ENVIRONMENTAL CONFLICT AT THE ENERGY-WATER NEXUS

by

ADRIANNE KROEPSCH

B.A., Cornell University, 2003

A thesis submitted to the

Faculty of the Graduate School of the

University of Colorado in partial fulfillment

of the requirement for the degree of

Master of Arts

Department of Geography

2011

This thesis entitled:
Environmental Conflict at the Energy-Water Nexus
written by Adrianne Kroepsch
has been approved for the Department of Geography

____
Mark W. Williams, PhD

____
Patricia Limerick, PhD

____
William Travis, PhD

Date______________

The final copy of this thesis has been examined by the signatories, and we
Find that both the content and the form meet acceptable presentation standards
Of scholarly work in the above mentioned discipline.

Adrianne Kroepsch (M.A., Geography)
Environmental Conflict at the Energy-Water Nexus
Thesis directed by Professor Mark W. Williams

ABSTRACT

The present disagreements over natural gas development in the United States and abroad are currently being described as the next environmental "superdebate" – on par at least with contention over acid rain in earlier decades and at most with altercations over climate change in more recent years (Byrne, 2011). Natural gas development is controversial for a number of environmental reasons; among them, the potential harm done to groundwater systems by way of aquifer drawdown or contamination (EPA, 2011). The possibility of these harms puts society squarely in the crosshairs of the "energy-water nexus"— the tightening linkage between rising energy demand and finite water supplies, and vice versa (DOE, 2006). The energy-water nexus implies conflict in its very definition, as an intersection where the use of one resource often requires use of the other. I suggest here that groundwater systems at the energy-water nexus exacerbate one particular source of conflict, known in conflict resolution literature as a factual dispute. The concealed nature of groundwater systems make them frequent subjects of factual disputes at the energy-water nexus (Narasimhan, 2009), as demonstrated here by case studies presented at regional and local geographic scales in Colorado's southern coalbed methane basins. At the regional scale, in the Northern San Juan Basin, a factual dispute is ongoing over whether groundwater withdrawals in the process of coal bed methane (CBM) extraction will impact overlying aquifers (Papadopulos, 2006; SJPLC, 2006; Riese et al., 2005). At the local scale, in the Raton Basin, a factual dispute is underway over a single landowner's domestic well, which became unusable in the days following the hydraulic fracturing of a nearby CBM well for reasons that could not be determined by regulators (COGCC, 2011d). In the analysis presented here, I discuss the major uncertainties specific to groundwater systems that exacerbate factual disputes over environmental impacts. I also present ways that academic researchers might productively engage in these disputes via fact-finding efforts. I present a neutral fact-finding effort using isotopic/geochemical tracers and a groundwater monitoring guide designed to enable joint fact-finding efforts at individual domestic well sites.

ACKNOWLEDGEMENTS

It takes a village to raise a graduate student, and I am extraordinarily grateful for the one that has built up around me since I arrived in Boulder in the autumn of 2009. I could not then have anticipated the insightful mentors and good friends that would coalesce in my life in the subsequent two-and-a-half years under the tutelage of the Chancellor's Office, to which I owe immeasurable thanks for a top-notch graduate fellowship. I am especially grateful for the guidance of my intrepid faculty advisor, Mark Williams, on what has turned out to be a fascinating research project. I am also indebted to my brilliant committee members, Bill Travis and Patty Limerick, for their thoughtful comments and contributions along the way. I owe a special thanks to Patty and the Center of the American West for bringing me aboard the Gilder Lehrman conference during the summer and giving me, in the process, far more intellectually than I could repay by way of logistical assistance. My deep appreciation also goes to Jordan VanSickle, Koren Nydick, Gary Gianniny, Chris Peltz, Marcie Bidwell and the Mountain Studies Institute writ large for their work on the Northern San Juan Basin study and support of my data analysis; to Tracy and Amy Dahl for their willingness to share the details of their domestic well case; to Guy and Heidi Burgess for their permission to sit in on various conflict resolution seminars; to the C.U. Outreach Office for two well-timed funding opportunities; and to Mark, Joe Ryan, and Wynn Martens for their insights on and dedication to the Colorado Water and Energy Research Center. My family and friends have featured centrally in my master's work as well. I owe much to the hospitality (and the espresso machines and kitchen tables) of Lou Vito in Durango and Holly and Steve Hultgren in Boulder; you have made me a lucky grad student indeed. Speaking of kitchen tables, many thanks to my parents, who do a very good job of trying to understand what it is that I'm researching and writing about, whatever it is at the time and no matter how far afield of their personal experience. And though a mere sentence does no justice, my deepest appreciation goes to Corey: your support has been unwavering, your good humor invaluable, and your advice always on target, for this adventure and, no doubt, the many others to come.

- Adrianne

CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 3

CHAPTER 4

CHAPTER 1

ENVIRONMENTAL CONFLICT AT THE ENERGY-WATER NEXUS

INTRODUCTION

Groundwater is not pretty. It does not conjure images of babbling brooks or majestic rivers, though it often contributes much of their volume. It is not something to sink a fishing line into, though it is critical to many aquatic habitats. It is not usually the subject of watershed rallies or community cleanup events, though it connects the hydrologic bodies we build our cities around and works as their natural filter. It is rarely the focus of interstate water compacts, until somebody's stream water goes missing. Most of groundwater's work goes unseen and unappreciated – until it is gone, or has turned saline, or is polluted or threatened in some way. Then we begin to recognize its import.

The present contention over natural gas development in the United States and abroad typifies this dynamic. In a fascinating and somewhat unexpected turn of events in the past three years, a national boom in the extraction of previously unworkable gas deposits has brought groundwater protection to the forefront of environmental and energy policy debates (DOE, 2011; EPA, 2011), as well as to the front pages of the national and international press (Urbina, 2011). Along with this heightened focus on groundwater resources, the drilling increase has made mainstream techniques and tactics of energy extraction that had otherwise inhabited the outskirts of public attention. The 2010 documentary *Gasland*, for example, promoted the term "hydraulic fracturing" from esoteric industry parlance to household word and lofted a Garfield County, Colorado gentleman's flaming tap from kitchen hazard to fare for Comedy Central's *The Daily Show*.

With these boosts – in the national drilling rig count[1] and corresponding media attention – residents of developing natural gas fields across the country have grown concerned that their groundwater might be depleted or contaminated by natural gas operations neighboring their aquifers in the subsurface. So many people have grown concerned about groundwater, in fact, that the controversy over natural gas development is being dubbed by some as the next environmental "superdebate" – on par at least with contention over acid rain in earlier decades and at most with altercations over climate change in more recent years (Byrne, 2011). Here, I examine aspects of the "superdebate" currently underway in scientifically, institutionally, and environmentally complex conditions in and around Colorado's coalbed methane fields. In more academic terms, these debates can be called environmental conflicts over energy and water resources.

The question of how natural gas can be extracted without doing harm to groundwater puts society squarely in the crosshairs of what is increasingly known as the "energy-water nexus"— the tightening linkage between rising energy demand and finite water supplies, and vice versa (DOE, 2006). The energy-water nexus implies conflict in its very definition. It is a crossroads where energy and water resources meet head-on, an intersection where the extraction or use of one resource requires the expenditure of the other. The nexus can be found anywhere that rivers power hydroelectricity, steam spins turbines, pumps deliver water over mountain ranges, or aquifers overlie hydrocarbon deposits. It is the space in which costs and trade-offs are considered between two important and intertwined resource categories. And when it comes to natural gas development, the energy-water nexus is increasingly the site of one particular variety of environmental conflict: the factual dispute.

[1] The number of active oil and gas drilling rigs at work in the United States grew by 688 between 2004 and 2007, or 60 percent, increasing to 1,880 from 1,192, as reported by Baker Hughes, Inc. in its national rotary rig count (Hughes, 2011).

A factual dispute is a disagreement over the technical facts of a situation, or their interpretation. In conflict resolution literature, factual disputes are also sometimes called data disputes, scientific disputes, or technical disputes. A host of circumstances can be credited for their initiation and/or intractability: adversary science, irreducible uncertainty, data restrictions, and opposing assumptions, to name just a few (Jasanoff, 1990; Mostert, 1998). In this thesis, I explore the dynamics of factual disputes that contribute to environmental conflicts at a particular energy-water nexus in Colorado perhaps more appropriately termed the "coalbed methane-groundwater nexus." Specifically, I consider the reasons why groundwater systems prove so problematic when it comes to resolving factual disputes, discussing aquifers' concealed nature, the uncertainty that hydrogeologists face in their work, and the different (and often conflicting) ways that people conceptualize groundwater systems' inner workings (Narasimhan, 2009). I do so with case studies that present scientifically intensive environmental conflicts over groundwater in two heavily developed unconventional natural gas fields in southern Colorado, the coalbed methane (CBM) plays of the San Juan and Raton basins.

The coalbed methane-groundwater conflicts in question are currently underway at different geographic scales relevant to the national natural gas debate: the regional (basin-wide) scale and the local (well-to-well) scale. At the regional scale, I will describe the case of the Northern San Juan Basin, site of persistent uncertainty about how dewatering Fruitland Formation coals in the process of CBM extraction might impact domestic wells, springs, and rivers near the Fruitland Outcrop (Papadopulos, 2006; Riese et al., 2005; SJPLC, 2006). At the local scale, I will describe the case of a single landowner's domestic water well in the Raton Basin, which became unusable in the days following the hydraulic fracturing of a nearby CBM well for reasons that could not be determined by state regulators (COGCC, 2011d).

At each scale, I will discuss the knowledge gaps and uncertainties specific to groundwater systems that exacerbate associated factual disputes over environmental impacts. Drawing from insights developed in applied environmental conflict literature, I will also posit ways that universities or university researchers might productively engage in these factual disputes to provide a clearer picture for those involved. For the regional scale, I will present the results of hydrogeologic inquiry using isotopic and geochemical tracers as an example of a neutral fact-finding effort. At the local scale, I will put forward a groundwater monitoring guide designed to enable citizen science and the collection of baseline data at individual domestic well sites as an example of a starting point for potential joint fact-finding efforts.

RESEARCH QUESTIONS

- What are the factual dispute dynamics of *regional* scale groundwater conflict in Colorado's Northern San Juan Basin?
    - How might universities/researchers productively engage in this type of factual dispute? Specifically, what insights can geochemical and isotopic tracers bring to arguments about regional groundwater flow?
- What are the factual dispute dynamics of *local* scale groundwater conflict in Colorado's Raton Basin?
    - How might universities/researchers productively engage in this type of factual dispute? Specifically, how might groundwater monitoring guidance for domestic well owners transform disputes over potential impacts from hydraulic fracturing and other drilling operations?

- What do regional and local scale groundwater conflicts in Colorado’s coalbed methane basins have in common? How might these commonalities be addressed in conflict transformation efforts going forward?

REVIEW OF THE LITERATURE

Colorado's Coalbed Methane-Groundwater Nexus

Groundwater is a critical resource in Colorado. It accounts for 18 percent of total residential water supply in the state, provided via approximately 200,000 groundwater wells permitted for residential, household, and municipal use (CDWR, 2010; Ivahnenko, 2005). In addition to private domestic wells that serve individual homes, a total of 1,483 groundwater-based community water systems supply water to 703,829 people. Hundreds of these municipal systems depend solely on groundwater (GPC, 2007; NGWA, 2010). Natural gas is also a critical resource in Colorado. In 2008, natural gas heated 75 percent of Colorado homes, and in 2009, natural gas produced 27 percent of electricity used in the state (DOE, 2008; EIA, 2009).

Ten of the United State's 100 largest natural gas fields are found in Colorado. Among them are Colorado's coalbed methane basins, which account for more than a quarter of all CBM production in the U.S. and about one-half of Colorado's natural gas production (EIA, 2009). As in other parts of the West, and across the country, natural gas operations and domestic groundwater use occur in close proximity to one another. In fact, in many Western energy fields, the two cannot be entirely distinguished. For example, Figure 1.1 presents a map displaying the chemistry of water produced from oil and gas wells in the U.S. in the form of Total Dissolved Solids (TDS). In most regions of Colorado, including a few scattered data points for the Northern San Juan and the Raton basins, the TDS levels in produced water meet the federal regulation for underground sources of drinking water, which is 9,999 mg/l or less. The same is true for other Western states, in contrast to higher TDS levels elsewhere in the country.

Extraction companies drill for natural gas in deposits composed of different types of rock that are located at various depths underground. These deposits are considered to be "conventional" if they are made of sandstone or "unconventional" deposits if they are made of tight sands, shale, or coal. At the time of this writing, Colorado hosts approximately 45,975 active oil and gas wells, 5,398 active drilling permits, and 73 active drilling rigs, according to the Colorado Oil and Gas Conservation Commission (COGCC), the state regulator of oil and gas resources (COGCC, 2011b). These oil and gas wells can be found in two-thirds of Colorado counties (42 out of 63), but because hydrocarbons are not distributed evenly underground, wells are not distributed evenly either. Roughly speaking, production hotspots can be found in the direction of each of Colorado's corners: northeastern Colorado (Weld, Morgan, Adams, Washington, and Logan counties), south-southeastern Colorado (Las Animas and Huerfano counties), northwestern Colorado (Rio Blanco, Garfield and Mesa counties), and southwestern Colorado (La Plata and Archuleta counties).

Coalbed methane (CBM) reservoirs are considered to be unconventional natural gas deposits in part because they are composed of coal, but also because the gas source rock is also the reservoir rock is and because gas is stored by adsorption on the coal surface (Questa, 2000). Water resource issues and questions are prevalent in CBM basins because coalbeds are typically saturated with groundwater, which is actually to credit for trapping the targeted methane via hydrostatic pressure. In order for methane to flow to a CBM wellbore, groundwater must be drawn off until fluid pressure drops to a point that allows the gas to desorb from the coal surface. This reduction of fluid pressure for CBM production, performed for thousands of wells in a basin, can affect the availability and sustainability of other local groundwater supplies in important, but only marginally understood, ways (Watts, 2007). CBM development is an incredibly water-intensive process: wells remove orders of magnitude more water from the subsurface than can be recharged naturally. Approximately 3,000 af/y of groundwater is withdrawn from the Northern San Juan Basin by CBM development per year, and another 8,900 af/y is withdrawn from the Raton Basin (Papadopulos, 2006; Watts, 2007). Combined, this is enough water by volume for 37,250 Colorado households based on state average use of 0.4 acre-feet of water per household, per year.

In addition to these potential impacts to groundwater quantity, concerns about groundwater quality arise in CBM basins because Colorado's coalbed methane formations are typically shallower than other unconventional gas plays – on the order of 300-900 m deep (~1,000-3,000 ft), as compared to deep shale ventures such as the Niobrara in northeastern Colorado, which is drilled at up to three times that depth. Vertical separation between domestic water wells and CBM wells can be as shallow as 30 m (100 ft) in some parts of Colorado (Watts, 2006), which raises questions about potential damage to shallow aquifers during well stimulation activities, such as hydraulic fracturing. Separately, CBM development includes a number of surface activities that can also provide potential pathways for groundwater contamination, such as disposal to evaporation ponds and surface discharge of the many thousands of acre-feet of water produced from CBM wells in each basin each year (Maest, 2011; Peers, 2011)

Understanding Environmental Conflict

The analysis to follow draws upon research and pedagogy from the social science field of Peace and Conflict Studies, which itself draws from a multidisciplinary arrangement of political science, geography, sociology, psychology, anthropology, and economics. As an academic project, Peace and Conflict Studies concerns itself with the identification and analysis of the structural mechanisms of social conflicts.

As a normative project, the field's aims include preventing, managing, limiting, and overcoming conflict through mechanisms such as mediation. Peace and Conflict Studies' pedagogical history in the United States can be traced back to campus clubs that formed in the years immediately following the American Civil War. The field began to emerge as a full-fledged research discipline in the decades between the end of World War II and the end of the Vietnam War, which is when Peace and Conflict Studies scholars staked out their own academic concepts, research tools, and publications (Dugan, 1989).

As the discipline enters the 21st Century, the study of environmental conflict is a major area of focus and scholarship in Peace and Conflict Studies, and one that I would argue deserves increased attention as complex and turbulent environmental disputes challenge societies worldwide, and as citizens and decision-makers call for "wiser outcomes that are conceptually more sound, explicitly equitable, and have practical staying power… [as well as] reduced transaction costs" (Adler et al., 2007, p. 3). Several (sometimes conflicting) strands of research are currently ongoing under the banner of environmental conflict resolution, but I will not focus on all of them[2]. Here, I work with the ideas and strategies developed via investigations of, and interventions in, non-violent conflicts typical of environmental policy settings the United States, which best describe my research subject.

Environmental conflict resolution as it is practiced in the U.S. emerged in the 1980s and was institutionalized at the federal level in 1990 when Congress passed the Administrative Dispute Resolution and Regulatory Negotiation Acts. In 1996, the

[2] For example, some credit security scholar Arthur Westing with launching environmental conflict as a research paradigm by putting forward the new theme of "environmental security" in the mid-1980s. By the end of the Cold War, Westing others had produced a body of literature that shifted security thinking to the concept of "resource wars," which sought to tie resource scarcity and environmental degradation to violent conflict (Libiszewski, 1991). Because the present analysis focuses on non-violent environmental conflict in Colorado policy settings, I do not draw from this "correlates of war" literature.

two laws were combined in a reauthorization signed by President Clinton that required all federal departments and agencies to adopt policies for internally implementing alternative dispute resolution. In the same time period, nearly half the states created dispute resolution offices as well (Cohn, 2002). In 1998, Congress established the U.S. Institute for Environmental Conflict Resolution, which operates as a federal program within the congressionally chartered Udall Foundation. The U.S. Institute seeks to resolve environmental disputes that involve federal agencies, boost the use of environmental conflict resolution, and reduce conflict overall by building consensus during early stages of environmental decision-making. The institute gives priority to disputes that include highly technical or scientific issues, and the expertise gained in the cases it has handled since its opening will shape my analysis of energy-water nexus conflicts (Adler et al., 2007).

