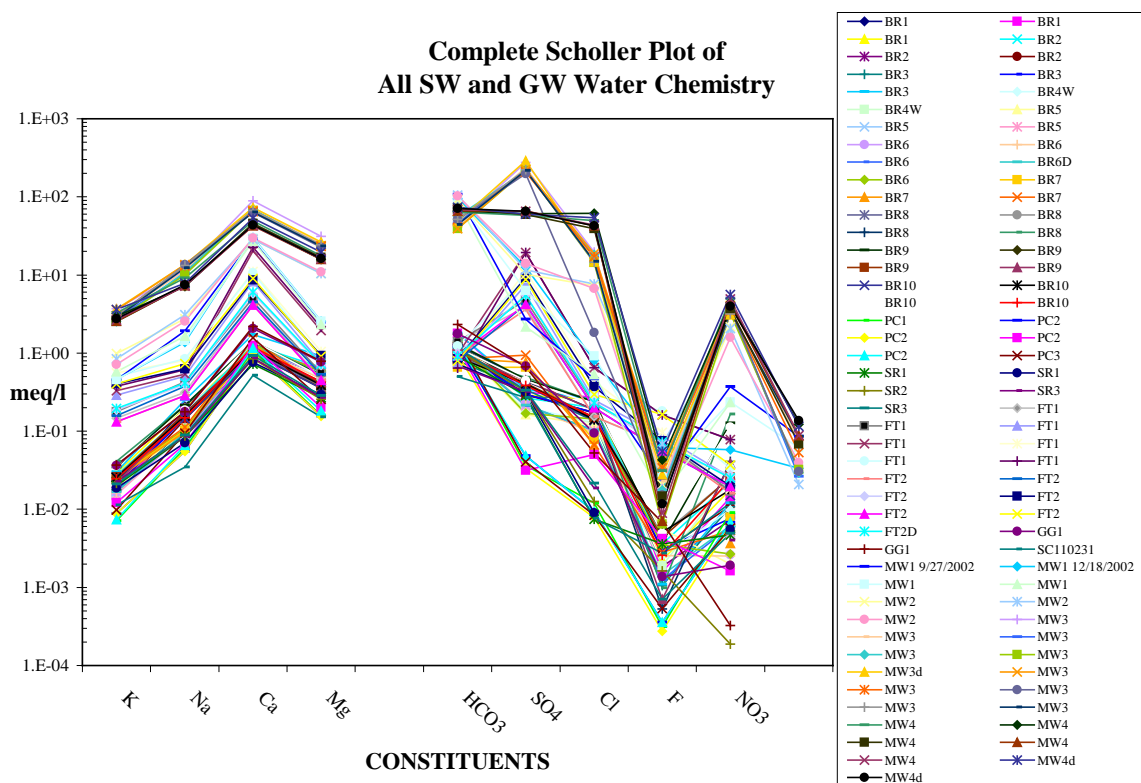


Figure 6-3: Schoeller Plot of Surface Water / Groundwater Samples

These 87 individual samples were grouped visually based on their constituent trends. The 87 plots were consolidated into six trend lines, with the average of each group plotted.

The “Group 1” samples are derived from the Pennsylvania Creek and MW-1. The water is primarily composed of Ca and HCO₃ with low total dissolved solids (TDS). These traits are typical of natural un-impacted mountain drainage waters. The chemical signature seen in group 1 was considered to be “background” for the Blue River drainage, without any significant anthropogenic influences. The similarity of the surface and well

water chemistry strongly suggests that the groundwater in MW-1 and the local surface water are hydraulically connected.

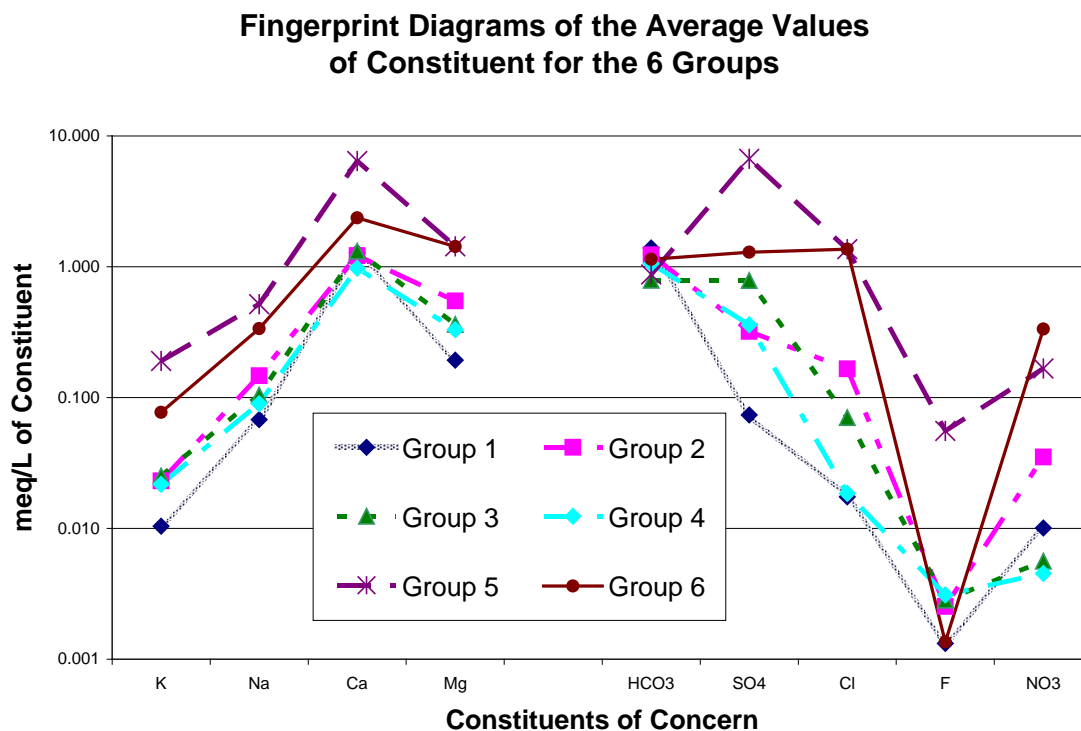


Figure 6-4: General Geochemical Groups

“Group 2” samples are derived from a length of the upper Blue River and monitoring well, MW-2. These samples have slightly higher TDS and are also primarily composed of Ca and HCO₃ like Group 1, but have higher concentrations of SO₄, Cl and NO₃. Chloride and nitrate are anthropogenic indicators, consistent with the fact that the river flows through the towns of Blue River and Breckenridge. Sulfate can be

anthropogenic, but is mainly derived from mineralized rocks and mine tailings. The similarity of the surface and MW-2 water chemistry indicates that the groundwater sampled by MW-2 and the Blue River water are hydraulically connected

“Group 3” has only surface water samples in it, all taken from the confluence of French Gulch and Blue River. French Gulch, west of Breckenridge, drains a series of old mine workings. The group 3 samples are mostly composed of Ca and HCO_3 , but have elevated SO_4 concentrations and low Cl values. The Cl values are still within the range that is consistent with normal background water.

“Group 4” samples are from the Swan River drainage and are also completely comprised of surface water samples. The confluence between the Blue River and Swan River is downstream from French Gulch. The chemistry of the Swan River samples is very similar to those of group 1, with low TDS and the solutes are primarily composed of Ca and HCO_3 , normal background for the area. This is supported by the hydraulic head information described earlier, which showed that groundwater was generally flowing toward the stream system, although conditions during the past year suggest that the stream can recharge the groundwater system during dry periods.

“Group 5” samples are from the FT area and include surface water samples from North Tenmile Creek as well as groundwater samples from well MW3 (both Upper and Lower zones). These samples have much higher TDS, with significantly elevated SO_4 and higher Cl and NO_3 concentrations. This aqueous chemistry is interpreted as a combination of anthropogenic input and mine tailings influence. The elevated SO_4 concentrations are coupled with somewhat lower pH values in these samples, a definite indicator of sulfide ore rock interaction. In addition, these elevated sulfate values are also coupled with elevated trace metals such as Mn, Mo, Sr, Sn and Zn (Figure 6-4). The similarity of the surface and groundwater chemistry from both Ten Mile Creek and the local well, MW-3, indicates that the well and the local surface water are hydraulically

connected. Based on the hydraulic information discussed previously in this study, it is likely that the stream in this area has been recharging the groundwater over the past year.