As Peace and Conflict Studies has evolved as a research field, its normative aims have also changed. An initial focus on "conflict resolution" or "conflict management" has given way, at least for some theorists and practitioners, to the pursuit of "conflict transformation" (Lederach, 1995). As defined by Lederach, conflict transformation asks that we recognize the "dialectic nature" of conflict and work with it, rather than aiming to simply eliminate or control conflict. Lederach argues that conflict transformation reflects a better understanding of the nature of conflict than conflict resolution or management. Conflict, in his view, is not something wholly bad that must simply be stopped, nor is it something that can be directly controlled or managed as though it were a physical object; rather, conflict is an important social process naturally created by humans involved in relationships (Burgess & Burgess, 1997). In a dialectic fashion, people involved in relationships create conflict, which then changes people and relationships, which then change conflict, and so on.

As a prescriptive concept, conflict transformation posits that conflict can be transformed "so that self-images, relationships, and social structures improve as a result of conflict instead of being harmed by it" (Burgess & Burgess, 1997). Since conflict usually changes perceptions of people and positions by accentuating differences between them, conflict transformation works toward improving mutual understanding between parties. "When people's interests, values, and needs are different, even non-reconcilable, progress has been made if each group gains a relatively accurate understanding of the other," according to Burgess & Burgess (1997). This view lofts process over product with a focus on dialogue rather than on outcome. Lederach suggests that this mode of conflict transformation take place at both the personal and the systemic level.

Before going any further, I should define what I mean when I say "conflict" in the context of this thesis. "Conflict" has many synonyms, among which "dispute" stands out as the most frequently used. The terms "conflict" and "dispute" sound similar, but conflict scholars draw a distinction between the terms. They draw this distinction differently, however, and I find one of these distinctions to be useful here. Douglas Yarn defines a conflict as a *state*, rather than a process (Yarn, 1999). People or organizations with opposing interests, values, or needs are in a state of conflict, according to Yarn's definition, and this state may be latent or manifest. If the conflict is manifest, it is brought forward in the form of a dispute. By this definition, "a conflict can exist without a dispute, but a dispute cannot exist without a conflict" (Yarn, 1999, p. 115).

An "environmental conflict," by Yarn's definition, is therefore a state in which people or organizations with opposing environmental interests, values, or needs are in a state of conflict. This latent state of opposition becomes an "environmental dispute" when it is acted upon. To put this idea in context, in the case studies to follow, stakeholders hold opposing interests, values, and needs regarding use of the energy and water resources in question. This opposition manifests in disputes across different legal and policymaking venues at the state and federal level. For example, the environmental *conflict* in the Northern San Juan Basin case study to follow is over whether CBM-related groundwater withdrawals will dry up other important water bodies in the area. An example of a related *dispute* is the escalation of the related *Vance v. Wolfe* case to the Colorado Supreme Court (*Vance v. Wolfe*, 2009).

As a whole, environmental conflicts can be divided into any number of popular sub-themes, such as "water conflicts," for example. (In fact, water conflicts have become so commonplace in the U.S. and elsewhere, that conflict resolution techniques are now seen as an important component of modern water resources management (Mostert, 1998)). One could describe the conflicts presented in this thesis as "energy-water nexus conflicts." In applying categories to conflicts, however, some conflict scholars argue for a typology based on conflict source rather than other variables – acknowledging, in the process, that a single source may not suffice, since conflicts are often caused by multiple sources (Mostert, 1998). Environmental conflicts may have any number of sources, but they almost always involve contested scientific and technical information as a central cause (Adler et al., 2007). Indeed, environmental conflicts are typically high in both their stakes and levels of scientific uncertainty (Yearley, 1995).

The emergence and progression of scientifically and technically intensive environmental conflicts – particularly in situations of great uncertainty and risk – has also become a major theme of research about the science-policy interface in recent decades (Holifield, 2009). Among the findings of these studies is that the production of science and policy is interrelated, often inseparable. One impetus for the conceptual development of these "co-productionist" studies was the development, beginning in the 1970s, of regulatory science focused on assessing risks to health, safety, and environment (Jasanoff, 1986; Jasanoff, 1992). The U.S. Environmental

Protection Agency (EPA) has been a major focus of research in this arena, as has the EPA's Superfund hazardous waste cleanup program (Holifield, 2009). Co-productionist studies use environmental conflicts to turn a critical eye on science and society, such as by examining the phenomenon of "dueling experts" and "adversary science" (Martin & Richards, 1995), among other issues at the science-policy interface.

Factual Disputes

As illustrated by the front page of any newspaper, many different sources of conflict challenge human society, and some are more difficult to resolve than others. The most intractable conflicts – those intense, often highly destructive, conflicts that go unresolved for long stretches – are typically sourced by manifold historical, religious, cultural, political, and economic issues (Coleman, 2000). It would be naïve to assume that environmental conflicts at the science-policy interface in the U.S. do not share some of these attributes as well – pitting different political and economic values against environmental values, or political and economic values against human health values or risk, for example (Nelkin, 1995). More often than not, environmental conflicts are charged by deeply held social and economic values and interests, and are rife with political and ideological fault lines. The actual disputes themselves, however, often focus on technical questions (Hilgartner, 1992).

One might think it would be straightforward, the process of bringing relevant scientific information to a conflict and expecting that it serve as a foundation for decision-making. Using "the best available science," as it is often called in policy settings, should be simple: one asks appropriate questions, carefully gathers data using accepted methods, analyzes and interprets that data in the most logical way, submits the findings to peer review, and then presents it to the world.

Unfortunately, it is rare for so simple a process and so direct a route to occur. Indeed, much of the complexity of environmental conflict "is directly attributable to the way that information is organized, interpreted, communicated, and differentially judged to be useful" (Adler et al., 2007, p. 4). High-stakes, high-uncertainty, scientifically intensive, and technically fraught environmental conflicts make ideal circumstances for all the worst incidences and varieties of factual disputes.

A factual dispute is a disagreement over the facts of a case, situation, or conflict. While conflicts between people and organizations differ in emotional intensity, interests, value assumptions, and cultural context, they most always – even in the most basic interpersonal dispute – include factual components. And the facts involved in any dispute are almost always open to some kind of debate. Moreover, because facts carry critical persuasive value and are powerful components of conflict it is to be expected that they will be debated whenever possible. "If facts relevant to a conflict leave any room at all for differing opinions, and it is to one side's benefit to call them into question, a factual dispute is nearly inevitable" (Schultz, 2003a). Factual disputes can serve as the primary source of an environmental conflict or they can come into play as a secondary (often distracting) complication in an environmental conflict that, at its root, is caused by something else. Either way, facts are manipulated in many conflicts in order to gain power – such as when either or both sides of a conflict strategically present "facts" that are slanted or selectively chosen in ways that benefit their argument.

Factual disputes are especially complicated when a conflict, such as an environmental conflict, involves highly technical issues or questions. Technical facts differ from historical and legal facts in that they require empirical evidence and endorsement from scientists or technical experts, as opposed to lawyers, historians, or eyewitnesses. A technical fact is "a fact that requires some practical, trade, or scientific expertise in order to discover, verify, explain, and understand" (Schultz, 2003b). When key technical facts demand the use of scientific expertise, "dueling experts" or "adversary science" often results. As parties try to win technically complex conflicts, they seek out and present data that contradicts the other side's exerts. Because of this, biases may creep into the fact-finding effort and show up in the results. "This gradually polarizing process tends to cloud the facts, obscuring the truth (or the best information)" (Schultz, 2003a). The result is a default position of mutual distrust and, sometimes, the tossing out of technical information entirely.

The term "factual dispute" categorically describes any instance in which the parties of a conflict disagree over the facts of the case. That disagreement, of course, can stem from a number of different causes, which I will combine into three broad categories. First of all, the factual dispute may stem from real problems with the data. The available data itself may be poor, in error, or incomplete. It may not be considered thorough or objective by those involved in the conflict, or it may not have been collected by an authoritative, respected agent (Schultz, 2004a). The data may be a product of "adversary science" and therefore questionable in its neutrality and at odds with the data of other experts. If the information is presented in subtly biased or strategically deceptive ways, estimates may have been made in one's own favor, background evidence may have been selected to fit a specific theory or story, undesirable anomalies may have been ignored, and erroneous assumptions may have been made.

Second, the available facts may be genuine but subject to scientific uncertainty or knowledge gaps. Some of this uncertainty may be irreducible and unavoidable – in many cases, scientists cannot necessarily vanquish uncertainty given enough time and funding. There may always be some degree of "unknown and presently unknowable" information in a decision. Where real scientific uncertainty exists, the first set of causes (i.e., those related to bad data and bad handling of data) may emerge as well to complicate the situation. Gaps in the facts can be used as strategically than the facts themselves. According to Schultz, "Where uncertainty exists, debates and distrusts commonly follow. Unknowns provide the most basic fuel for debates because they allow parties to fill in knowledge gaps with whatever is to their own advantage" (Schultz, 2004b). Uncertainty may be manufactured and presented strategically for this reason (Michaels & Monforton, 2005).

In a third set of circumstances, data may be genuine and adequate, but people may understand it differently. Parties might agree on the available facts but disagree as to how they should be interpreted or applied because of differing starting assumptions or experience. Parties may also consider uncertainty and risk differently. For example, some see risk-taking as a sign of strength, others as a sign of carelessness. Either way, most people have a natural inclination to avoid, and even resent, any risk that they feel has been imposed on them by an outside force (Schultz, 2004b). People want to feel that they have the ability to make an informed choice about risks, and resent situations where they feel this is denied to them, particularly when they are risking something they value. In many respects, environmental justice is all about the equitable distribution of risks.

In the process of trying to fill knowledge gaps, deal with uncertainty and risk, and interpret available data, drastic differentials in resources and expertise between conflict parties may emerge between parties to an environmental conflict (Schultz, 2004). For example, citizens and communities may feel "outgunned" by authoritative organizations or industries that have access to expensive scientific and technical resources. Transparency may also be a big issue, as may be dueling definitions of expertise and whose facts are relevant to the conflict (Forsyth, 2003). Citizens with detailed local knowledge of an environmental problem may be discounted or ignored by authorities that are used to dealing with experts in the traditional sense. Together, these dynamics may work in a negative feedback loop to further stoke adversary science.

When it comes down to it, environmental disputes usually focus on any several of the following core questions, as identified by Adler et al. (2007):

- Who bears responsibility for something that allegedly went wrong environmentally?
- How shall a current condition that is harmful be remedied?
- Will a proposed project, policy, or rule prove potentially deleterious to human or environmental health?
- How should an environmental resource, with its attendant issues of risks, costs, and benefits, be managed into the future?

It is in the answering of these questions (or the attempts to do so) that scientifically intensive factual disputes ignite. While I have listed three general categories of the causes of these factual disputes above, mediators from the U.S. Institute of Environmental Conflict Resolution (and elsewhere) further parse these causes into 23 problems and patterns that hinge on generation, management, interpretation, and use of scientific and technical information in environmental conflict resolution[3] (Adler et al., 2007). The authors call these problems "Rocks on the Road to Agreement" (p. 7-11). In the context of the groundwater conflicts underway in Colorado's southern coalbed methane basins, the subjects of the next chapters, I will discuss three of these obstacles to conflict resolution or transformation. As defined by Adler et al. (2007), they are:

---

[3] In a 2007 white paper entitled *Managing Scientific and Technical Information in Environmental Cases*, which is based on the experiences of more than a hundred mediators of environmental conflicts in the U.S. as well as the relevant literature, Adler et al. present a list of 23 problems that confront negotiating parties and those who seek to assist them in conflict resolution.

- **Inconclusive Data.** The scientific or technical information disputants are relying on is spotty, does not show strong cause-and-effect relationships and does not invite an obvious decision. Conclusions can be suggested or inferred about cumulative effects but there is no completely logical basis for policy.
- **Uncertainty and Division among the Scientists.** Despite great amounts of advocacy, research, and applied studies, massive scientific and technical uncertainty remains. Peer reviewed studies are equivocal and the opinions or credible experts are deeply divided.
- **Shifting Conceptual Framework.** Data or technical information exists but the framework or paradigm for interpreting and understanding the meaning and relevance of the data is undergoing a significant knowledge shift.

Groundwater Systems as Sites of Factual Disputes

Groundwater systems make frequent sites of environmental quandaries. Many of our most hazardous acts as a society – and even more of our less hazardous, but more proportionately more frequent acts – directly foul groundwater systems. Over 80 percent of the most serious hazardous waste sites in the U.S. (those under the jurisdiction of the EPA Superfund cleanup program) in some way involve groundwater contamination problems (EPA, 1996). Where groundwater is not contaminated, it is often being drained at unsustainable rates, as illustrated on a grand scale in places like the Central Valley of California and the Ogallala Aquifer beneath the Great Plains.

Because groundwater systems are so often the receiving bodies of contamination or the sites of overzealous withdrawals, they are also particularly prone to environmental conflict between groundwater users. More specifically, groundwater systems frequently wind up as the subjects of protracted factual disputes. By my count, they are prone to 18 out of 23 of the problems typical of scientifically intensive environmental conflicts mentioned above. Why is this so? The central project of this thesis is to examine what stokes factual disputes over groundwater systems and what makes them so difficult to resolve in context of natural gas development. But first, a little bit about groundwater systems in general and the ways that we study them.

An instructive apologia can be found toward the end of the EPA's summary of groundwater clean up activities at Superfund sites, titled: "Why Can Ground Water Cleanup Take So Long?" One might imagine that the EPA added this section to its Superfund brochure in response to frustration by those impacted by groundwater contamination, and the explanation that follows is succinctly explains why cleaning up polluted groundwater is, in the EPA's words, "extremely difficult." The EPA gives four reasons for the hardship: "1) aquifers are complex structures; 2) not all contaminants behave the same in groundwater; 3) locating the contamination can be difficult; and 4) technology has limitations." These reasons apply to the potential impacts of natural gas development just as they do to a leaky hazardous waste disposal pit, and they make a good jumping off point for my discussion of why groundwater systems are so difficult to understand and, therefore, are so prone to factual disputes.

Groundwater and surface water systems abide by the same laws of chemistry and physics, but they differ greatly in the degree to which they can be seen and controlled. Surface water bodies – lakes, rivers, oceans, glaciers, etc. – are readily observable. We can touch them, hear them, smell them, taste them, and capture them visually at many scales. We can also exercise control over surface water systems (or at least attempt to) by damming, channeling, dredging, piping, tunneling, filtering, purifying, and otherwise engineering them to suit societal needs and specifications. Neither of these things can be said so decisively for groundwater systems, however. Groundwater systems are hidden from view. They are accessible to us only in limited ways, generally through "windows" drilled into the subsurface in the form of wellbores. While the layman can go far in describing a body of surface water by sight alone, it takes scientific training in hydrogeology or related fields to even begin to characterize groundwater systems. What's more, these fields are still relatively young as academic disciplines.

A rational understanding of the physical laws that describe groundwater evolved only in the last century and a half since a French engineer named Henry Darcy devised a mathematical model to describe the motion of water flowing through sand as part of his effort to improve the City of Dijon's water supply in the 1850s (Darcy, 1856). (It should be noted that much has been achieved in hydrogeology since. For example, hydrogeology is now a mainstream branch of the geosciences and is recognized as a key component in the understanding and management of the natural environment (Skinner, 2008).) Judicial decisions did not begin giving credence to scientific understanding of groundwater until the beginning of the twentieth century, which is partly why groundwater is treated differently than surface water in many legal proceedings (Narasimhan, 2009). One need only consult the many groundwater-related mythologies and traditions that exist even today to be reminded of groundwater's mysterious cultural status. Whether via water dowsers, wishing wells, or healing springs, groundwater has always fueled the human imagination (Ellis, 1917). People have long imagined the different ways that it might behave underground, and disagreed over the possibilities. As will be borne out in later chapters, many still do.

Characterizing Groundwater Systems

The aspects of groundwater systems that are the most difficult to characterize are some of the most important for resource management. The quantity of potable water resource in storage in a groundwater system is a leading source of confusion and contention, as far as resource planning is concerned, report Tidwell and van den Brink (2008) in a paper about cooperative groundwater modeling that aims to link science and public communication in the context of water resources planning. In fact, most of the broad characteristics of groundwater systems critical for resources planning are difficult to measure, according to the authors. Basin depth, recharge rates, interactions between groundwater and surface water, and evapotranspiration losses are frequent topics of contention in groundwater policy, they say.

Significant uncertainty in the characterization of groundwater systems stems from the fact that researchers' view of the groundwater system is limited. "Boreholes, which sample only a small fraction of the entire aquifer, are often our only portals to measuring key petrophysical and water quality characteristics," explain Tidwell and van den Brink (p. 175). "Further complicating matters is the spatial and temporal heterogeneity inherent to the physical characteristics of the ground water system as well as in land-use function and management," they add. Which is to say, we have small, imperfect, and unevenly distributed windows into groundwater systems (unspecified "boreholes" in this case; coalbed methane wells or water wells in others) that often fail to capture the incongruous nature of the system we use them to peer into. At these windows, scientists must often settle for measuring parameters of interest only indirectly. For example, because a direct velocity measurement is impossible to make, hydrogeologists use water chemistry and water age to assess whether groundwater is moving in the subsurface, and if so, how quickly.

In an effort to deal with the limitations of borehole sampling, a number of geophysical field methods have evolved to indirectly determine the extent and nature of geologic materials beneath the surface. Many of these geophysical techniques were developed by the mining and petroleum industries and have been adopted and refined for hydrogeologic purposes. The thickness of unconsolidated surficial materials, depth to the water table, location of subsurface faults, and depth of basement rocks can all be determined using geophysical methods. In some instances, the location, thickness, and extent of subsurface bodies, such as gravel deposits that may serve as aquifers or clay deposits that might serve as confining layers, can also be evaluated (Fetter, 2001). This is done most effectively if geophysical data can be correlated to well logs or borehole data. Combined, this data is much more reliable than each type of information used by itself.

In general, surficial methods consist of transmitting some kind of energy into the ground and deciphering subsurface characteristics based on how that energy changes in the process of bouncing back to a receiver. Some methods use electricity, such as direct-current electrical resistivity and its inverse, electromagnetic conductivity. Other methods rely on sound, such as seismic testing performed using small explosive charges, "thumper trucks," or other devices. Most can also be applied to boreholes. For example, geophysical well logging is the application of surficial resistivity techniques to a borehole using electrodes lowered down a well. Other methods, such as caliper or temperature measurements, can also be used in boreholes. These geophysical methods are quite advanced and can go far in helping to illuminate general characteristics of the subsurface that might not be possible to measure otherwise. But according to Tidwell and Van der Brink (2008), the use of these advanced geophysical methods is usually cost-prohibitive in the context of resource planning.