“Group 6” consists of groundwater samples collected from well MW-4, which is located near MW#3, but is more squarely within the FT development. In spite of the spatial proximity to N. Tenmile Creek and MW-3, MW-4 has a distinct chemistry with lower TDS and SO_4 , but higher Cl and NO_3 . This distinct chemical signature would indicate that the groundwater sampled by the well is not as well-connected to the local surface water system which was sampled by Guelfo 2003. It is possible that the groundwater sampled within this well may be similar initially to the groundwater described in Group 5 and found at MW-3, but is impacted by soil-treated wastewater recharge within this high home-density area. The dilution effects from increased recharge to the overall system from OWSs in the vicinity would explain the lower TDS and SO_4 found in this water grouping, as well as the increased NO_3 and Cl. More detailed geochemical and hydrological modeling is required to fully understand the groundwater and chemical mixing that may be occurring in this area.

The groups defined above are spatially located as described in Figure 6-5 below. Group 1 is found at the highest point in the watershed, up Pennsylvania Creek. Group 2 is located at the confluence of Pennsylvania Creek and Blue River, including MW2 and the waters from Blue River up gradient and partially down gradient from the confluence. Group 3 is surface water only, collected near Breckinridge. Group 4 is also a surface water group only, with waters derived from Swan Creek. Both groups 5 and 6 are located in FT. It is reasonable that the chemistry of these waters alters as it progresses down the watershed. As more inputs are joined to the system, the water will reflect the chemical changes caused by additions into the water system from additional surface water bodies or other water outputs like wastewater treatment plants or OWS systems.