Computer modeling is also an important tool in groundwater characterization, and a central effort of the discipline of hydrogeology. Because it is possible to measure only small fractions of groundwater systems in the field, computer modeling is typically utilized to illustrate broad system dynamics, such as regional groundwater flow. Groundwater modeling began with mathematical (a.k.a., analytical) models like Darcy's Law, which rely upon basic equations and work well in answering simple questions under simple conditions. Analytical modeling evolved into numerical modeling, alongside advances in computing technology. In the last 20 years, one of the most important developments in hydrogeology has been advanced numerical modeling in the form of stochastic and finite-difference modeling. These computer models are designed for complex conditions. They allow parameter variation within the model area, for example, and better represent true system dynamics as a result.

Advanced as they may be, groundwater models are prone to several types of error. First, all models are simplifications, and simplified reality is not true reality. We cannot expect a one- or two-dimensional model to accurately portray three-dimensional processes. Second, we build models despite our knowledge gaps regarding the processes in question, and this results in parameter errors (Gaganis & Smith, 2006). Parameter errors are inevitable, since, in addition to uncertainty over the parameters in question, we also have to consider errors that creep into parameterization via shortcomings in measurements and scaling. Third, in order to model a system, hydrogeologists must first imagine the basics of how it works – that is, modelers must come up with a general idea that serves as a guideline for constructing a model at all. When this basic framework for modeling a groundwater system does not match reality, the result is conceptual model error. Conceptual model error is a real problem in groundwater modeling, though it has not received as much attention in the literature as parameter uncertainty (Demissie et al., 2008).

Groundwater models are also prone to error because they are inherently value-laden. Modelers must make numerous simplifying assumptions and other decisions in the course of building models, which can insert subjectivity into key points of the calculation change. Kiopproge and others (2011) have identified these assumptions categorically as epistemic (eg., which modeling approach an analyst chooses to use); epistemic/disciplinary (eg., which discipline the analyst is trained in); socio-political (eg., the analyst's personal views on the environmental question at hand); and practical (eg., the time constraints on the analyst's work) (Kioprogge et al., 2011). Ultimately, the danger of the uncertainty and subjectivity that accompanies groundwater modeling is that it may fuel "dueling models and polarization of views by competing interests" (Tidwell & van den Brink, 2008). Unfortunately, this does happen, as has been borne out in modeling-based conflicts presented in political ecology literature.

In the Verde River watershed of Arizona, for example, an ongoing conflict over rapid growth and groundwater exploitation is being waged via adversary modeling (Bolin et. al, 2008). A key element in the conflict is the physical groundwater-surface water link between the Big Chino Aquifer and the Upper Verde River, respectively. U.S. Geological Survey (USGS) groundwater studies suggest that Big Chino groundwater is tributary to the Upper Verde River (Wirt & DeWitt, 2005; Wirt et al., 2005), while consultant-generated hydrogeologic studies commissioned by the city of Prescott (users of the groundwater) suggest that this tributary connection to be insignificant (Southwest Ground-Water Consultants, 2005; 2004). The parties to the conflict interpret this uncertainty in opposite ways: Verde River defenders articulate a precautionary principle, while the Prescott groundwater users say that precaution is clearly unnecessary.

At the St. Regis Superfund Site in Minnesota, a similarly adversarial groundwater modeling contest has been underway over contamination issues. In the

Minnesota case, the Leech Lake Band of the Ojibwe Tribe protested an over-simplified single-layer model produced by Champion International Corp., the firm responsible for the hazardous waste cleanup, to represent a system known to include two aquifers with an inadequate confining layer (Holifield, 2009). Efforts by the tribe to bring in independent university experts resulted in the acceptance of the significant shortcomings of the model, which claimed that contaminant plumes were contained when they were not (Richards et. al, 2002). After much argument over how to address modeling of the system, the EPA constructed a multi-layer MODFLOW model and moved forward on improved monitoring and better operations of extraction wells.

As demonstrated by the examples from the Verde River and the St. Regis Superfund Site in Minnesota, the concealed nature of groundwater systems has, over time, been advantageous to some and disadvantageous to others. In the words of a longtime USGS hydrologist (Chapelle, 1997): "Hiddenness extracts costs." As described above, the inherent complexity of groundwater systems and they ways we study them make it difficult to assess the nature and extent of groundwater effects and assign their causes to responsible parties. "The considerable complexity and inherent time-lag on many aquifer flow regimes mean that cause and effect often tend to become 'decoupled,' both when considering groundwater abstraction and pollution," according to Stephen Foster, director of World Bank Groundwater Management Advisory Team, quoted in a 2010 review of U.S. groundwater protection law (Eaton, 2010, p. 115). In other words, proving causation – a tall order even under clearer circumstances – can be very difficult in groundwater conflicts. It is fitting, then, that the determination of cause-and-effect relationships is often the central project of factual disputes.

Fact-Finding Efforts

The good news about factual disputes, generally speaking, is that a well-supported fact can be a powerful thing, and agreeing on well-supported facts can go a long way toward improving the dynamics of a conflict (Schultz, 2003a). The bad news about factual disputes is that getting to the relevant facts and eliminating speculation and bias in the process is no small task, as demonstrated in the previous discussion of adversary science and other obstacles to factual agreement. But it can be done. Campaigns to straighten out the facts in a factual dispute are called "fact-finding efforts" in the conflict resolution literature. Fact-finding efforts can be designed in myriad ways, and the fact-finding strategy put to use in a given environmental conflict must be appropriate for the factual dispute at hand. Properly designing and implementing fact-finding efforts can be particularly challenging in scientifically intensive environmental conflicts (Adler et al., 2007; Mostert, 1998; Schultz, 2004b).

In environmental conflicts, facts are only as good as the routes and resources used to discover them. Conflict mediation and facilitation place a strong emphasis on process and relationship management; for the results of a fact-finding process to be considered legitimate by parties involved, they must all be on board with the process used to arrive at them (Schultz, 2004b). When it is possible for parties to work together in fact-finding efforts, joint fact-finding is advantageous. When that is not possible, conflict experts recommend that a neutral fact-finder or a fact-finding body be used (Schultz, 2004b). Joint fact-finding efforts show an inclination toward compromise, and they set the stage for open communication and a level of interaction between conflicting parties that might not otherwise occur. A joint fact-finding effort might start from ground, or be conducted under an oversight committee. Under a joint fact-finding effort, the net effect of both parties' interests and inquiries should balance the endeavor such that the facts that emerge are considered to be accurate and fair. Conversely, such an investigation might prove to both parties that neither knows what they think they know, which can also improve conflict dynamics.

A neutral fact-finding effort, on the other hand, is an investigation run by experts who are neutral with respect to the conflict at hand, rather than stakeholders who may suffer from conflicts of interest because they stand to gain or lose from a conflict's outcome (Schultz, 2004b). For a neutral fact-finding effort to function properly the right neutral experts must be enlisted and they must establish to stakeholders' satisfaction that they are, in fact, neutral. In the St. Regis Superfund site case described above, neutral academic fact-finders were enlisted from a nearby Minnesota university to bring independent perspective to the groundwater modeling dispute underway. In other cases, a diverse body of experts might be appointed. Experts with reputations for knowledge and fairness can greatly influence the thinking and attitudes of conflicting parties, but only if they are transparent regarding the underlying assumptions and approaches that guide their analyses and interpretations of information.

Joint or neutral fact-finding can go a long way toward minimizing adversary science and the bias that comes with it. It can also go a long way toward leveling the playing field in complex conflicts wherein parties have access to disparate technical resources and scientific budgets (Adler et al., 2007), such as in groundwater disputes that require expensive modeling projects and field studies. In cases where one group cannot match the resources or expertise of another, one side often has a greater say in the kinds of facts that are collected, which can skew results. Joint or neutral fact-finding efforts can do well to counter this dynamic. In order for fact-finding efforts to work at all, however, parties must first have faith in the general value of the scientific method and, second, they must be willing to ratify facts that have been uncovered by fair means (Schultz, 2004).

There are limitations to fact-finding efforts as a strategy for transforming or resolving environmental conflicts, however, and I would be remiss not to note them explicitly. To start, research rarely provides definitive and absolute answers. More often, it assigns probabilities to some things and raises questions about others. In cases of high uncertainty, in particular, fact-finding is not a silver bullet. Irreducible uncertainty can remain frustratingly irreducible, and fact-finding efforts may be limited to explaining pros and cons, or the potential risks and gains of available options (Schultz, 2003c). Measurements or observations may be insufficient to answer research questions or may conflict. Theoretical frameworks may conflict, or reductionism may introduce error and fail to account for unintended consequences (Adler et al., 2007). Once facts are gathered, they must also be communicated clearly to interested parties and decision makers. Moreover, despite the neutral or joint nature of a fact-finding body, it cannot be assumed that stakeholders will accept facts in the same way.

Despite their limitations, both of these types of fact-finding efforts are proposed in the ensuing chapters as strategies for transforming or resolving groundwater conflicts in Colorado coalbed methane basins. In the case of the Northern San Juan Basin, I present a variation on neutral fact-finding. In the Raton Basin case study, I put forward a type of joint fact-finding effort.

CHAPTER 2

DUELING CONCEPTUAL MODELS IN THE NORTHERN SAN JUAN BASIN

INTRODUCTION

The geologic area known as the San Juan Basin (SJB) was the first major CBM play in the United States – and by some accounts, the first in the world. CBM wells began appearing in the San Juan Basin in the 1980s, spurred by the energy crises of the 1970s and the federal tax incentives for pursuit of unconventional fuel resources that followed them[4]. Research on the geology, gas reserves, and hydrologic regime of this region of southwest Colorado and northwest New Mexico (Figure 2.1) had been underway since the first commercially successful conventional gas well was drilled in the area in the 1920s, but it accelerated in earnest in the 1970s, when it became apparent to the USGS that the basin had a high potential for oil and gas development (Fassett & Hinds, 1971). Most federal mineral leases in the SJB were issued in the 1970s and field production has proven USGS's estimates correct: three decades into development, calculations peg methane volumes in the Colorado reach of the basin at 2.5 trillion cubic feet, worth more than $15 billion (San Juan Public Lands Center, 2006) (EIA, 2007).

Approximately 30,000 conventional and unconventional natural gas wells had been drilled in the SJB writ large by 2008 (API, 2009). Of these wells, more than 2,000 are CBM wells in the Colorado portion of the SJB, known as the Northern San Juan Basin (NSJB). The NSJB makes up a small fraction (roughly one tenth) of the entire basin, and it has been divided into a patchwork of state, federal, and private mineral leases on state, federal, private, and tribal land (Figure 2.3). As in any gas

[4] The 1980 Crude Oil Windfall Profits Tax Act incentivized CBM development.

play, production varies spatially across the NSJB, and also over time. Such patterns are distinct in images of cumulative gas production in the NSJB, particularly those divided by well, an example of which can be found in Figure 2.4. All told, the San Juan Basin supplies around 6 percent of total U.S. coalbed methane, and is California's largest supplier of natural gas (API, 2009)

Numerous scientific studies have made the SJB their focus since CBM production became a reality there. Indeed, some consider the SJB to be the most studied CBM basin in the world (Snyder & Fabryka-Martin, 2007). While these investigations date back to the 1950s, if not before (Silver, 1951), a particularly intense period of NSJB study began in 1999, as state, federal, and tribal resource managers foresaw a new wave of production in what was already a maturing CBM play. In 1999 and 2000, operators were beginning to signal their desire to increase production in the NSJB by way of infill drilling applications that asked for reductions to well spacing in the basin, in addition to requesting permission to drill in previously untapped areas (for a schematic of proposed new wells in the NSJB as of 2006, please refer to Figure 2.5). In anticipation of increased drilling intensity – and in response to adverse environmental impacts identified in the 1990s – the Bureau of Land Management, Colorado Oil and Gas Conservation Commission, and Southern Ute Indian Tribe in 1999 launched a multi-year hydrogeologic modeling effort called the "3M Project." This modeling project spurred several others, in addition to multiple empirical analyses, most of which will be discussed in the coming chapter. At least six major groundwater and/or gas reservoir modeling projects focused on the NSJB were completed between 1999 and 2009. Yet despite all of this scholarly attention, profound and entrenched disagreements still exist over the basin's hydrogeologic inner workings and how natural gas development may or may not change them.

The environmental conflict that I present here is the result of two opposing ideas regarding if and how water moves in the depths of the NSJB and along its margins –

the subsurface one might trod upon near Durango, Bayfield, Ignacio, and points north and south. These competing ideas take the form of "conceptual models," to apply a common hydrogeologic term, which stands for how one envisions a groundwater system to operate. A conceptual model serves as the starting point for modeling efforts and field campaigns alike. As the foundation upon which other scientific endeavors build, one might at least hope for general agreement over its details among the scientific community, industry, and resource managers – in other words, for one conceptual model to reign. This is not the case in the NSJB. In the NSJB, two very different conceptual models exist to describe the general components and processes of the basin's hydrogeology, and they are contested to this day. The two conceptual models have evolved – and collided – in several important policy and legal settings in the past decade, which I will explain in more detail below. The collisions have arisen primarily because of the models' disparate implications for resource development. At their core, these differences are about whether withdrawing 3,000 acre-feet per year (af/y) of groundwater from Fruitland Formation coals in the process of CBM development will dewater overlying aquifers and rivers and impact senior groundwater and surface water rights in the NSJB.

Disagreement over conceptual models is not uncommon in environmental conflicts. Two problems common to factual disputes over highly technical or scientific environmental information, as identified by Adler et al. (2007), are "Shifting Conceptual Frameworks" and "Uncertainty and Division Among Scientists." These two problems are central components of the environmental conflict underway in the NSJB. Adler and his coauthors define occasions of shifting conceptual frameworks as situations where data cannot be effectively understood because the framework or paradigm used to interpret it is "undergoing a significant knowledge shift." As for Uncertainty and Division Among Scientists, Adler et al. describe the phenomenon as massive scientific and technical uncertainty and division among credible experts despite great amounts of "advocacy, research, and applied studies." Environmental conflict over NSJB hydrogeology is a combination of these two problems – a division among scientists because of competing conceptual frameworks. I will address the conflict in detail below. Before discussing the dueling conceptual models in detail, however, let me first provide background on the aspects of NSJB geology and hydrology that are not as contested.

NORTHERN SAN JUAN BASIN HYDROGEOLOGY

Geographic and Geologic Setting

Located at the eastern edge of the Colorado Plateau, the San Juan Basin is a structural depression that began its downwarp in the early Paleocene and continued to do so throughout the Eocene (Fassett, 2000). Vast in size, the basin covers an area of approximately 17,353 km^2 (6,700 mi^2). Approximately 2,331 km^2 (900 mi^2) of this area is in Colorado – a region of badlands, mesas, and hogbacks known as the Northern San Juan Basin (NSJB). Locally, this area is more likely to be called La Plata County (to the west) or Archuleta County (to the east), home of Durango, Bayfield, Ignacio, Pagosa Springs, and other cities that have grown along with coalbed methane development. The remaining 6,000-odd square miles of the San Juan Basin stretch into northwestern New Mexico, where the city of Farmington serves as a major natural gas industry hub.

The NSJB's southern boundary is a political one – the Colorado-New Mexico state line – whereas its boundary to the north is geologic. The basin's northern rim is just that: a prominent ridge of outcropped Fruitland Formation coals and Pictured Cliffs Sandstone shaped like a horseshoe that tops out at 2,750 m (9,000 ft) between the Florida and Pine Rivers and generally decreases in elevation going south, dropping to 1,800-2,150 m (6,000-7,000 ft) by the time it reaches the state line (Fassett, 2000). (For a diagram of NSJB topography, please refer to Figure 2.6). Much like the rim of a bowl, the hogback monocline dips steeply toward the basin interior, though it does so variably, flattening significantly as it stretches to the east through the Piedra River drainage and beyond (Carroll & Kirkham, 1998; Carroll et al., 1999; Carroll, et al., 1997). (For a cross-section of the San Juan Basin illustrating its shape and the steep deep of the northern rim, please refer to Figure 2.7). The outcrop of the Fruitland Formation and Pictured Cliffs Sandstone (hereafter, the "Fruitland Outcrop") is a key area of contention for resource managers, industry, and scientists alike, since it is at the Fruitland Outcrop that the implications of one conceptual model of the basin or another will manifest. As such, the northern rim of the NSJB represents much more than a topographic high point and geologic boundary, and will be discussed in further detail below. Interactions between groundwater and surface water near the Fruitland Outcrop are the focus of the neutral fact-finding effort and analysis to come.

In its entirety, the SJB is made up of many sedimentary formations lain as long as 500 million years ago (Ma), during the Upper Cambrian, to as recently as 40 Ma, during the middle Paleogene. The coal deposits targeted by CBM developers are found only In the Upper Cretaceous sedimentary layers. (For reference, a simplified stratigraphic column from the Cretaceous to the present day can be found in Figure 2.8). The Upper Cretaceous sedimentary sequences can be credited to the Western Interior Seaway of that era, which covered much of interior North America for more than 20 million years. The seaway's western shoreline spent much of that time advancing and retreating across the present-day NSJB, depositing shales such as the Mancos and Lewis during times of advance and sandstones such as the Mesa Verde Group (in between the Mancos and Lewis shales) during times of retreat (Ayers Jr, Ambrose, & Yeh, 1994; Wray, Streufert, Morgan, & Survey, 2000). When the seaway withdrew for the last time near the end of the Cretaceous, it deposited the Pictured Cliffs Sandstone, Fruitland Formation and Kirtland Shale on top of the Lewis Shale.