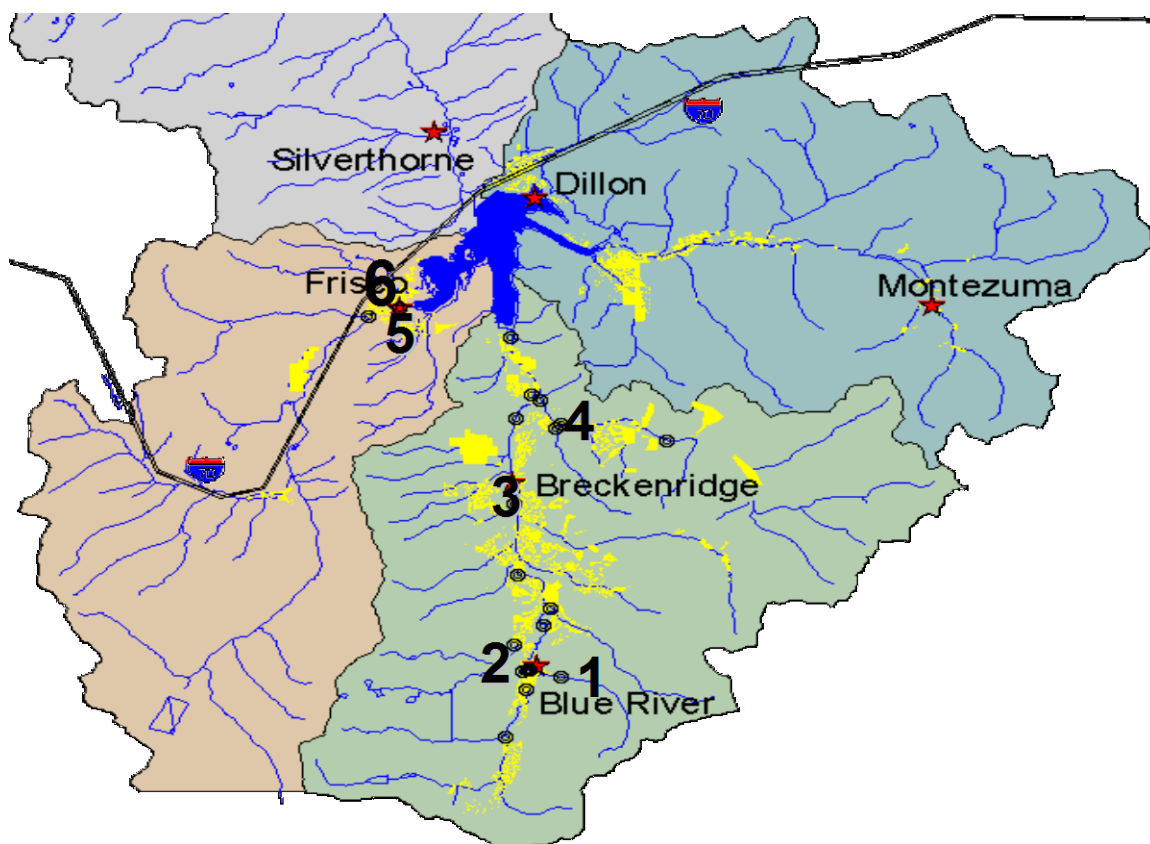


Figure 6-5: Spatially Referenced Geochemical Grouping Locations

6.3.2 Geochemical Modeling – PHREEQC

PHREEQC is a geochemical modeling tool that was used in this assessment to define the natural system of this watershed. Charge balanced water chemistry is modeled using PHREEQC to determine if natural precipitation passing through the mineral assemblages found in the natural geologic system of this area can produce the water chemistry from our field samples without the additional input of anthropogenic sources. The saturation indices for the water samples were also used to check if the models described by PHREEQC were realistic.

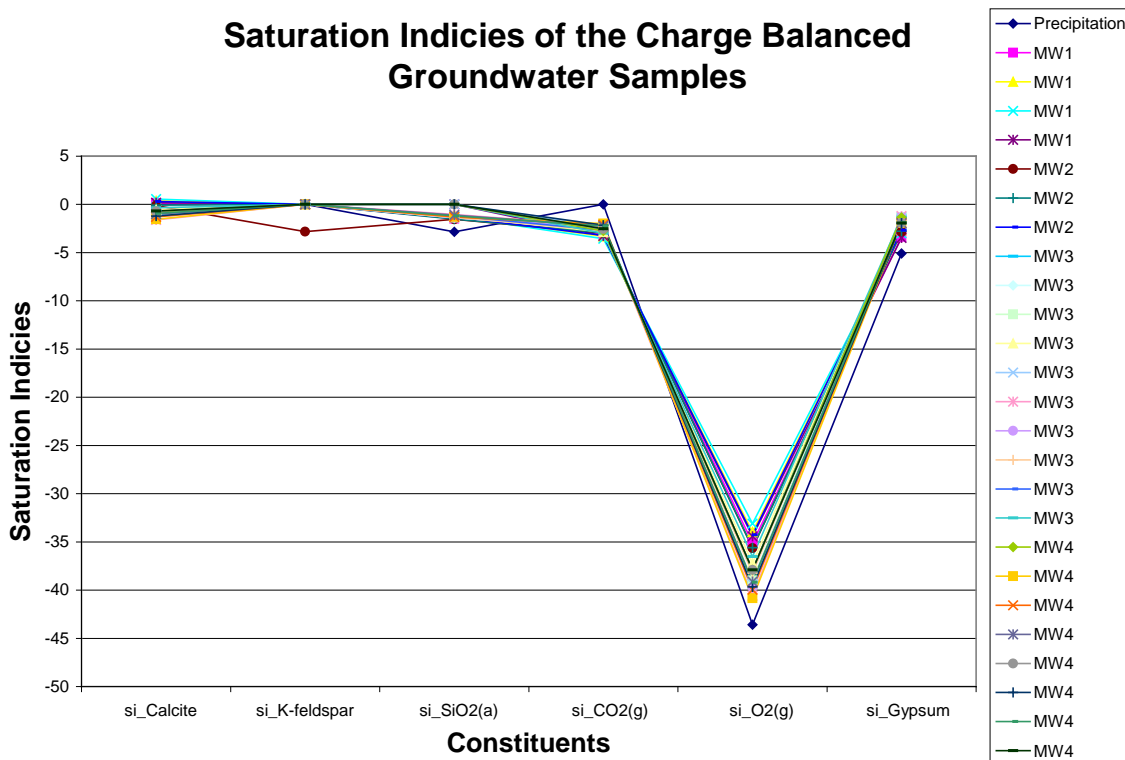


Figure 6-6: Saturation Indices of the Charge Balanced Groundwater Samples

The saturation indices for the water samples indicate that (with zero (0) being saturated), these minerals are close to being saturated in this system. Biotite, pyrite, and hornblende were not included in this plot because with values at -999 , they were very under-saturated. The negative values in this output indicate the varying degrees of under-saturation of the minerals from this system. The background waters in this system are not saturated with any of the modeled minerals in this system. Saturation indices of the water samples derived from all 6 groups reflected under-saturated conditions (i.e. conditions capable of dissolving these minerals). We know that there is pyrite rock in

this system, and pyrite is realistically a likely source of at least a portion of the sulfate in this system, however without good Fe data pyrite could not be included in the model.

Inverse Modeling. Inverse modeling was performed in PHREEQC as addressed in section 6.0. Inverse modeling is a tool which combines the geochemical concentrations of rain water and the mineral assemblages that we see or expect to see in the specific field area and tries to determine if these can combine and create the basic water chemistry results we have derived from the sampling events. The inverse modeling described in this section was performed on the following data table.

Table 6-3: Inverse Modeling Data for PHREEQC

Description	pH su	K mg/L	Na mg/l	Ca mg/L	Mg mg/L	C(4) mg/L	S(6) mg/L	Cl mg/L	N(5) mg/L	PO ₄ ³⁻ mg/L
Precipitation	5.9	0.41	0.43	0.84	0.19	9	1.10	0.47	0.02	0.01
Group 1	8.04	0.41	1.6	25.7	2.3	85	3.5	0.6	.141	.047
Group 2	7.82	0.9	3.37	24.4	6.65	75.4	15.4	5.88	0.49	0.03
Group 3	8.17	0.98	2.4	26.4	4.4	48	37.7	2.5	.079	0
Group 4	7.64	0.85	2.1	19.6	4.0	64	17.3	0.7	.063	0
Group 5	7.42	7.44	11.9	128.7	17.4	53.3	320.6	14.2	2.34	0.04
Group 6	6.7	3.02	7.7	47.7	17.4	70	62.1	48.4	4.69	0.09

A typical input deck used for PHREEQC inverse modeling typically consists of the following descriptions and input commands:

SOLUTION_SPREAD

-units meq/L

Number	Description	pHK	Na	Ca	Mg	C(4)	S(6)	Cl	N(5)	Phosphate
1	precipitation	5.9	0.41	0.4	0.8	0.2	1.1	0.5		
2	Group 1	8.04	0.41	1.6	25.7	2.3	853.5	0.6	0.141	0.047
3	Group 2	7.82	0.9	3.37	24.34	6.65	75.36	15.39	5.88	0.49
4	Group 3	8.17	0.98	2.4	26.4	4.4	4837.7	2.5	0.079	0
5	Group 4	7.64	0.85	2.1	19.6	4	6417.3	0.7	0.063	0
6	Group 5	7.42	7.44	11.88	128.68	17.41	53.3	320.55	14.17	2.34
7	Group 6	6.7	3.02	7.7	47.4	17.4	7062.1	48.4	4.686	0.092

SELECTED_OUTPUT

-file hes5.csv

-inverse_modeling

INVERSE_MODELING 1 2, 1 3, 1 4, 1 5, 1 6, 1 7

-minimal

-uncertainty 0.25

-phases

CO2(g)

N2(g)

O2(g)

SiO2(a)

Hornblende diss

Plagioclase diss

Calcite

Kaolinite

Halite

K-feldspar diss

Fluorite

Hydroxyapatite

Pyrite diss

Gypsum diss

Biotite diss

END

The inverse modeling derived in this thesis used precipitation falling in the watershed and naturally interacting with the rocks observed in this system to derive the chemistry of the waters sampled in Groups 1-6. The mineral assemblages selected to react with the precipitation included:

- CO₂(g)
- N₂(g) – to account for any potential nitrogen naturally introduced into the system
- O₂(g)
- SiO₂(amorphous)
- Hornblende dissolving only
- Plagioclase dissolving only
- Calcite
- Kaolinite – a clay to account for the alteration of primary minerals into clay
- Halite - derived from atmospheric input
- K-feldspar dissolving only
- Fluorite – to account for the small amounts of F in the water samples
- Hydroxyapatite – to account for the PO₄⁻³ concentrations in some of the water samples. This mineral is not likely actually found in this .
- Pyrite dissolving only
- Gypsum dissolving only
- Biotite dissolving only

Each of the average water chemistries of the 6 defined groupings (Table 6-3) as well as the typical geochemical composition of precipitation, which is assumed for this model to be the primary source of all the water in this watershed were input into this program. The precipitation chemistry is then made to react with the defined mineral assemblages (listed above) in an attempt to model what compositional input each mineral

is required to contribute to derive the chemistry of the water samples collected in the field. The graph in figure 6-7 defines which minerals are needed (dissolving or precipitating) in order to naturally create each geochemical signature for each of the groups. If the results are positive then the mineral would be precipitating, and if the results are negative then the mineral is dissolving. The magnitude of the number indicates how great a quantity must be dissolved or precipitated.