To describe the lithology central to this study, starting from the bottom, one must begin with the Lewis Shale, which is the uppermost marine shale in the San Juan Basin. It increases in thickness from the southwest to the northeast, up to a maximum thickness of 730 m (2,400 ft) in the NSJB (Craigg, 2001), and acts as a hydrogeologic confining unit below the Pictured Cliffs Sandstone. The Pictured Cliffs Sandstone lies on top of the Lewis Shale and the Fruitland Formation sits atop the Pictured Cliffs Sandstone. The Fruitland Formation is conformably overlain by the Kirtland Shale, which reaches a maximum thickness of 600 m (2,000 ft) in the northwestern part of the basin (Fassett & Hinds, 1971). The Kirtland Shale acts as a regional confining unit on top of the Fruitland Formation, while the Lewis Shale confines the Fruitland from below (Kernodle, 1996).

Fruitland Formation and Fruitland Outcrop

The Fruitland Formation itself is a mixture of sandstone, mudstone, siltstone, shale, and coal. Geologists hypothesize that the Fruitland coals were deposited by a system of barrier-bar swamps and river deltas along the shore of the Western Interior Seaway, where abundant plant debris formed vast peat deposits that were eventually buried by beach and delta sands (for a rendering of the Seaway, please refer to Figure 2.9). The slow eastern migration of the sea left extensive peat deposits behind, and the shifting shoreline caused the Fruitland Formation and the Pictured Cliffs Sandstone to intertounge. The Fruitland and Pictured Cliffs were later buried by continental sedimentation from river systems that deposited the Kirtland

Shale, and later by the Animas and San Jose Formations deposited during the Laramide Orogeny (Late Cretaceous into the Eocene, approximately 70-30 Ma) (Carroll et al., 1999). Over time, compaction and thermal maturation turned the Fruitland peat deposits into coal. The pressure and heat that created the Fruitland coals were also ideal for methanogenesis, or the formation of methane.

Methane gas seeps have been known to emanate from the Fruitland Outcrop and Fruitland Formation coalmines since the 1930s (BLM, 1999). By USGS estimates, the Fruitland Formation holds as much as 50.6 trillion cubic feet (Tcf) of coalbed methane throughout the entire SJB (Ridgley, 2002), and it does so in a manner that is favorable to drilling technology and economics. Fruitland coal seams average 300-350 feet thick, stacked with up to five coal-bearing intervals and 12 individual seams in some places, with increasing thickness from the southeast to the northwest (Fassett & Hinds, 1971). CBM development favors thick coals, which hold more gas and can produce more gas because they can be more effectively depressurized. A region of such coals, known in industry parlance as "The Fairway," runs southwest of Durango, through La Plata County, and southeast into New Mexico, roughly parallel to the Western Interior Seaway shoreline. Depths to the extensive basal coal seams are relatively shallow, at less than 3,500 ft in Colorado. CBM wells are generally 600-915 m (2,000-3,000 ft) deep in the NSJB, though they can be as deep as 1,200 m (4,000 ft) in the deep basin and as shallow as 168 m (550 ft) nearer the Fruitland Outcrop (API, 2009; Papadopulos, 2006).

The Fruitland Outcrop belt extends in an arc nearly 85 miles long (Figure 2.10), and varies considerably along its length in terms of dip and width of exposure. Documented Fruitland Formation dips in La Plata and Eastern Archuleta Counties range from as little 5^0 along the eastern and western margins to as much as 53^0 between Durango and Archuleta County (Carroll & Kirkham, 1998; Carroll et al., 1997; Carroll et al., 1999). Lower angle dips occur on both the eastern and western margins of the outcrop belt in Colorado, while the steepest dips occur in the middle. Where the dip is particularly steep in La Plata County, the Outcrop is as narrow as 65 m (0.1 mi). At shallow dips in Archuleta County, this exposure width can be up to 1.4 km (2 miles) (Carroll et al., 1999). In terms of total surface area, the Fruitland Outcrop spans approximately 8,900 acres in La Plata County and 9,900 acres in Archuleta County, based on calculations by Norwest Corp. (2009). To date, detailed surface geologic mapping has not been completed over the entire length of the Outcrop in Colorado. Most efforts, cited above, have focused on the north and central Outcrop regions, near the most extensive CBM development. The eastern portion, extending into Archuleta County and the Southern Ute Indian Tribe Reservation, has yet to be mapped in detail.

Precipitation, Recharge, Surface Water Hydrology

The San Juan Basin's topography influences the amount of precipitation it receives, as well as where it falls. The volcanic San Juan Mountains rise to elevations of 4,300 m (14,000 ft) to the north of the San Juan Basin, where they generally catch moisture from the Pacific Ocean carried by the westerly jet stream in the wintertime and from the Gulf of Mexico carried by southeasterly circulation patterns in the summer. Because of this orographic effect, maximum annual precipitation along the northern rim of the SJB is 61-71 cm (24-28 in) – twice that in the southern basin. Moving south into the basin, where elevation drops to 1,800 m (6,000 ft), annual precipitation averages 30-36 cm (12-14 in). A few studies have attempted to estimate groundwater recharge to the Fruitland Formation using precipitation as a starting point and have derived mean annual recharge rates of around 0.03-0.3 cm (0.01-0.10 in) per year for the NSJB area (Kernodle, 1996; Norwest, 2009). These low recharge values reflect the extremely high evapotranspiration of the arid Southwest. Considering recharge rates and the total area of the Fruitland Outcrop in the NSJB, the most recent estimate for annual net recharge at the Fruitland Outcrop is 74-158 af/y (Norwest, 2009).

The San Juan Mountains source five major streams with hydrology typical of a snowmelt-dominated system, which run north to south through the NSJB and ultimately converge in New Mexico to form the San Juan River (Figure 2.11). The San Juan River is a tributary of the Colorado River, which it joins at Lake Powell in southeastern Utah. From west to east, the major rivers or streams that cross the Fruitland Outcrop in La Plata County are: the Animas River, the Florida River, South Fork of Texas Creek, and the Pine (or Los Pinos) River. The major rivers or streams that cross the Fruitland Outcrop in Archuleta County, also from west to east, are: Beaver Creek, Squaw Creek, the Piedra River, Stollsteimer Creek, Cat Creek, and the San Juan River. A number of smaller tributaries to these rivers – ephemeral in nature or supporting very low baseflow – have headwaters in the hogback region adjacent to the NSJB. Other ephemeral tributaries begin inside the basin itself, south of the Fruitland Outcrop.

Perennial streams have gouged the sandstones and coals along the Fruitland Outcrop to elevations hundreds of feet lower than nearby terrain. For example, the Florida River and Pine Rivers cut across the northern rim at just over 2,134 m (7,000 ft), on either side of 2,743 m (9,000 ft) high points of Fruitland Formation and Pictured Cliffs Sandstone (Fassett, 2000). Because streams cross the Fruitland Outcrop at lower elevations than the surrounding hills and therefore exhibit lower hydraulic head, many assume that the Fruitland discharges into streams at these points, which would make these areas gaining stretches of river (AHA, 2000). Some modelers estimate that Fruitland discharge to rivers is very low relative to the base flow in these streams (i.e., less than 1 percent) (AHA, 2000). These major streams and rivers have produced loose, unconsolidated alluvium of sand and gravels along their paths across the Fruitland Outcrop, which is an important site of surface-groundwater interaction (Kernodle, 1996). The lithology of the alluvium has been studied in La Plata County (Fassett, 1997), but the stream crossings in Archuleta County have not received as much attention.

Groundwater Hydrology and Aquifer Use

Residents of the NSJB rely heavily on groundwater as a primary water source (for a map of water wells in the region, please refer to Figure 2.12). In La Plata and Archuleta Counties alone, at least 8,322 wells have been permitted for domestic use or irrigation since 1972, according to Colorado Division of Water Resources records[5]. Domestic well owners rely on several aquifers in the NSJB. The most important of these are the alluvial aquifers around the major rivers (Animas, Florida, Los Pinos, and Piedra primarily), as well as the sandstone bedrock aquifers of the Animas Formation (Tertiary), Mesa Verde Group and Dakota Sandstone (Cretaceous), and Morrison Formation (Jurassic) (Topper, Spray, Bellis, Hamilton, & Barkmann, 2003). Near the Fruitland Outcrop, the alluvium and Animas Formation are the most commonly tapped aquifers, primarily for domestic water supply, irrigation, and stock watering (Papadopulos, 2006). The Fruitland Formation and Pictured Cliffs Sandstone aquifer system is deeper than the Animas Formation and the alluvium, so it is not as frequently targeted by domestic well drillers. However, near the Fruitland Outcrop, where burial depths are less than about 150 m (500 ft), San Juan Public Lands Center field staff have identified as many as 40 domestic wells that tap the Fruitland Formation coalbed aquifer (SJPLC, 2006). One of these wells is a flowing artesian well. The others are not under artesian pressures and appear to be situated

[5] Web-searchable state records do not go all the way back to the advent of state well permitting in 1957. Permits can be found on the Colorado Division of Water Resources website http://www.dwr.state.co.us/ (retrieved 4/30/10).

in immediate recharge areas. In two separate near-Outcrop cases, wells deeper than 300 m (1,000 ft) draw water from the Pictured Cliffs Formation.

The Fruitland and Pictured Cliffs Sandstone are considered to be hydraulically interconnected because of the way they interbed and the odds that fracturing at the Outcrop may further interconnect them. Where natural fractures connect the Fruitland and Pictured Cliffs Sandstone, the latter is a large source of water, as inferred from gas wells that produce higher-than-average amounts of water where the Pictured Cliffs Sandstone is known to be highly fractured in the north-central basin near the Pine River (Questa, 2001). The Fruitland/Pictured Cliffs Sandstone aquifer extends from the Outcrop at the hogback monocline south into New Mexico. As a whole, the basin lacks widespread faulting and may be relatively unbroken. Detailed mapping by Carroll et al. (1997, 1998, 1999) identified only a few minor faults along the Outcrop. In the basin itself, faulting has been identified in only a few places in the subsurface and in coalmines, but fracturing is pervasive near the Fruitland Outcrop (Ayers Jr et al., 1994; Tremain, Laubach, & Whitehead III, 1994). The Fruitland Formation and upper Pictured Cliffs Sandstone contain natural joint sets that are believed to have tectonic origins and may be younger than cleats found in the coal seams and trend a similar direction (north-northwest) (Condon, 1988). The most prevalent orientation of these joints is north-northwest. A structural hingeline in the deep interior of the San Juan Basin trends east-southeast and is located just south of the Colorado-New Mexico border (Ayers et al., 1994).

Permeability is a critical aquifer property that describes the ability of rocks to transmit water. The coal seams are the most permeable layers within the Fruitland and Pictured Cliffs Sandstone aquifer because of coal's cleated structure (Kaiser, Hamilton, Scott, Tyler, & Finley, 1994). The Fruitland coals' permeability has been published in some empirical work, and has been estimated by modeling based on production records, though these estimates vary widely. In a review of these reported parameters, Norwest came up with a permeability range of 2-20 millidarcy, or a hydraulic conductivity of 0.0055-0.055 ft/day (2009). The non-coal portions of the Fruitland (sandstones, mudstones, etc.) are considered to be much lower in permeability than the coals (Kaiser et al., 1994; Questa, 2000).

A DECADE OF DUELING CONCEPTUAL MODELS

A Tale of Two Ideas

For as much as is known about the NSJB's structural geology and its surface water and groundwater systems, a great deal remains contested – primarily the dynamics of regional groundwater flow in the basin as embodied by a set of dueling conceptual models held by stakeholders in the NSJB. The two conceptual models differ primarily in their views on hydraulic connectivity, or put in other words, the "degree of flow-through within the system" (Papadopulos & Associates Inc, 2006). The disparities between the two sets of views on hydraulic connectivity, in turn, stem from different beliefs and assumptions regarding the "number, location, and completeness of flow barriers" in the NSJB (AHA, 2000). Because official names have never been assigned to these conceptual models, I will call them the "Hydraulically Connected Basin Model" and the "Compartmentalized Basin Model" in this analysis, borrowing terms used haphazardly in previous studies (AHA, 2000; Papadopulos, 2006).

It is difficult to pinpoint exactly how, where, and when the two models came into being, but their role as a dueling conceptual conundrum came into sharp public focus in a policy setting in 1999, when state, federal, and tribal resource managers launched the 3M Project to better understand the potential impacts of increasing CBM development in the NSJB. The 3M Project's name stood for "Mapping, Modeling, and Monitoring," and a regional groundwater model – to built by Applied Hydrology Associates, Inc., a water resources consultancy then based in Golden, CO – was its first major modeling effort. The groundwater model would be used as a planning tool for CBM development and mitigation strategies as CBM production, and associated environmental impacts, intensified. The groundwater model would also provide the starting conditions for a sister model being built by Questa Engineering Corp. – an oil and gas engineering consultancy then based in Denver, CO – to simulate the NSJB gas reservoir. Together, the models would be used to predict and evaluate the effects of various future management scenarios.

The 3M Project was initially driven by concerns about methane seepage occurring at the Fruitland Outcrop, which had increased by the late 1990s and had begun to kill trees in some areas and, in two instances, filled crawl spaces of houses to explosive levels.[6] Worries about gas seepage were high, but they would only be eclipsed by controversy over surface water and groundwater in the years to come. Annual CBM water production in the NSJB increased rapidly in the first decade of heavy drilling, peaking at over 4,300 af/y in 1993, and declining to a relatively constant rate of 3,000 af/y, since then, according to (Papadopulos, 2006). Considered from another angle, one might describe CBM development as groundwater development with methane production on the side. Extraction of CBM requires the removal of groundwater by definition, since it is hydrostatic water pressure inside coal cleats that holds adsorbed methane on the coal surface in the first place. As put by Questa (2001), "CBM recovery requires reducing the pressure

[6] The Pine River Ranches subdivision is an important area of methane seepage monitoring in the NSJB. Complaints of methane gas in domestic wells and the Pine River began around 1993, according to the BLM (1999). BP American Production Corp. (then Amoco Corp.) eventually purchased the methane-filled houses from residents and demolished them.

in the coal beds to a point where gas will dominate the two-phase flow system." Water pressure must therefore be reduced to allow methane to desorb and flow to a well, which means that CBM wells produce mostly water early in life. This pattern is demonstrated at the regional scale in Figure 2.13, which compares cumulative water and gas production in the basin.

The CBM wells that produce the most water are close to the Fruitland Outcrop (Figure 2.14), which exacerbates concerns that CBM development may intercept groundwater that would normally discharge to rivers as they cross the Outcrop or otherwise support the San Juan Basin's natural hydrogeologic regime. Exactly how much water is potentially being removed from NSJB's rivers – and through exactly what mechanisms and flowpaths – is a difficult question at the forefront of environmental conflict in the NSJB. (For a cross-section illustrating the potential linkage between groundwater and surface water systems at the Outcrop, please refer to Figure 2.15). At present, federal resource managers agree that CBM development will drive a number of unavoidable adverse effects near the Fruitland Outcrop including, but not limited to: drying of water seeps and springs as well as associated wetlands, dewatering of domestic wells, and depletion of surface water flows in rivers (SJPLC, 2006).

3M Project Hydrologic and Reservoir Models (2000)

The environmental conflict about the adverse hydrologic impacts of CBM development came to the forefront of NSJB public policy debate with the Applied Hydrology Associates, Inc. (AHA) modeling project of 2000. A stated objective of the AHA effort was to evaluate the dueling conceptual models of the San Juan Basin, which AHA did via a single-layer, one-phase flow regional groundwater model of the entire SJB. The model discretized 6,700 mi^2 into 0.5 mi grid cells and was built in a way that allowed AHA to simulate different conceptual model dynamics in an effort to find the correct starting point for their groundwater model. In particular, the AHA model allowed analysts to evaluate proposed barriers to groundwater flow within the Fruitland Formation/Pictured Cliffs Sandstone aquifer.

The possible presence of barriers or baffles in the NSJB "was a frequent discussion topic in the 3M Technical Peer Review Team meetings," according to Questa Engineering Corp. (Questa), authors of the sister gas reservoir model the hydrologic model (2000). The 3M Technical Peer Review Team was made up of representatives from state, federal, and tribal agencies, as well as the CBM industry. Industry participation was critical to the process, wrote Questa in the final report (2000). The project "benefitted greatly from industry cooperation, data, financial assistance, and peer review," it said. Industry presence brought contention with it, however, as CBM interests advocated for the Compartmentalized Basin conceptual model of the NSJB. "Industry representatives suggested that many additional barriers or baffles may be present in the Fruitland, but did not provide definitive data to support more barriers," wrote Questa in its summary of the project. Ultimately, the AHA modelers decided only to include barriers or baffles "whose existence could be conclusively demonstrated either through incontrovertible evidence, or through multiple reasons for inferring their existence," according to Questa (2000).

The first conceptual model AHA simulated was the Hydraulically Connected Basin. The Hydraulically Connected Basin is the traditional conceptual model of a confined aquifer such as the Fruitland Formation. Following this model, regional groundwater flow would move from areas of high elevation recharge to lower-elevation discharge points through more permeable, laterally extensive coal seams sandwiched between less permeable sandstones and shales. In keeping, potentiometric heads in a Hydraulically Connected Basin would be highest in topographic high points and would gradually decline with distance into the basin and towards the presumed discharge point of the San Juan River near Farmington, NM – the topographically lowest outcrop of the Fruitland Formation. Regional groundwater flow would be conducted first to discharge at river cuts in the NSJB following primary flowpaths and then along deeper, secondary flowpaths into the central San Juan Basin, toward the San Juan River.

Stratigraphic relationships support the Hydraulically Connected Basin conceptual model, as do geochemical data that suggest recharge of meteoric water from Outcrop southward into the basin. Up to ten miles from the Outcrop, Fruitland Formation water has a meteoric isotopic signature and is relatively low in chloride (for maps that illustrate Oxygen-18 and chloride in CBM produced water, please refer to Figures 2.17 and 2.18). Potentiometric surface measurements also support this model – showing a relatively smoothly changing pressure gradient with a maximum of 2,438 m (8,000 ft) at the Outcrop that decreases basinward to about 1,830 m (6,000 ft) at the state line following a relatively smooth pattern of about 60 m per 16 km (200 ft per 10 miles).