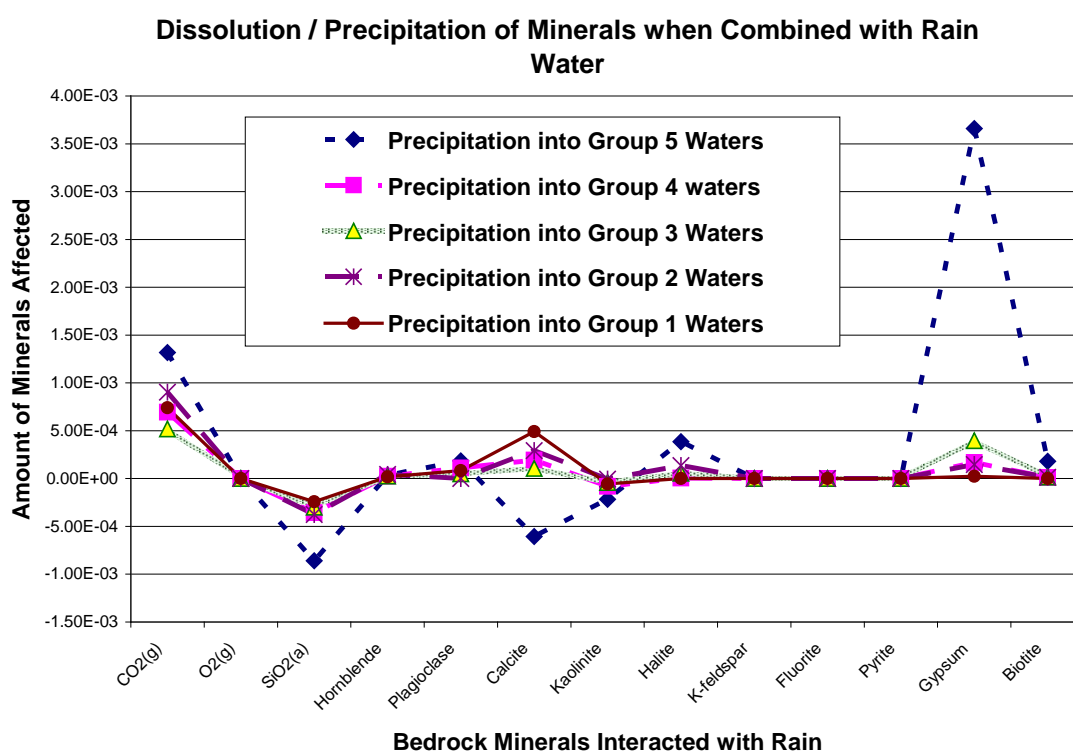


Figure 6-7: Dissolution and Precipitation of Minerals in PHREEQC

In order for the geochemistry reflected in Group 1 to be derived naturally, this inverse model predicts that amorphous SiO₂ must be precipitated and CO₂(g) and calcite are dissolving.

Group 2 waters can be created if amorphous SiO₂ is being precipitated and CO₂(g), calcite, halite, and gypsum are being dissolved. This system was modeled without the nitrate and phosphate found in the sampled geochemistry, as there are no nitrate or phosphate bearing minerals among the source rocks.

Groups 3 and 4 can also be created with the mineral system in this watershed. Their water chemistries were able to be completely defined by rock-water interactions, with the exception of the trace amounts of nitrate observed in both these groups.

Group 5 needs the greatest input of gypsum to explain the elevated sulfate levels observed in its waters. Realistically, this is likely derived from pyrite and other ore bearing minerals found in the watershed, which are unable to be modeled due to a lack of additional trace metals inputs (Fe) for the water samples. Group 5 was only able to be modeled by not including the nitrate and phosphate, as they are not accounted for in the natural mineralogy of the source rocks that were identified in this watershed. Thus, nitrate and phosphate are assumed to be a result of anthropogenic influence in these waters.

Group 6 was unable to be modeled, due to the high concentrations of chloride in this sample group. Nitrate and phosphate was also not able to be attributed to the natural system. Group 6 is comprised entirely of groundwater collected from MW4. The nitrate and phosphate could be derived from the same source as the additional chloride, as they are all potentially representative constituents of wastewaters. Whatever the source of the impacts, the water in Group 6 could not be described in this model, solely through the interaction of precipitation with the defined natural rock systems in the area. This suggests non-native sources for these components.