The formulation of a potentiometric surface for the Fruitland Formation has been difficult due to the scarcity of data points and the nature of those available. Water wells completed in the Fruitland Formation/Pictured Cliffs Sandstone are clustered near the Fruitland Outcrop, leaving most aquifer data downgradient of the Outcrop to be collected from CBM wells, which might be completed in more than one aquifer (Leavings et al., 1996). Potentiometric surface measurements have been collected over the years nevertheless – imperfectly, sporadically, and using a variety of techniques with gas wells (shut-in pressure tests, drill stem test pressures, bottom hole pressures, etc.), among other approaches, such as measuring the elevations of springs and depth to water in COGCC monitoring wells (Leavings et al., 1996; Kernodle et al., 1990; McCord, 1988; Kaiser et al., 1994). Some support the Hydraulically Connected Basin based on trends in these measurements. Kaiser et al.

(1994) concluded, for example, that "the Fruitland Formation is a single hydrologic unit" at the regional scale, with compartmentalization indicated only locally (to see Kaiser et al.'s potentiometric surface map, please refer to Figure 2.19).

AHA also simulated the Compartmentalized Basin conceptual model at the outset of its hydrologic modeling project. According to this model, groundwater flow is quite limited, if not absent, in the basin due to two types of flow barriers, or a combination of them: a "hinge-line barrier" and/or "shingle stratigraphy." Because the Fruitland Formation juts from a gentle dip inside the basin to a steep dip at the basin margins, some argue for the presence of a sharp tectonic division such as a displacement fault that would act as a no-flow boundary paralleling and approximately 2.4 km (1.5 mi) from the Fruitland Outcrop (AHA, 2000). According to this theory, the hinge-line fault would also serve to seal off "fossil" heads from an earlier time period "via fault compartmentalization and low formation permeability," producing a stagnant system in which groundwater flow stopped when connate waters were trapped in the coal bed. Shingle stratigraphy might further compartmentalize the basin, or simply halt groundwater flow on its own, in areas where the Fruitland coals are laterally discontinuous and "off-lapping" due to "transgressive-regressive" stratigraphy, (AHA, 2000). Following this conceptual model, coal seams are characterized by lack of continuity and discontinuities of groundwater flow between them; any groundwater flow that does occur moves slowly by refraction through coals and shale. More complicated to simulate, this type of stratigraphy required a separate multi-layer model build by AHA (to see a schematic of this conceptual model, please refer to Figure 2.20). Evidence supporting the Compartmentalized Basin conceptual model includes major element and isotopic composition of the waters associated with CBM and the chemical and isotopic composition of methane (Riese et. al, 2005), though disagreements exist about these interpretations, to be discussed below.

AHA ran simulations of the two conceptual models and calibrated the results by comparing them to field data. After attempting both, AHA determined that the results of the Hydraulically Connected Basin conceptual model most closely matched observed reality. The Compartmentalized Basin conceptual model failed to "pressurize" appropriately. AHA set up the hinge-line barrier scenario for 65 million years, and found that most head measurements equilibrated to an average value within 2 million years. For "fossil" heads to be trapped in place and sealed off by a hinge-line fault, a major "trapping event" must have occurred more recently than 2 million years ago, AHA reasoned, and this did not fit with the region's known geologic history. Compartmentalization due to shingled coal seam architecture also did not prove to be as severe a barrier as anticipated. In fact, flow in shale between coal seams ultimately enhanced groundwater flow in the coal seams, according to the model.

Based on the results of the two models, AHA concluded that the Fruitland Outcrop and deep NSJB must be hydraulically connected to one another. The modeling exercise suggested that the Fruitland Formation behaved simply and consistently "like a classic confined aquifer system, which is regionally interconnected despite the presence of structural and stratigraphic discontinuities," they wrote in the final report (2000). AHA then went on to map the flowpaths produced by the model: primary flowpaths return Fruitland Formation recharge to rivers at topographic lows along the Outcrop, while secondary flowpaths run into the deep basin (Figure 2.21). Questa used this hydrologic model as the framework for its reservoir modeling project in 2000.

Questa Stream Depletion Model (2001)

With hydraulic connectivity put forward by the 3M Project studies, modeling work moved toward making quantitative assessments of groundwater-surface water interactions along the Fruitland Outcrop. Together, the Questa and AHA models had simulated pre-CBM development Fruitland Formation discharge into NSJB rivers of approximately 200 af/y into the Animas, Florida, Pine, and Piedra rivers, combined, with another 80 af/y carrying on into the deep basin and ultimately discharging into the San Juan River in New Mexico. While these regional models were limited in their ability to predict fine-scale groundwater-surface water interactions, they provided the best estimate up to that point of how much water the Fruitland was likely contributing to surface hydrology in the region.

When it became evident that depletions from CBM might exceed 280 af/y "by an unknown but potentially large amount," due to the fact that CBM wells were withdrawing more than 3,000 acre-feet of produced water per year, resource managers and the public began to raise concerns (Questa, 2001). The 2000 regional models suggested that dewatering associated with CBM production had been reducing artesian pressures on a regional scale. Resource managers feared that CBM's large-scale groundwater removals could effectively reverse the hydraulic gradient between the rivers and the Fruitland Formation at the Outcrop, turning gaining stretches of river that received groundwater from the Fruitland into losing stretches of river that gave up water to the Fruitland instead (Questa, 2001). With this dilemma in mind, Questa initiated a second modeling effort in 2001 funded by the Ground Water Protection Research Foundation, an industry-supported groundwater protection research and education organization based in Oklahoma City, OK.

The 2001 modeling effort aimed to simulate groundwater-surface water interactions associated with CBM development in the NSJB and to quantify maximum surface water depletions that might occur because of it. The model that resulted demonstrated that CBM development would ultimately intercept much of the 200 af/y presumed to be discharging from the Fruitland formation to the Animas, Pine, Florida, and Piedra rivers, though the final volumes were less than had been determined in the 2000 models. Questa developed multi-layer models for the intersections of the Animas, Florida, and Pine Rivers with the Fruitland Outcrop, based on field work that developed geologic cross-sections at each river crossing and gathered stable isotope samples from CBM wells (Questa, 2001). The Piedra River drainage received less attention, as its intersection with the Fruitland Outcrop was still being mapped and considered for the first time in these studies and CBM development had not yet extended into Archuleta County. The river-cross sections "illustrate a near-direct connection between the rivers and the Fruitland/Pictured Cliffs Sandstone subcrops," said the final Questa report, but the consultancy reduced discharge estimates after running the model. Pre-development discharges into the Animas, Florida, and Pine turned out to be 134 af/y according to the study, versus estimates of 152 af/y in the earlier modeling projects. Running the simulation out to 2050, Questa estimated that CBM development would deplete a maximum of 140 ac-ft/yr of surface flows by that year in the Animas, Pine and Florida, with another 15-60 ac-ft/yr depleted from the Piedra.

By the time Questa's 2001 model had been completed, the consultancy started to modify its description of the hydraulic continuity of the NSJB. The original, single-layer 3M Project models had been built on the assumption of general continuity in the system after AHA's experiments with different conceptual models as starting conditions. Questa's multi-layer run in 2001 suggested, however, that "there are probably more barriers or flow restrictions in this area that restrict or prevent some of the water movement computed in this model." Questa had begun suggesting this after completing its methane seepage model in 2000. The model suggested that methane seepage at the Outcrop would increase 4-20 times over rates seen in 2000, to as much as 10 MMcfd over predevelopment levels. During calibration efforts, the model predicted more gas seepage than was actually observed at the Outcrop, however. Based on that disparity, Questa inferred that the "connection between the Outcrop and the basin is not perfect in nature." The consultancy also estimated combined baseflows in the Animas, Florida, and Pine to be 188,231 ac-ft/yr, and reasoned that predicted depletions would be less than 0.07 percent. The model estimated then-current depletions (in 2001) for those rivers at approximately 65 af/y.

San Juan Public Lands Center Environmental Impact Assessment (2000-2007)

It was upon this uncertain footing that the Bureau of Land Management and U.S. Forest Service found themselves beginning an extensive Environmental Impact Statement process in 2000/2001, under National Environmental Protection Act procedures. By 2002, roughly 310 CBM wells had been drilled on San Juan National Forest and BLM San Juan and San Miguel Resource Area lands in the NSJB, overseen by the BLM and USFS, together known as the San Juan Public Lands Center (SJPLC) at their combined Durango, CO headquarters. Taking state and tribal leases into account, a total of approximately 1,000 CBM wells had been drilled in the Colorado portion of the SJB by 1999 (SJPLC, 2006). Drilling followed 320-acre spacing rules by the state and the federal agencies, until industry began to request infill drilling and spacing requirements started to shrink.

In 2000, NSJB operators submitted a plan for 170 new CBM wells on existing leases in La Plata County, then revised it in 2001 and resubmitted plans for approximately 300 new wells on existing leases in La Plata County (about 160 wells) and Archuleta County (about 140 wells). The infill drilling would reduce well spacing on federal lands to 160 acres, matching spacing reductions already imposed by the state (COGCC, Orders 112-156 and 112-157). (In 2005 and 2006, COGCC reduced spacing again to 80-acres in some places (Papadopulos, 2006)). SJPLC filed notice in the Federal Register that they would begin to prepare an Environmental Impact Statement (EIS), and began to hold public meetings in Durango and Bayfield on the proposal.

The federal agencies were concerned about the effects of CBM groundwater withdrawals on rivers, domestic wells, and springs in the Fruitland Outcrop area. SJPLC staff knew that the regional Fruitland potentiometric surface had declined since drilling began, though few studies ventured to predict the drawdown at that point. CBM development requires depressurization, which propagates outward from the well and has the potential to reduce formation pressures enough to affect surface and groundwater flow. (Later studies would show potentiometric surface declines of 2,000ft in the Fairway region of the basin and 700 ft near the Pine River, south of where it crosses the Outcrop (Papadopulos, 2006).) At the time, SJPLC field staff knew that some adverse effects were already occurring at specific locations in La Plata County and that others might occur in lesser-known Archuleta County, where baseline data had yet to be collected. SJPLC personnel had measured decreases in the water table in outcropping coal beds in the Texas Creek area, for example. In the vicinity, a 90-foot-deep domestic well that had run at 20 gpm for 16 years could no longer draw water; a replacement well had to be drilled to 190 feet. Springs and seeps had not dried up on the federal lands of the NSJB, but they were declining in areas to the south (Janowiak, 2002). Further, surface water rights owners were growing concerned about depletions from rivers already over-appropriated during the irrigation season.

To assess "unavoidable adverse effects," as termed by NEPA, and consider monitoring and mitigation efforts, SJPLC staff in 2001 turned to the 3M Project models, peer-reviewed empirical research, and public and industry comments, beginning a process of interpretation and decision-making that would last until the final EIS was published in 2006 (SJPLC, 2006) and the record of decision was published in 2007 (SJPLC, 2007). The debate over which conceptual model best described the NSJB gained fresh energy and a higher profile during this process of consideration. In comments submitted to the SJPLC, BP American Production Corp.[7] (BP) made a case for its conceptual model of choice, the Compartmentalized Basin, using a new study published in 2005 as a *Geological Society of America Special Paper* (#387) by W.C. (Rusty) Riese, PhD, geoscientist for BP. Riese's work was undertaken partly under the auspices of the 3M Project and partly outside of it, supported by BP and other gas companies.

Based on geochemical data from 100 CBM wells, Riese et al. described a stagnant system in the Fruitland Formation, with connate waters trapped in the coal beds since they were deposited in the Late Cretaceous. The authors explained the pressure regime in the base by the introduction of recharge waters 30-35 Ma, during the San Juan up-lift in the Eocene, and total cessation of flow within the system after this point. Riese et al. concluded that water in the San Juan Basin was about 60 million years old, based on a water aging technique that used the ^{129}I isotope. When corrected for the addition of fissiogenic ^{129}I, Riese suggested that water ages in the SJB were compatible with the depositional age of the Fruitland Formation. Riese et

---

[7] BP is the top natural gas producer in Colorado with a regional headquarters in Durango, operating more than 1,500 wells in the NSJB, most of which are CBM wells. BP operates 2,200 gas wells on the New Mexico side, most of which are conventional. (www.bp.com, retrieved 10/1/11.)

al.'s work indicated a static hydrologic system disconnected from the rest of the basin, and suggested that CBM production would not affect shallow groundwater and surface water systems near the Fruitland Outcrop.

Riese's work forced SJPLC to wrestle the dueling conceptual models again, despite the 3M Project's conclusions that the Fruitland Formation behaved as a hydraulically connected confined aquifer. The agencies were left to consider two fundamentally different hypotheses regarding the characteristic of the basin in its evaluation of the effects of CBM groundwater withdrawals. In the SJPLC's words in the final EIS, Riese et al. presented "a somewhat diverging hypothesis of the operation of the groundwater system and the impacts of CBM development" that arose from "different interpretations of the basic nature, character, and operation of the Fruitland Formation aquifer system." (For a breakdown the differences in interpretations and implications associated with the dueling conceptual models, please refer to Table 2.1.)

Riese et al. argued that their isotopic and geochemical results proved the Compartmentalized Basin model correct, but other researchers contested the isotope data presented in the study. Researchers using different isotopes had found what they thought to be much younger ages for NSJB water – younger by several orders of magnitude. Zhou et al. (2002 and 2003) and Zhou & Ballentine (2006) estimated groundwater ages in the Fruitland Formation using ^{4}He and found them to be on the order of 30,000 BP (years before present). Their ^{4}He groundwater dates using average crustal flux rates in the center of the under-pressured area were consistent with major recharge events reported for the San Juan Basin by other scientists (e.g., 22,000 years BP by Phillips et al., 1986). These ages also agreed with ^{14}C dates, and were close to hydrological modeling dates up to 20 km from the basin margin recharge area (Mavor et al. 1991). Zhou and Ballentine (2006) concluded: "Our results do not support the groundwater ages of ~60 Ma reported by (Snyder et al., 2003) in any sense or form."

The conflicting conceptual models and isotopic data argued during the EIS process highlighted for SJPLC "that there are areas of uncertainty and conflicting research that would benefit from additional monitoring data to validate and/or improve conclusions" (p. 3-19). The federal agencies ultimately decided that neither interpretation of the Fruitland Formation hydrogeologic regimes could be considered fully conclusive, but they needed to decide on one conceptual model to structure their analysis of potential environmental impacts. After reviewing the available evidence, SJPLC decided to go with the Hydraulically Connected Basin and the conclusions of the 3M Project models, noting the large dataset they were built upon, widely accepted scientific assumptions about confined aquifer dynamics, peer-reviewed literature supporting hydraulic connectivity, and anecdotal observations and field data collected by local, state, and federal agencies. SJPLC concluded that Riese et al.'s conceptual model "developed from 100 data points of poorly understood geochemical data cannot be supported when 100 data points do not match the work of others who have analyzed multiple lines of physical evidence of fluid flow and workers who have used hundreds of thousands of data points in the analysis" (p. 3-21).

The agencies were not convinced that Riese et al. had presented a supportable model of groundwater flow characteristics. Siding with AHA's simulation from 2000, they argued that pre-development pressures "could not have been maintained for the millions of years required by the conceptual model put forward by Riese et al." Where Riese et al. saw compartmentalization, stagnancy, and isolation from the Outcrop, SJPLC saw an interconnected aquifer system that conducted water to local rivers and into deeper groundwater flowpaths despite its sometimes variable flow characteristics. The Hydraulically Connected Basin conceptual model moved to the forefront of policy discussion at the federal level, but it would soon become a point of contention in state proceedings in the water courts and State Engineer's Office as well.

In August 2006, the SJPLC published its final EIS on the proposed CBM well downspacing in the NSJB. Six energy companies had proposed to drill 284 new CBM wells in the region, 185 of them on federal mineral estate, as well as construction of the ancillary facilities needed to support those wells. The agencies had received 4,505 unique comments from the public, many of which focused on "evaluating all available evidence related to Fruitland Outcrop impacts" and "protecting water resources by addressing surface and groundwater impacts, water depletions, and watershed impacts" (SJPLC, 2006). SJPLC analyzed seven alternative development scenarios and decided to allow development of 127 new CBM wells on federal leases. In the process, the agencies maintained a 1.5-mile drilling buffer from the Outcrop that had been instituted in 2000, and said they would not allow wells to be drilled inside the buffer zone until more information had been gathered from test wells inside the boundary. The federal agencies estimated that industry would likely develop 100 wells on private lands in addition to the wells permitted on federal lands.

Vance v. Wolfe Case (2005-2009)

In November 2005, two NSJB-area ranching families – the Vances and the Fitzgeralds – filed a complaint with the water court in Durango that would, in the course of four years, escalate to the Colorado Supreme Court and completely change oil- and gas-related groundwater law in Colorado. Both ranching families live more or less on the Fruitland Outcrop, near to where it intersects the Piedra River. The Vance's own and operate a 313-acre ranch in Bayfield, CO, just to the east of the La

Plata-Archuleta county line in Archuleta County. There, they irrigate 50 acres of hay and water livestock with a decreed 1.5 cfs water right appropriated in 1952 from Squaw Creek, a tributary to Yellow Jacket Creek, which is a tributary to the Piedra River. At the time of the complaint, the Vances also had an application for water rights pending for two springs and one seep located on the ranch, also primarily used for stock watering and irrigation. The Fitzgeralds live nearby, on a 380-acre ranch just to the west of the county line in La Plata County that is just inside the Pine River drainage. The Fitzgeralds use their water rights to irrigate pasture and hay, as well as produce sold at the local farmer's market. The Fitzgeralds have four decreed water rights, all appropriated in 1970: 2.5 af of spring run-off on Beaver Creek, 1 cfs from springs tributary to Beaver Creek, 1 cfs from Armstrong Canyon, and 15 af on Beaver Creek, all of which are tributary to the Pine River.

In their complaint to District Court, Water Division Seven, in Durango, CO, the Vances and Fitzgeralds argued that their senior water rights were being infringed upon by CBM development in the NSJB (Klahn, 2005). To make this argument, the ranchers' attorneys cited the statements that SJPLC had made in its June 2004 draft EIS about hydraulic connectivity between the Fruitland Formation/Pictured Cliffs Sandstone and area streams, as well as the agencies' conclusions about CBM interception of Fruitland Formation discharge at the Outcrop – all of which had been predicated on the 3M Project model runs and rejection of the Compartmentalized Basin conceptual model. The ranchers also noted that Colorado groundwater law embodies the Hydraulically Connected Basin conceptual model as a central tenant: by default, all groundwater in Colorado is legally presumed to be connected, or tributary, to the state's natural streams, unless proven otherwise in a proceeding before the State Engineer's Office. That legal reality, established in a 1951 Colorado Supreme Court case known as *Safranek v. Town of Limon,* effectively allowed the plaintiffs to make twice the case for a Hydraulically Connected Basin. The ranchers could point to the AHA and SJPLC conclusions of hydraulic connectivity in the basin, and because no study had ever proven groundwater in the NSJB to be nontributary, they could also point to tributary groundwater law. The legal precedent made District Seven water court judge's work (and eventually the Colorado Supreme Court's work) simple. The water court did not have to decide between the Hydraulically Connected Basin and the Compartmentalized Basin conceptual models. The judge could accept as a statement of fact that the groundwater in question was tributary in nature and move on to related legal issues, which were less simple.

The Vances and Fitzgeralds claimed that the Colorado Division of Water Resources, specifically the State Engineer's Office (SEO), was abdicating its responsibilities by allowing CBM companies to remove groundwater from the NSJB without permits. Tributary groundwater and surface water are supposed to be similar in the eyes of Colorado's prior appropriation doctrine since they are connected to one other, and allocation of tributary groundwater is permitted by the SEO. However, the SEO had never actually regulated groundwater removed in the process of mining, in part because it had never been declared a "beneficial use" of water under Colorado water law. CBM operators saw produced water as a waste product that must be removed in order to extract methane, and which had simply to be disposed of properly[8]. Characterizing produced water in this way left it out of the water rights regime under Colorado law. Had it been called a beneficial use, a CBM well would need a water well permit from SEO. The state of Colorado formally and informally held the position that produced water from petroleum operations was merely a nuisance. While oil and gas wells did not have an explicit exemption from the permitting requirements set forth in groundwater regulation and water rights

[8] In the NSJB disposal of produced water is predominantly accomplished by re-injection into regulated disposal wells constructed in sandstone formations much deeper than the Fruitland Formation.

laws, the agencies and interpreted the law so that COGCC regulated it as a mining waste. For the most part, the SEO stayed out of produced water regulation.

The Vances and Fitzgeralds wanted the state's approach to produce water to change, however. They wanted the SEO to permit groundwater withdrawals from CBM wells and to require those withdrawing tributary groundwater to replace what they removed, so as not to impact senior surface water rights. The ranchers asked the court to declare that removing groundwater in the process of CBM development be considered a "beneficial use " under Colorado water law, one that would fall under water rights regime just like all of the other beneficial uses in of water in the state. The SEO disagreed, and responded with a motion to dismiss the case in December 2005 (Suthers, 2005). The SEO said they did not have jurisdiction over produced water, and deferred to the COGCC. In a few statements about the scientific merits of the case, SEO also said that they "neither denied nor admitted" that the ranchers' claims about hydraulic connectivity were true, though they argued that predicted depletions to streams were miniscule and that significant uncertainty still existed about CBM development's impacts to shallow aquifers.

The Compartmentalized Basin conceptual model officially appeared in the case in a motion for summary judgment filed seven months later by BP (Miller, 2006). The CBM operator had been allowed to participate in the case as a Defendant-Intervenor after arguing that they were "in a far better position than either the state or plaintiffs to describe the substantive and technical aspects of CBM production and well operations, the extraction, handling and disposal of water, and the impacts from a ruling in favor of Plaintiffs on both CBM production and natural gas supplies in Colorado." At the time, BP operated over 1,100 CBM wells on state, federal, and private mineral leases in the NSJB, producing over 640 million cubic feet per day of

CBM and employing over 540 people in the area to carry out multi-billion dollar[9] oil and gas operations, according to their brief (Miller, 2006). BP argued that withdrawals of produced water were not a beneficial use under the law and that previous research and modeling had overestimated the tributary nature of groundwater in the NSJB. BP then put forward the Compartmentalized Basin conceptual model, citing the Riese et al. study (2005) and a study by Snyder and Riese (2003). BP concluded by arguing that the ranchers couldn't demonstrate any actual material injury to their water rights. In a reply to the court filed in August (Suthers, 2006), the SEO said they agreed with all of the arguments and facts set forth by BP.

The court ultimately considered the evidence and arguments submitted by BP "in regards to non-tributariness" to be immaterial to the case, however (*Vance v. Wolfe*, 2007). BP's efforts to put forward the Compartmentalized Basin model did not matter because Colorado groundwater law assumed tributariness and the court did not have to argue otherwise. In a ruling issued in July 2007, Judge Gregory G. Lyman of the District Court, Water Division Seven wrote that the court had reached the "unavoidable conclusion that non-exempted mineral-related activities, such as oil and gas activities, are subject to the scrutiny of state water law… The statute implies that dewatering of geologic formations by removing tributary ground water to facilitate or permit mining of minerals requires a water well permit." The ranchers had won their case at the water court, but their legal work was not finished, nor was the expense[10]. All parties involved knew that the case was headed for the Colorado Supreme Court. In a later statement (Lyman, 2007), Judge Lyman would acknowledge the importance of the case this way: "For better or for worse, this

[9] Applying the average profit per MCF of natural gas in the U.S. in 2005 ($6.78 per MCF produced) to BP's stated production volumes, the ranchers' lawyers came up with an estimated profit of $1.5 billion from one year's production in La Plata County.
[10] The cost of the case to the plaintiffs was $29,002.31 at the time of Judge Lyman's 2007 ruling, according to court documents.

Court's order overturns longstanding policy concerning the need for well permits under the circumstances of this case. Serious legal issues are involved, and the court has been well aware from the inception of the case that the issue will ultimately be decided by the Supreme Court of Colorado."

Two years later, in April 2009, the Colorado Supreme Court affirmed the Durango Water Court's decision and ruled in the ranchers' favor for a second time. The court upheld Judge Lyman's ruling that extraction of groundwater in the process of CBM constitutes a beneficial use, and therefore an appropriation, of water under the Colorado water rights regime. CBM wells producing tributary water would therefore be subject to water well permitting, water court adjudication, and administration in Colorado's water rights priority system. That process would include a requirement that CBM operators replace tributary water withdrawals and file augmentation plans that described how they would do so. In so ruling, the court declined to give deference to the State Engineer's long-standing contrary interpretations of Colorado groundwater and water right administration laws (Holland & Hart, 2009). Nontributary groundwater withdrawals would have to be permitted, too, since that water was also being "beneficially used," though operators would not have to provide augmentation plans to replace it.

The ruling initiated a deluge of groundwater permit applications at the State Engineer's Office, and DWR staff braced for the many thousands of inbound requests. In anticipation of the new regulatory requirements for thousands of CBM wells across the state, the Colorado General Assembly moved the deadline for tributary well permits by nine months, to March 31, 2010, and set the deadline for augmentation plans to no later than December 31, 2012 (Hanel, 2010a). The legislature also directed the SEO to determine which wells could be considered nontributary, which spurred another controversial policy proceeding.

State Engineer's Stream Depletion Study (2005-2006)

Back in 2005, the State Engineer's Office, together with COGCC, commissioned yet another stream depletion study (a fourth model, after the two 3M Project models in 2000 and Questa's 2001 model). The earlier studies had made it apparent to regulators that Fruitland Formation discharge was indeed tributary to streams and that CBM development was intercepting some of that water. The SEO and COGCC anticipated that they might need to administer CBM groundwater withdrawals at some point in the future due to legal challenges from senior water rights holders such as the Vances and Fitzgeralds. Because administering groundwater withdrawals for thousands of CBM wells would be an enormous undertaking, the agencies wanted to see if a simple analytical tool might help them do two things: 1) quantify stream depletion from CBM groundwater withdrawals, and 2) determine which regions of CBM basins could be considered nontributary groundwater areas[11]. In essence, the SEO wanted to divide CBM basins into areas of tributary and nontributary water in order to reduce state permitting requirements. (For a visual schematic of this boundary, please refer to Figure 2.22).

The state agencies decided to apply a simple analytical solution called the Glover Balmer method to the problem to see if they could come up with a relatively quick first-order estimate of tributary/nontributary boundaries in CBM fields across the state. Developed in the 1950s, the Glover Balmer method is designed to solve for the ratio of stream depletion to total pumpage for a well pumping from an aquifer that is fully connected to a stream (Glover et al., 1954). The following equation describes the basic form of Glover Balmer, where q/Q is the ratio of the quantity of

[11] The definition of nontributary groundwater is water that will not, within 100 years, deplete the flow of a natural stream at an annual rate greater than one tenth of one percent of the annual rate of withdrawal.

stream depletion to pumping rate for time t; a is the distance of the pumping well from the stream, and T and S are the aquifer transmissivity and storativity, respectively. The complementary error function, erfc, is a probability function that returns a proportion between 0 and 1 for the input value.

$$q / Q = erfc\left(\sqrt{\frac{a^2 S}{4tT}}\right)$$

The agencies hired S.S. Papadopulos & Associates, Inc. (Papadopulos) for the analysis – an international environmental engineering firm with an office in Boulder, CO. The study relied on COGCC and 3M Project data on monthly gas and water production for approximately 1,650 gas wells in the NSJB. In coming up with tributary/non-tributary boundaries, Papadopulos had to address the many simplifying assumptions of the Glover Balmer approach, and make a case as to why Glover Balmer could be used in such a complex environment, where all of its simplifying assumptions would be violated to some degree. (The approach, for example, assumes that the aquifer does not contain gas and is homogeneous and isotropic with horizontal-only flow.) Papadopulos also had to address the NSJB's dueling conceptual models in order to move forward in their analysis. Estimating the transmissivity and storativity of the aquifer – moreover, coming with average terms for transmissivity and storativity across the entire NSJB – required deriving averages for aquifer parameters like hydraulic conductivity, and aquifer thickness, and permeability. Doing this for the entire NSJB required Papadopulos to clearly state what kinds of assumptions they would start with in their analysis – or, in other words, which conceptual model they would use.

Papadopulos took an interesting new turn in doing this. In their final report (Papadopulos, 2006), they summarized the two dominant conceptual models of the

NSJB, and described how they differed and what evidence and/or assumptions supported each idea. Then, instead of pegging the Hydraulically Connected Basin model and the Compartmentalized Basin model as two endpoints on a spectrum defined by hydraulic connectivity, the authors focused on the conceptual models' commonalities and made a case for why the two models were not that far apart. "Examination of the hydraulic characteristics of the aquifer and consideration of recharge-discharge volumes suggest that the models do not represent substantially different flow dynamics," Papadopulos wrote (p. 22). The differences between the conceptual models "primarily are a matter of degree," the engineers reasoned, and those differences "could be handled practically by the assignment of appropriate parameters."

Instead of choosing between the two conceptual models, as AHA and the SJPLC had done, Papadopulos merged them. The basin could be both hydraulically connected and compartmentalized at the same time, they argued, by being hydraulically connected at a low level in some areas but not others. Low permeability areas and spatially preferential recharge flowpaths were compatible with a "flow-through" system, just on a more restricted level than they would be in another system with greater permeability, they said. Papadopulos therefore built their analysis on a merged conceptual model, which held that the Fruitland Formation/Pictured Cliffs Sandstone aquifer discharged into streams and also conducted water into the deeper basin, but very slowly – severely restricted by low permeability within the aquifer and virtually impermeable adjacent formations. "In the aggregate, there is hydraulic communication within the Fruitland-Pictured Cliffs aquifer and between this aquifer and the streams where they traverse the Outcrop areas," Papadopulos wrote (p. 27), it was just very limited hydraulic communication.

The consultancy came up with a tributary/nontributary borderline of about 17 km (10.5 mi) basinward from the Fruitland Outcrop and the SEO released the report to the public in April 2006. Following the Papadopulos conclusions, groundwater inside of 10.5 miles from the Outcrop would be considered tributary, while groundwater beyond it would be considered nontributary. CBM development within the 10.5 mi tributary/non-tributary boundary was depleting streams by an average 155 af/y at the time, according to the analysis. This depletion and would peak at 170 af/y in 2035, which the SEO reasoned in comments prefacing the report, was a small amount compared to the combined mean yearly baseflows for the Animas, Florida and Pine Rivers. The figure was generally consistent with the 3M Project predictions, but that did not mean it was met with widespread agreement.

Several hydrogeologists submitted comments on the analysis as part of a technical review process, and all criticized the Glover Balmer analysis for oversimplifying a complex system. Commenters said the analytical model was a poor choice for such an important policy-making process, though they were divided in their disagreement over its shortcomings (Papadopulos, 2006). Representatives of the Southern Ute Indian Tribe thought 155 af/y was a significant overestimate of stream depletions because it ignored the reduction in permeability that that accompanies gas desorption and dual-phase flow dynamics, among other criticisms. Jams T. McCord, PhD, an employee of Hydrosphere Resource Consultants based in Boulder, CO. and author of early work that proposed a Hydraulically Connected Basin model (McCord et al., 1992), considered 155 af/y to be a significant underestimate. McCord argued that analysts should not have modeled the Outcrop as a constant head boundary that could provide unlimited amounts of water to the aquifer when, in reality, it would be better represented as a no-flow boundary with limited recharge. McCord also asked why the study had not attempted to modeled expected water level declines in the Outcrop area, and argued that the remaining 2,800 af/y of CBM groundwater withdrawals in the NSJB was probably coming from, or impacting, groundwater storage at the Outcrop.

State Engineer's Tributary/Nontributary Rulemaking and Norwest's Tributary/Nontributary and Stream Depletion Model (2009-2010)

In the fall of 2009, a few months after the Vances and Fitzgeralds had won at the Colorado Supreme Court, the State Engineer moved forward on a rulemaking to formally determine and establish the Fruitland Formation tributary/nontributary boundary in the NSJB. The rulemaking was being driven forward by the March 31, 2010 deadline for CBM operators to submit augmentation plans for tributary groundwater withdrawals. The decision about the NSJB was just one tributary/nontributary determination in a rulemaking on gas basins across the state, but it received special consideration. On October 16, 2009, Norwest submitted a new NSJB groundwater model to supplant the SEO's analysis using the Glover Balmer equation (Norwest, 2009). Norwest Corp. (Norwest) had merged with AHA and Questa, and had combined the consultancies' oil, gas, and water resources business. The Southern Ute Indian Tribe (SUIT) submitted the model to the proceeding on behalf of BP, Chevron U.S.A. Inc., ConocoPhillips Co., XTO Energy Inc., and other gas operators in the NSJB who had funded the project. The model had been built with oversight from a technical advisory group made up of representatives from the companies, as well as the COGCC, SEO, and Colorado Geological Survey, but not the SJPLC. The advisory group members provided data and input on the conceptual model, numerical model construction, and model calibration, according to Norwest (2009).

The SEO adopted Norwest's model in the rulemaking as being superior to its own analysis, and used the tributary/nontributary boundary derived by Norwest in place of the 17 km (10.5 mi) boundary produced by Papadopulos. Norwest used USGS-developed MODFLOW code to develop a numeric model of groundwater flow in the Fruitland Formation and Pictured Cliffs Sandstone, which they described as "a refinement of previous regional models," and which they used to evaluate the degree of interaction between groundwater and surface water and delineate the tributary/nontributary line in the region. According to Norwest, the new model incorporated many of the complexities of the NSJB, including the heterogeneous geology of the Fruitland Formation and Pictured Cliffs Sandstone. Norwest embraced the conceptual model compromise put forward by Papadopulos to some degree, suggesting that there were "relative differences in groundwater circulation" in certain areas of the basin – more active circulation near the Fruitland Outcrop, for example – but that there weren't any "areas of complete compartmentalization." To Norwest, the patterns of three primary geochemical indicators from previous studies (TDS, chloride, and stable isotope ratios) indicated a spatially varied mix of water types in the basin consistent with areas of preferential groundwater flow paths, primary discharge to rivers and limited groundwater flow across the state line into the deep basin.

Following that conceptual model, Norwest came up with a much narrower tributary region than SEO had via the Glover Balmer analysis, meaning more CBM wells were determined to be drawing nontributary water. Compared to the SEO's original 10.5 mi dividing line, Norwest came up with a maximum extent of approximately 13 km (8 mi) down the Pine and Animas Rivers, with closer to a 6.5 km (4 mi) extent along the Florida and Piedra drainages, and no boundary in several places (for a map of Norwest's boundary, please refer to Figure 2.23). The differences in the boundaries, according to Norwest, could be attributed to "geological heterogeneities in the Fruitland (thickness, hydraulic conductivity, geometry, and extent of saturated alluvium), variances in river stages, and related factors." The SEO adopted Norwest's boundaries, effective January 10, 2010. In doing so, SEO shrunk the tributary groundwater designation in the NSJB for the second time that year. At first, the entire basin had been considered tributary under the default assumptions of Colorado groundwater law, affirmed by the Supreme Court. After that, the tributary area had been conceptually downsized to a distance spanning 10.5 mi from the Outcrop, and finally to a distance measuring much less in the formal rulemaking decision. (To see the Norwest-derived boundary superimposed on the Papadopulos-derived boundary, please refer to Figure 2.24).

Legal Challenges to Tributary/Nontributary Rulemaking (2009-Present)

During the SEO's tributary/nontributary rulemaking, a diverse group of parties expressed concern that the decision-making process was moving too quickly and that the general public did not have enough time to consider the proposed rules and provide comments on them. After the SEO completed the rulemaking, the group filed a legal complaint against the State Engineer, again at District Court, Water Division Seven (Klahn, 2010). The new legal complaint included the Vances and the Fitzgeralds, now veterans of NSJB energy-water legal issues, as well as the San Juan Citizen's Alliance and the Oil and Gas Accountability Project of the NSJB. The complaint also included diverse new parties, however – the City of Boulder, the Centennial Water and Sanitation District, and Natural Soda Inc., among others – all who thought their vested water rights might be infringed upon by the SEO's tributary/nontributary rulemaking.

The parties sued for lack of due process. Any determination that certain groundwater is nontributary could adversely effect senior groundwater and surface water rights such as theirs, they argued in their opening complaint (Klahn, 2010). Under Colorado law, the right to withdraw nontributary ground water belongs to the overlying landowner. The parties were concerned that gas companies might be granted rights to nontributary ground water without consideration of the overlying landowner's rights. This case is ongoing, now at the District Court in Greeley, CO. The parties were also skeptical of Norwest's industry-supported modeling and mapping, and filed a separate lawsuit to challenge it. The parties decided to hold on pursuing the second case until the first case had been decided (Hanel, 2010b).