As it turns out, the samples with elevated Sulfates and Nitrates are not effectively modeled by the natural rock systems that PHREEQC evaluates, and as a result it can be interpreted that system is being affected by external inputs as was theorized previously in this paper (potentially mining impacts or wastewater impacts).

CHAPTER 7: CONCLUSIONS

The overall purpose of this research was look at data that might be typically available for any given watershed and determine if it is possible to characterize the groundwater aquifer physically, chemically and hydraulically with respect to OWS pollutants. Clearly, a broad scale analysis was possible, and could be beneficial for watershed managers, city planners and others interested in broad scale watershed management issues. Data such as hydrological engineering parameters and aquifer characterization values are derivable in general terms from existing data.

Specifically this work on the Blue River Watershed in Summit County Colorado, was evaluated with a goal to examine if OWS pollutants could be impacting the Dillon Reservoir, (a key water storage facility for Denver Water, which provides drinking water resources to the city of Denver). Blue River specific information derived in this research is as follows:

The groundwater in the Blue River Watershed is located with in an unconfined, glacially derived, sandy aquifer. Physically, in this coarse-grained lithologic environment, there is no aquitard or other continuous confining unit seen or documented that would separate surface water from groundwater. Since conditions exist that facilitate groundwater and surface water interaction throughout this watershed, surface water conditions also became important to evaluate in comparison with the groundwater data collected through this research. Hydraulic head information at BRE and FT indicates that the surface water in these areas during this investigation, was feeding the local groundwater. Since OWS discharges in the subsurface and the flow direction of the water in this research is down, from the surface water to the groundwater, it is not likely that OWS pollutants are traveling counter to the preferential flow of the groundwater and

getting into the surface water system. OWS pollutants in these instances would travel deeper into the soils towards the groundwater system. While ultimately the outfall of the groundwater is: in FT, Dillon Reservoir, and in BRE, Goose Pasture Tarn, which ultimately flows as surface water to Dillon Reservoir. The flow paths through which the potential contaminates must follow through the subsurface to reach the surface water however, are extensive. See Figures 3-1 and 3-2. This allows a long treatment period for the potential contaminants by the soils in the subsurface. The period of migration of the potential OWS contaminants through the subsurface is significant because the time required for the pollutants to reach the surface water bodies and thus the outfall of Lake Dillon, increases exponentially from the transport times that would have been seen if pollutants moved just through the surface water system. The longer the “pollutants” are in the subsurface, the more they are treated through soil interactions, decreasing the levels of constituents of concern such as P and N.

Basic chemical analyses indicate that total dissolved solids, chemicals and nutrient concentrations increase as spatial approximation to the watershed discharge point (i.e. The Dillon Reservoir) decreases. Generally, MW2 in BRE located down gradient of the community shows impact when compared to groundwater collected at the background well (MW1). FT shows considerably more impact from anthropogenic sources than BRE. This could be due to older OWS’s at FT, the cumulative effects of the entire upstream watershed discharging at FT, or some combination of both coupled with what appears to be specific impacts from the historic mining activities in the vicinity of FT.

The drinking water analyses tentatively confirm the validity of the chemical constituent concentrations found in the monitoring well samples, as they were similar to the temporal data collected in the monitoring wells. Geochemical analysis of the drinking water well samples indicated that the water quality at BRE is consistently well below the MCL values the EPA sets for chemical drinking water standards. The central

location of the home sampled with ID # 19PC which depicted elevated concentrations of constituents when compared to the surrounding homes in the development may suggest either analytical difficulties, sample contamination, or that even though the results are lower than the EPA MCL guidelines, additional development up-gradient of the flow path of the groundwater, may impact some of the homes closer to the outfall of the system. Additional evaluation of this home and surrounding wells is advised. The drinking water analysis of FT homes also depicted values of constituents that were lower than the EPA's MCL regulations in all but one component with a significant number of FT wells depicting sulfate concentrations near the regulatory limit of 250 mg/L.

Geochemical fingerprint analysis confirms that the groundwater and the surface waters are connected in this watershed, and that the signature of the water from FT shows a clear impact from anthropogenic activities presumed to include OWS (N and Cl) and mining (sulfate).