DISCUSSION

When fathoming the level of disagreement about the NSJB's inner-workings – and the number of years that resource managers, industry, and scientists have spent doing that disagreeing – it is sometimes difficult to imagine that 900 square miles of badlands, mesas, and hogbacks can produce so much discord. When we are reminded, however, that CBM operators profit considerably from mining underneath those badlands, mesas, and hogbacks, and that doing so provides California with a large fraction of its natural gas, the contention becomes easier to grasp. The potentiometric groundwater surface in the basin may be dropping by hundreds, even thousands, of feet in some places, but pressure levels of the associated environmental conflicts certainly are not.

Returning to the research question at hand, the groundwater system in the NSJB proves to be particularly problematic when it comes to resolving factual disputes about its dynamics in large part because of the conflicting conceptual frameworks described above, held in different regard by key stakeholders involved in its use and management. The differing conceptual models are so fundamental to resource manager and industry views that the parties are capable of interpreting the same sets of data in opposite ways, as highlighted by SJPLC in their EIS (2006). Conversely, the conceptual models are malleable enough to be merged into one, as done by Papadopulos (2006) and Norwest (2009), who argue that the NSJB is *both* compartmentalized and hydraulically connected to some degree.

Returning to the obstacles that plague complex factual debates, as identified by Adler et al. (2007), a Shifting Conceptual Framework in a highly technical environmental conflict occurs when data cannot be effectively understood because the framework or paradigm for interpreting it is "undergoing a significant knowledge shift." Based on the cases presented above, that definition may not be adequate in this setting. Describing the NSJB conflict over conceptual models as victim of a mere "knowledge shift" leaves out the agency of the parties invested in the conceptual models, as well as the models' significant strategic value as they are proposed and debated in different policy and legal settings. Adler et al.'s definition of "Uncertainty and Division among Scientists" works rather well without adjustment, however. The authors define this type of division as massive scientific and technical uncertainty remaining despite great amounts of "advocacy, research, and applied studies." In cases of uncertainty and division among scientists, "peer reviewed studies are equivocal and the opinions or credible experts are deeply divided," according to Adler. Combining these two "Rocks on the Road to Agreement," to borrow Adler et. al's term, provides an accurate portrait of the factual dispute dynamics underway at the energy-water nexus in the NSJB: significant uncertainty and division among researchers and resource managers that persists despite great amounts of investigation and analysis, primarily because of strategic and opposing paradigms for understanding the results. It would appear that Tidwell and van den Brink's (2008) warning about groundwater modeling has been proven true in a new case: "Ultimately, the danger [in groundwater modeling] is uncertainty leading to dueling models and polarization of views by competing interests."

If factual consensus were easy to achieve in the NSJB, the current dispute over conceptual models would not have lasted for over ten years and appeared in state and federal administrative and judicial proceedings. Still, as explained earlier, fact-finding efforts can go a long way toward resolving factual disputes, and while one might imagine that the NSJB could not possibly be studied any more than it already has been, major gaps in our understanding of regional groundwater flow and groundwater-surface water interactions at the Fruitland Outcrop do still exist. The previous decade's focus on groundwater modeling based from deep-basin CBM well data has not moved resource managers much closer to understanding, empirically, what might be occurring at the Outcrop. The next chapter focuses on addressing some of those knowledge gaps using isotopic and geochemical tracers.

The scientific and modeling work described thus far has primarily been industry-funded, and all of it has relied in one way or another on industry-provided data. Getting beyond the concealed nature of groundwater systems requires peering through "windows" into the subsurface that, more often than not, are CBM wells – and accessing CBM wells requires industry approval and assistance. Understanding groundwater movement at a regional sale requires expensive modeling efforts that must somehow be funded; in the NSJB, most models have been at least partially funded by industry and reviewed by advisory groups composed of industry members and industry consultants. Based on what we know about environmental conflict, it is not surprising, therefore, that domestic well owners in the NSJB do not trust these studies, or that they are challenging them in court. Due to disparities in scientific resources, parties on one side of the groundwater conflict have dominated the investigation of the resource question at hand, resulting in due process and legitimacy concerns by the other side. The dynamics of this environmental conflict, and the related disputes, could potentially be improved by neutral fact-finding efforts.

The work that follows in Chapter 3 is one attempt at remedying these disparities and focusing empirical attention on the immediate Fruitland Outcrop region, where the biggest questions still await answers and where, at the outset of this project, important baseline data still needed to be collected. In essence, the isotopic and geochemical investigation presented here is just the kind of neutral fact-finding effort that could improve the dynamics of the NSJB environmental conflict at hand. The study was conducted by independent university scientists from the University of Colorado and Fort Lewis College, as well as independent scientists and field staff the Mountain Studies Institute. The San Juan Public Lands Center funded the data collection and analysis in order to add a monitoring component to the research and modeling it had funded in conjunction with state agencies and industry operators under the 3M Project. (In 2007, the 3M Project gained an additional "M" in its name, for "Monitoring," and became the 4M Project.) The research that follows embodies the SJPLC's new monitoring emphasis.

In circumstances of dueling conceptual models, empirical work and monitoring gain increased importance. Yes, conflicting parties can interpret data differently (and as we have seen, they often do), but that does not mean that empirical evidence is not important. In fact, when our goal is to gain a better understanding of the regional dynamics of a system that we cannot see – a system typically described by computer models – empirical, "ground-truth" data becomes critically important. Monitoring is empirical work executed repeatedly, and it, too, gains critical importance in a case of dueling conceptual models. It may take another ten years for parties involved in CBM development in the NSJB to come to consensus on a single conceptual model of regional groundwater – or they may never achieve it. Meantime, long-term monitoring will have captured the actual manifestations of one conceptual model or another at the Fruitland Outcrop.

CHAPTER 3

FRUITLAND OUTCROP ISOTOPIC & GEOCHEMICAL INVESTIGATION

INTRODUCTION

As detailed in the previous chapter, there remains considerable uncertainty about how CBM production from the Fruitland Formation may affect the quantity and quality of surface waters, springs, wetlands, and groundwater systems near the Fruitland Outcrop in southwest Colorado. The Northern San Juan Basin (NSJB) is one of the most extensively studied CBM basins the world (Snyder and Fabryka-Martin, 2007), having been the subject of many chemical and isotopic investigations (Scott and Kaiser, 1994; Snyder et al., 2003; Riese et al., 2005; Zhou et al., 2005; Zhou and Ballentine, 2006), geophysical logging studies (Clarkson et al., 1988; McCord et al., 1992), stratigraphic analyses (Ayers and Kaiser, 1994; Fassett, 2000), and regional modeling efforts (AHA, 2000; Questa, 2000, 2001; Papadopulos, 2006; Norwest, 2009).

Yet for all the research activities that have focused on the NSJB, there remains significant controversy over its hydrogeologic dynamics: specifically, over whether the deep basin Fruitland Formation is hydraulically connected to the Fruitland Outcrop, the extent to which the Fruitland Formation aquifer undergoes active hydrologic through-flow, as well as if, and/or how, CBM production will affect surface–groundwater interactions at the Outcrop. Conflicting conceptual models of the natural flow dynamics of the Fruitland Formation fuel this disagreement. The dueling conceptual models of the Hydraulically Connected Basin and the Compartmentalized Basin differ in their descriptions of hydraulic connectivity within the Fruitland Formation aquifer, as well as on the aquifer's level of connectivity to shallow groundwater and surface water features near the Fruitland Outcrop. The manifestation of this scientific disagreement is an ongoing series of disputes over whether CBM-related groundwater withdrawals from the Fruitland Formation will cause near-Outcrop declines in natural springs, domestic water wells, and baseflow to rivers and streams. Confounding the evaluation of these contrasting views on the hydrologic connectivity of the NSJB is the interplay of other factors such as drought and domestic well use, which may accelerate groundwater depletions alongside CBM development. The number of domestic water wells in the Project Area is growing at a fast rate: new permits issued in La Plata County have averaged more than 300 annually for the past 10 years (SJPLC, 2006).

FACT-FINDING OBJECTIVES AND QUESTIONS

The present study aims to more closely characterize Fruitland Formation hydrology using geochemical and isotopic data from several sources: precipitation, streams, springs, piezometers, domestic water wells, and CBM wells. The study was designed with specific focus on groundwater-surface water interactions in the near-Outcrop environment, as well as with a new emphasis on the Piedra River drainage. The Piedra has received less attention than its western neighbors in earlier research on the Fruitland Formation; it is also the area that may see the largest increase in CBM activity in the years to come, as previously un-developed federal mineral rights are brought into production under the SJPLC's 2007 decision on well spacing (SJPLC, 2007). The overall objectives of this analysis are the following:

1. Provide baseline information on the current isotopic and geochemical content springs, rivers, and domestic wells along and near the Fruitland Outcrop prior to increased CBM development.

2. Use this data to evaluate the following scientific questions and management concerns:

   a. Is the Fruitland Outcrop an active recharge and discharge area?
   b. Will CBM-related groundwater withdrawals from the Fruitland Formation cause declines in groundwater levels near the Outcrop that could impact domestic water wells?
   c. Will CBM-related groundwater withdrawals from the Fruitland Formation intercept groundwater that would normally discharge via springs, thereby decreasing spring flow?
   d. Will CBM-related groundwater withdrawals from the Fruitland Formation intercept groundwater that would normally discharge to rivers and streams, thereby decreasing baseflow to those rivers?

ISOTOPIC AND GEOCHEMICAL TRACERS

Isotopes in Hydrology

When used as a tool in hydrology, isotopes can give direct insight into water's origins in, and routes through, the hydrologic cycle. In their natural state, groundwater and surface water contain isotopes that vary in concentration in ways that provide useful information. Isotope hydrology can often be the most cost effective means by which to assess the rate, age and sources of groundwater recharge, for example, or relationships between precipitation and surface water flow.

Isotopes are atoms of the same element that have the same numbers of protons and electrons but different numbers of neutrons. The variation in neutron count between the various isotopes of an element give isotopes similar charges but different atomic masses. The vast majority of oxygen atoms in water (99.76%) have an atomic mass of 16 ($^{16}0$). A small fraction (0.2%) has an atomic mass of 18 (^{18}O), however, and it is the heavy isotope of oxygen. Similarly, most hydrogen atoms (99.985%) have an atomic mass of one (^{1}H), but a small subset have a mass of two (^{2}H) and are known as hydrogen's deuterium (D) isotope. The so-called stable isotopes do not appear to decay to form other isotopes on geologic timescales, but may themselves be produced by the decay of radioactive isotopes. Both ^{18}O and ^{2}H are stable isotopes.

The isotopic composition of a water sample is expressed as the deviation of the ratio of heavy isotopes (^{18}O, ^{2}H) to light isotopes (^{16}O, ^{1}H) from an international standard set by the International Atomic Energy Agency (IAEA) in Vienna, Austria. To illustrate, the ^{18}O values are expressed in conventional delta (δ) notation in units of per mil (‰) relative to Vienna Standard Mean Ocean Water (V-SMOW).

$$\delta^{18}O = \left(\frac{R_{\text{sample}}}{R_{\text{standard}}} - 1\right) \times 1{,}000$$

Deuterium values are expressed with the same notation, as δ^2H. The isotopic values of V-SMOW are set at 0 ‰.

Radioactive (unstable) isotopes are nuclei that spontaneously disintegrate over time to form other isotopes. A second isotope of hydrogen, this one unstable, is called tritium and has an atomic mass of three (^3H).

Fractionation of Stable Water Isotopes in Precipitation

Whenever water changes state, such as during condensation/evaporation and melting/freezing, a process called isotopic fractionation occurs, during which water's isotopes segregate themselves by means of their different masses and, thereby, different vapor pressures. For example, in Figure 3.1, note that precipitation becomes more negative during the phase change from rain to snow. In fact, fractionation becomes more efficient with colder air temperatures. Because cool air contains less energy, heavy and light isotopes fractionate more readily. The process of fractionation leaves water samples tagged with an isotopic signature that can elucidate their history and pathway(s) through the hydrologic cycle. In general, evaporation selects for lighter isotopes and condensation selects for heavier isotopes. Moisture evaporated from the ocean into clouds, for example, holds relatively fewer heavy water isotopes (^{18}O, ^2H) than the body of water it evaporated from because it takes less energy for lighter isotopes to vaporize into gas. Conversely, heavier isotopes of water molecules more easily drop from clouds in rain and snow because of their larger mass (for a schematic of the "rainout effect" please refer to Figure 3.2).

Most clouds form over large water bodies such as oceans and seas. Since ocean water by definition has a value of 0 ‰ for both oxygen-18 and deuterium, a cloud's isotopic values will be negative because it is depleted in the heavier isotopes relative to the ocean. Moreover, a cloud that has traveled inland from the coast will be made up of even less $\delta^{18}O$ and $\delta^{2}H$, as heavy isotopes are the first to condense and "rain out" of clouds. The further precipitation falls from the coast, the fewer heavy isotopes it contains, or the more "depleted" it is in $\delta^{18}O$ and $\delta^{2}H$. Precipitation thus "gets lighter" in its isotopic make-up with increasing latitude, movement toward the continental interior, uplift over mountain ranges, colder air temperatures, and snow versus rain.

For the San Juan Mountains, values of $\delta^{18}O$ for snow are around -18‰ and lower, while rainfall is characterized by less depleted (i.e., less negative, or more enriched) values around -10‰. These values vary by elevation, by temperature at which the precipitation formed in the atmosphere, and other conditions. Conveniently, because these values differ with snow versus rain, it is possible to determine if groundwater recharge is from snow or from rain, or a mixture of the two. Similarly, isotopic values of surface waters can tell us if snow or rain is the primary source of that water.

Global Meteoric Water Line in Precipitation

The informative power of water's isotopic content comes first from delta values, and even more information can be gained from the comparison of these values to each other, as well as to a related international point of reference known as the Global Meteoric Water Line (GMWL). Worldwide, the $\delta^{18}O$ and $\delta^{2}H$ values in precipitation behave predictably, demonstrating a linear relationship as defined by Craig (1961):

$$\delta^2H = 10 + 8\ \delta^{18}O$$

This equation reflects the different rate at which $\delta^{18}O$ and δ^2H isotopes partition themselves: the slope of 8 for the GMWL derives from $\delta^{18}O$'s fractionation factor, which is eight times larger than deuterium's. Rozanski et al. (1993) validated this model with a compilation of precipitation measurements made at stations throughout the IAEA global network (GMWL derived from worldwide precipitation presented in Figure 3.3). Note that in Figure 3.3, the more depleted or more negative values are from colder regions and the more enriched values are from warmer regions of the world. Similarly near the Fruitland Outcrop, at any particular site, winter precipitation (eg., snow) will have more negative values than summer precipitation (eg., rain). While the GMWL provides a global perspective on the $\delta^2H/\delta^{18}O$ relationship, the relationship for a specific region may vary and should be determined from empirical measurements of δ^2H and $\delta^{18}O$ in precipitation. Such measurements allow investigators to develop a Local Meteoric Water Line specific to the region of interest.

Fractionation of Stable Water Isotopes in Evaporation

As illustrated above, the $\delta^{18}O$ and δ^2H values of most of the world's precipitation reside at or near the GMWL. However, a handful of physical processes can change the relationship between water's heavy isotopes such that they plot differently. For water, the higher the mass number, the lower the vapor pressure. Thus, ^{16}O and ^{1}H preferentially enter the vapor phase, whereas ^{18}O and ^{2}H preferentially concentrate in the liquid phase. Consequently, in evaporation, water vapor is enriched in ^{16}O and ^{1}H, whereas the remaining liquid water is enriched in ^{18}O

and ^2H. At very low relative humidities (< 25 percent) the slope of the $\delta^2H/\delta^{18}O$ relationship in the remaining water will be close to 4; for moderate relative humidities (25–75 percent) the slope will be between 4 and 5; only for relative humidities above 95 percent does the slope approach 8, the slope of the meteoric water line (evaporative effect on the $\delta^2H/\delta^{18}O$ relationship presented in Figure 3.4). To illustrate for the Rio Grande River,

$$\delta^2H = -28 + 5.1\ \delta^{18}O$$

Thus, water bodies (eg., streams, wetlands, groundwater) in semi-arid areas such as the Fruitland Outcrop that have experienced significant evaporation will have $\delta^2H/\delta^{18}O$ slopes around 5 to 6.

The slope of the $\delta^2H/\delta^{18}O$ relationship may provide diagnostic information on source waters that contribute to a water body. For example, in a recent dispute over groundwater pumping in Arizona and California, a group of senior water rights holders on the Colorado River claimed that the groundwater being tapped by domestic wells in their region was in fact Colorado River water, for which the domestic well owners did not have a water right (Guay et al., 2008). Measurements of δ^2H and $\delta^{18}O$ provided a way to distinguish between withdrawals of Colorado River water or locally recharged groundwater (Figure 3.5). Waters recharged from snowmelt and local rain plotted on and near the GMWL. In contrast, nearby Colorado River water had undergone considerable evaporation and hence plotted below the GMWL. In keeping, well water samples could be classified as either locally recharged tributary water or nearby Colorado River water based on which $\delta^2H/\delta^{18}O$ line they matched.

Using Tritium (^3H) to Date Water

Tritium (^3H) is a rare but naturally occurring hydrogen isotope that arises from the interaction of cosmic rays and the Earth's atmospheric gases. Tritium is produced in the stratosphere by cosmic ray spallation, where it is also incorporated into water molecules and is a normal component of precipitation. Tritium is also produced during nuclear reactions. As a result, the aboveground testing of atomic weapons from 1952 until the late 1960s gave hydrologists an additional marker to add to the tritium dating scheme (Figure 3.6), particularly in the Northern Hemisphere (Kaufman & Libby, 1954). For the past five decades tritium has been widely used to obtain time scales for physical mixing processes in oceanographic and hydrologic systems based on interpretations of 1960s-era "bomb spike" values, as well as lower tritium concentrations found naturally in precipitation (IAEA, 1962; Michel, 2005; Suess, 1969).