Finally, this study and these data comparisons, have demonstrated that groundwater information from the CSEO well logs is useful to a limited extent in lieu of detailed monitoring-well data. These CSEO data are also likely to be very useful when initially designing a more comprehensive monitoring plan. A general methodology for assessing groundwater parameters in any given watershed is outlined in section 8.2 of this document. Deriving groundwater information is imperative in adequately defining potential impacts of any anthropogenic influence of concern on a watershed system. The integration of chemical and hydraulic data from groundwater as well as the more standard information derived from surface samples, when combined with the existing data such as CSEO logs, offers a picture of hydraulic and chemical properties of any hydrologic system that would satisfy the needs of most land use planners or developers, particularly at the watershed scale. Incorporating groundwater data need not be cost prohibitive if

existing data may be utilized, and its absence in a planning document or model which addresses water quality and land use proposals should be noted as a potential liability.

CHAPTER 8: RECOMENDATIONS FOR FUTURE STUDY

8.1 Future Work

This characterization of the physical hydraulics and geochemical assessment of the groundwater in Summit County Colorado, combined with the preliminary surface water groundwater interaction evaluation for the Blue River Watershed, Summit County, Colorado, has provided the frame work which additional investigations can use to further evaluate the Blue River Watershed. Some of the possible future work in this watershed may include:

- Advanced evaluation of hydraulic flow in this watershed
 - Consistent same day evaluations using GPS of surface water and groundwater levels to facilitate accurate elevation and flow direction assessments
 - Additional installations of piezometers near the existing “monitoring wells” to define flow direction utilizing 3 point problem equations. Well points can be simply direct push points so no complete well constructions are required.
- Additional Testing of the Sorption Capacities of the soils specific to this watershed for the specific constituents of concern
- Performance of a large scale tracer test with input starting at the septic systems running through a flow zone with piezometers installed consistently at regular intervals down gradient in the watershed, to monitor the rate of progression of the tracer through the sub-surface.

- Use both a conservative tracer, which does not interact with soils typically (such as the pharmaceuticals and anthropogenic pollutants such as B or Cl), as well as a tracer that would interact with the environment like N and P do as they progress not only through the leach field but through the watershed as well.
- Evaluate Physical properties of the watershed during a time when it is not a drought condition. This research has all been performed during a period of intense drought in Summit County, Colorado as well as throughout the entire West. Follow up work in June of 2003 presented conditions where water was actually in the upper piezometer points at MW1 and MW2. Flow direction conditions may actually change in a non-drought season.
 - Decreased input to the hydraulic systems here may have converted stretches of these streams from gaining to losing.
 - Groundwater may have had different concentrations of contaminants due to less dilution due to added surface water inputs into the groundwater system.
 - An evaluation of water characteristics during a “wet year”, similar to this characterization study would be interesting, facilitating the comparison of these parameters of concern, during periods of differing precipitation input.

8.2 General Methodology - Watershed Scale Groundwater Assessment

- Existing Data Evaluation
 - Review USGS Geological Maps to determine the general geological formations in the area of interest.
 - Information such as generalized overburden thicknesses or source rock material (i.e. glacially derived overburden, etc.) may also be included here.
 - State Engineer Logs
 - Including well installation logs or pump installation logs
 - Research documents on the areas of interest
 - University thesis documents for example are great sources
 - Topographic Maps to get an idea of the general layout of river locations and wetland areas.
 - Soil Surveys, typically put together by the US Department of Agriculture to define soil types and uses.
 - Test well information from commercial environmental consulting companies monitoring gas stations or other businesses in the areas of interest.
 - USGS NAQWA data sets or other Federal watershed evaluation program data that may be applicable to the area of interest.

- Additional Informational Sources
 - Collect drinking water well samples from the community in the area of interest.

- If additional information is required, or access issues prohibit repetitive sampling of community drinking water samples, install monitoring wells.
 - Perform both Anion and Cation analysis as well as field assessments of Temperature, Specific Conductivity, Dissolved Oxygen, pH, and Turbidity.
 - Fecal coliform assessments should be run periodically during the sampling to check specifically for OWS impacts.
-
- A compilation of these 2 data sources provide an adequate general methodology for analysis of a groundwater in a watershed of interest. Parameters including depth to water, basic flow regime, subsurface lithology, water quality and hydraulic conductivity are integral for incorporation into modeling and decision making programs.

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