Tritium is measured in tritium units (TU), with one TU equal to one tritium atom in 10^{18} hydrogen atoms. Age-dating using tritium is based on the radioactive decay of tritium to helium-3 (^3He). Tritium has a half-life of 12.3 years, providing effective age dating over about five decades. Because of the irregularly shaped bomb peak, tritium data can often give ambiguous ages. This may be resolved by measuring the change in tritium concentration over a time interval of a few years, or by comparison to CFC and SF_6 ages.

Present day concentrations of tritium in new precipitation are generally in the range of 5-15 Tritium Units (TU). Water that produces tritium levels higher than present day atmospheric concentrations must contain some "bomb spike" water from the weapons testing era. Conversely, water found to be "tritium dead," or with zero tritium, dates to before the atomic age. Clark and Fritz (1997) provide an overview of how to interpret the age of water using tritium values. Water with tritium values less than 0.8 TU are below the detection limit for tritium because of almost or complete radioactive decay of the atmospheric tritium in the water body, so we know that recharge to that water reservoir was prior to the 1950s and call this water "submodern." Tritium values in the range of 0.8 to 4.0 TU are a mixture of submodern and "modern" waters. Modern waters (less than 10 years old) are characterized by values near the current precipitation values, ranging from 5 to 15 TU. Tritium values greater than 30 TU occur if recharge occurred in the 1960s and 1970s, while tritium values greater than 50 TU are the result of recharge in the 1960s. While tritium alone cannot give an accurate estimate of age, its concentration can place limits on the possible time scales for hydrologic processes being studied in the system. The tritium time scale can also be used to assist in the interpretation of other isotopic data that is being used for studying issues such as climate variations and effects of changes in land use (Gibson et al., 2002) and surface-groundwater interactions (Michel, 2005).

An example of how tritium values change with perturbations of groundwater is presented in Figure 3.7. The Elkhorn Well was recently developed as a source of municipal water for the city of Leadville, Colorado. Tritium values prior to the initiation of pumping were high, about 23 TU, indicating a significant contribution of bomb spike water to the well and suggesting that much of the groundwater in the well was recharged in the 1960s and 1970s (Wireman et al., 2006). Tritium values dropped as water was pumped from the Elkhorn Well, however, declining until they more closely matched tritium values in modern precipitation. That tritium reduction occurred as groundwater pumping drew out old, weapons testing-era water – forming, in the process, what is known as a "cone of depression," which was then filled in by more recent, tritium-light water. Generally speaking, over-drafting of local groundwater results in the replacement of older water with recent water recharged from precipitation, as pumping-generated cones of depression with high hydraulic conductivity draw in any available water.

When interpreted jointly, isotopes give us information in the ways they co-vary with one another. Stable isotopes (^{18}O, ^{2}H) are excellent indicators of water's circulation, while radioactive isotopes (^{3}H) are of particular value in determining its residence time. In analyzing a groundwater source, for example, correlating the distribution of stable isotopes with tritium composition can shed light on its origin, flowpaths, and transit time.

Geochemistry

Since groundwater is in constant communion with rocks and soils, geochemical information can also provide important hydrologic insights. Geochemistry roughly combines sourcing and dating capabilities described thus far for water isotopes, but through a more diverse set of constituent elements, isotopes and ions, and the myriad relationships between them. For the purposes of understanding the Fruitland Formation and the San Juan Basin system, it is important to delineate the geochemical traits of groundwater that has traveled through CBM deposits. The geochemical processes inherent to these deposits modify groundwater significantly, giving it a distinctive signature. In transit through formations like the Fruitland, groundwater mixes with aged brines that elevate its concentrations of chloride, bicarbonate, sodium, other major ions, and total dissolved solids (Van Voast, 2003). Formation groundwater is just as unique for what it does not contain – namely, very little calcium and magnesium and an almost total absence of sulfate.

Formation water owes its unique chemical composition to the brackish, near marine environment that accompanied coalbed deposition during the Cretaceous Period, as well as the biological processes that accompany coal formation. Like water from other coal-producing areas, Fruitland Formation water tends to be sodium bicarbonate ($NaHCO_3$) to sodium chloride (NaCl) dominated. Chloride (Cl^-) and sodium (Na^+) are particularly high in parts of the San Juan Basin where coals are in stratigraphic association with ancient marine or marine-transitional beds (Van Voast, 2003). Their concentrations vary with residence time, depth and mixing or flushing by recharge (Toth, 1962). In the San Juan Basin, chloride, sodium and bicarbonate concentrations are the lowest where water is recharged at the Outcrop, and increase ten-fold as they move down-gradient into deeper parts of the basin (Kaiser et al., 1991). Saline, NaCl-type waters have been associated with under-pressured (non-artesian) groundwater conditions in the San Juan Basin (Ayers et al., 1991).

Of formation water's geochemical components, chloride is one of the most frequently assessed in hydrogeologic investigations. As an anion, chloride is highly mobile in solution, but it is also conservative in geochemical settings. That combination of characteristics makes chloride popular in mass balance approaches to groundwater questions, such as estimating recharge fluxes in semiarid, regional aquifers (Eriksson & Khunakasem, 1969) and also in the unsaturated zone (Allison & Hughes, 1978).

In addition to being found in coalbed methane deposits, chloride can be found in small amounts in precipitation, which can be concentrated by evaporation. Chloride can also be found in halite rock formations; in halite rock salts used to de-ice roads; and in landfill leachates and septic effluent. Chloride's concentration can be increased as well by land-use activities that increase the ground's salinity, such as irrigated agriculture and application of inorganic fertilizers. Chloride is regulated by the EPA and the state of Colorado in drinking water and surface water. Both regulators recommend levels below 250 mg/l, which is the detectable taste limit for chloride. International standards describe "unpolluted" water as containing 10 mg/l or less of chloride (Dept. National Health, Canada, 1978).

High sodium ($Na+$) levels are often associated with elevated chloride levels from the dissolution of sodium chloride, or with elevated bicarbonate levels from the dissolution of sodium bicarbonate. Sodium is not regulated in drinking water or surface water by federal or state regulators, but EPA recommends concentrations of less than 20 mg/l in its secondary drinking water guidelines. The American Society of Agricultural Engineers classifies hard water, which is typical for Colorado, as having sodium concentrations of 120-180 mg/l.

SITE DESCRIPTION AND RESEARCH DESIGN

The research design employed a synoptic water sampling strategy timed to capture local hydrodynamics during the fall of 2008 (baseflow) and spring of 2009 (high-flow) to assess the seasonal inputs to, and variations within, the hydrology of the Fruitland Outcrop area. Field work during the 2008/2009 seasons was performed by Mountain Studies Institute Executive Director Koren Nydick and field staff Jordan Vansickle, as well as Prof. Gary Gianniny of Fort Lewis College. Seven types of water bodies were sampled across three major hydrologic categories:

- (1) *Precipitation*;
- *Surface Water* – (2) rivers/streams and (3) irrigation ditches;
- *Groundwater* – (4) CBM wells, (5) springs, (6) piezometers, and (7) domestic wells.

To characterize each of these water bodies, a total of 67 sites (Table 1) were selected for sampling across a study area that encompassed roughly 1,750 km^2 in two Colorado counties: La Plata and Archuleta (Figure 3.8). Within these counties, sites were clustered in three main geomorphologic areas, which I will continue to refer to for both analysis and organizational purposes throughout the study. The three areas are: (1) the Florida River drainage in La Plata County, (2) the Basin Interior in La Plata County (part of which is known locally as Florida Mesa and which straddles the La Plata-Archuleta County line and includes the Pine River drainage in the area between the Florida and Piedra Rivers), and (3) the Piedra River drainage inside Archuleta County.

Sampling sites were selected in collaboration with SJPLC, and with SJPLC's scientific objectives, management questions, and existing field resources in mind. Due to the study's primary focus on Fruitland Outcrop hydrology, a majority of sampling sites were located “in Outcrop,” meaning they were positioned at points where the Fruitland Formation is known to be at, or very near, the ground surface. To capture the Outcrop’s impact, ten sample sites were also positioned upstream from the Outcrop (also referred to as “above Outcrop”). These were primarily surface water sites. In addition, a large number of sites were positioned downstream from the Outcrop (also referred to as “below Outcrop” or “down-gradient”). We sampled nine domestic wells in areas considered to be down-gradient in order to assess hydrologic relationships between the Fruitland Formation and shallow domestic wells. Domestic wells were generally the most southerly (or basin-ward) of sites sampled, with surface water, springs, and piezometers more likely to be in Outcrop or just below it.

Piezometers were installed by SJPLC field staff. All are assumed to be in the Fruitland Outcrop, either in the coal itself or associated sandstones. Piezometers were constructed with a five-foot length of galvanized pipe, crimped at the bottom, and punctured with 12 holes drilled in the bottom six-inches. The piezometers were driven perpendicular to the dip of the Outcrop. In some cases, two-foot extensions and collars were sometimes added onto the driven 5-foot section in order to make sure that the tubes extended above the highest anticipated stream water levels. Please note that part of the pipe does extend above the surface water level (which varies depending on the amount of stream flow in the channel). Thus, piezometer length does not represent exact distance below stream level, or even exact depths below the channel bottom (SJPLC field staff, personal communication 2010).

For a list of all 67 sites, their location within each of the three site clusters, position relative to the Fruitland Outcrop, and other relevant information, please refer to Table 3.1. General descriptions of the sites – grouped by Florida drainage, Basin Interior, and Piedra drainage – are included below. For a list of piezometer and domestic well depths, please refer to Table 3.2. The domestic wells sampled relatively shallow, generally ranging from 27–76 m deep (90–250 ft), with the notable exception of domestic well W1, which was 122 m (400 ft) deep.

Florida Drainage

The headwaters of the Florida River begin near 4,000 m (13,000 ft) in the Weminuche Wilderness. The Florida is impounded at 2,480 m (8,130 ft) in Lemon Reservoir approximately 22.5 km (14 mi) northeast of the City of Durango in La Plata County. Releases from Lemon Reservoir range from 20-625 cubic feet per second (cfs) annually. Peak flow of the Florida River occurs in mid-June, with a steady discharge at approximately a third of the maximum level through October; discharge declines to minimal flow in the winter and spring. From Lemon Reservoir's outfall, the Florida flows through areas of mixed land use, the majority of which are residential, agricultural (both ranching and farming), and extractive (oil and gas production). The river also feeds irrigation canals and ditches along the Florida Valley and on Florida Mesa, which support irrigated agriculture.

A total of 23 sites were sampled in the Florida drainage (Figure 3.9) (Please note that this figure does not show the surface water sites near the Lemon Reservoir due to scale considerations; the sampling sites near the Lemon Reservoir are shown in Figure 3.8). Among these 23 sites, five were surface water sites on the Florida River. Site FL1 was the furthest upstream from the Fruitland Outcrop, located roughly 15 kilometers below the Lemon Reservoir outfall. Site FL2 was also upstream from the Outcrop, while the sites below it (FL3 and FL7) were considered to be in Outcrop and downstream from Outcrop, respectively. Three piezometers were sampled in the Florida drainage – all in the Florida River, all in the Outcrop, and all of them managed by SJPLC field staff.

Four CBM wells were sampled in a northwest-southeast transect approximately 2.25-5.5 km (1.4-3.4 mi) south-southeast of the Fruitland Outcrop along County Road 225 and County Road 234 in La Plata County. All four wells are owned by XTO Energy Inc. and were identified by SJPLC staff as producing from the Fruitland Formation. In alphabetical order, they are named: Davis, Huber-Federal, Huber-Flanagan, and Huber-Nelson. Due to limited access to produced water from CBM wells, we were unable to sample multiple locations across the basin and at variable distances from the Fruitland Outcrop, which is necessary for capturing spatial variation in isotopic and geochemical composition. As such, the CBM well sites sampled for this study were limited in number (n=4) and location (clustered together in the interior of the basin). Six domestic wells were also sampled in the Florida drainage. Two of the domestic wells (FL5 and FL6) were near the Florida River and considered to be in Outcrop, while the remaining four were below Outcrop, toward the interior of the basin. Three irrigation ditches were also sampled in this region below the Outcrop: Ridge Ditch, Florida Farmers Ditch, and Florida Canal. The Florida Farmers Ditch is fed by the Florida River and impounded in Pastorius Reservoir, which feeds the Florida Canal. The Ridge Ditch is fed by the Pine River.

Precipitation was collected in two places in La Plata County. Rain and some snow were collected with a bulk precipitation collector from Nov. 21-Dec. 28, 2008 at Shamrock Meteorological Station (SHA), a USFS site in Beaver Meadows. Spring rain was collected at SHA from May 1-26, 2009. Two snowpack samples were collected from a north-facing slope at Cascade Creek (CA1 and CA2) – an area north of Durango Mountain Resort that is accessible from Highway 550 – on March 16, 2009.

Basin Interior

A total of nine sites were sampled in the region we refer to as the Basin Interior, which is divided between eastern La Plata County and western Archuleta County (Figure 3.10). The Pine River runs through the middle of this area, but it was not sampled for the present study. Instead, four domestic wells were sampled on the La Plata County side of the drainage. All of the domestic wells were considered to be below Outcrop based on their location. These domestic wells were the furthest south, or basin-ward, sites in the study. They were selected in a north-south transect to either side of the Pine River. Four springs were sampled in Outcrop on the Archuleta County side, all on private property (MS, RS, VS1, VS2). The ninth site, the Morrison Consolidated Ditch (MCD), is an irrigation ditch fed by the Pine River.

Piedra Drainage

Headwaters of the Piedra River reach the Continental Divide at nearly 4,000m (13,000 ft). The river is unregulated in Archuleta County as it flows south for over 64 km (40 mi) to join the San Juan River in the Navajo Reservoir located at 1,860 m (6,100 ft) on the Colorado-New Mexico border. Piedra River discharge above the Navajo Reservoir ranges from approximately 250-2,750 cfs. The Piedra displays a typical Rocky Mountain snowmelt-dominated hydrograph, characterized by a large peak (mean ~2,000 cfs) in May that attenuates through the summer, fall, and early winter. Piedra discharge patterns also reflect a significant contribution from the late summer monsoon typical of the San Juan Mountains, with secondary peaks in August and September.

The Piedra watershed above the sampling sites is primarily forested USFS land. As the Piedra River and its tributaries exit public lands, they flow through residential and agricultural areas, oil and gas production sites, and past major highways. Hot springs emerge on the Piedra River at an elevation of 2,210 m (7,250 ft) and at a temperature of 107° F. Land use becomes agricultural near site PR2. Also near site PR2 is a gravel operation that makes use of evaporation ponds. Tributaries Squaw and Little Squaw to the west flow through farming and ranching land, while eastern tributaries Devil Creek and Stollsteimer Creek flow through land with minor ranching and farming underway.

A total of 32 sites were sampled in the Piedra drainage (Figure 3.11). This drainage was assigned the most sampling sites because of the significant tributary network that contributes to the Piedra River near the Fruitland Outcrop, and because the Piedra drainage has received less attention than its western neighbors in previous work on the Fruitland Outcrop. The Piedra drainage is also the area that may see the largest increase in development of federal mineral rights under the increased CBM development scenarios set into motion in 2007 (SJPLC, 2007). Starting from the west, the Piedra's tributaries include Squaw Creek and Little Squaw Creek, which flow into Yellowjacket Creek. Yellowjacket Creek meets the Piedra just downstream of sample site PR2. Peterson Gulch and Fossett Gulch wetlands contribute water to the Piedra above main channel sites PR4 and PR5. Tributaries to the east include Devil Creek and Stollsteimer Creek. Of these, we sampled Stollsteimer Creek in five places (ST1, 2, 3, 6, 7), as well as tributaries Archuleta Creek and Cabezon Creek (AC1 and CC1). Both the Piedra River main channel and Stollsteimer Creek were sampled upstream, in, and downstream of the Fruitland Outcrop.

Four SJPLC-managed piezometers were sampled in the Piedra drainage. Three of them were located along Little Squaw Creek, upstream, in, and downstream of the Outcrop, respectively. A fourth piezometer was located in Peterson Gulch, in the spring system that feeds the wetland. Five domestic wells were sampled in the area – all of which were considered to be in Outcrop based on their location. Two of the domestic wells (MA1 and MA2) are within the Stollsteimer Creek drainage and three are within the Piedra River drainage (GAR1, DE, HD3433).

METHODS

Field Methods

This study employed a synoptic water sampling strategy aimed at assessing seasonal inputs to, and variations within, water resources in the Fruitland Formation area by capturing local base flow during the fall of 2008 and high flow during the spring of 2009. The sampling regime was designed to capture surface and groundwater pre- and post-Outcrop interaction, as well as from in the Outcrop system itself.

Stream samples were taken from moving water, away from the riverbank. Precipitation was collected with a bulk collector consisting of a polycarbonate funnel attached to HDPE tubing and a polycarbonate collection bottle. To prevent evaporation tubing was looped into a vapor lock and the collection bottle was insulated in a cooler. Snow samples were taken near the time of peak snowpack accumulation using depth-integrated methods (excluding the top and bottom 2 cm). Samples were collected with a plastic shovel from the fresh surface of a snow pit dug on a north-facing slope. Piezometers were pumped and allowed to recharge before samples were collected. Samples from domestic wells were collected as close to the well source as possible and, to the best of our knowledge, were not from treated systems. Production water from CBM wells was collected by an employee of XTO Energy Inc. in the presence of SJPLC staff.

Water samples collected for solute, pH, and acid neutralizing capacity (ANC) analyses were filtered through ashed Whatman GF/F glass fiber filters with an effective pore size of 0.7 μm. ANC and pH samples were also filtered due to the amount of debris contained in some of the samples. Samples collected for stable and radiogenic water isotopes were not filtered. All samples were stored in acid washed HDPE bottles and stored at 4 °C until analyzed.

Laboratory Methods

Water samples were analyzed for pH, specific conductance, ANC, H^+, NH_4^+, Ca^{2+}, Na^+, Mg^{2+}, K^+, Cl^-, NO_3^-, SO_4^{2-}, Si, DOC, DON, $\delta^{18}O$, δ^2H (deuterium (D)), and ^3H (tritium). Samples for chemical and nutrient content were analyzed at the Kiowa wet chemistry laboratory run by the Niwot Ridge (NWT) Long-Term Ecological Research (LTER) program, following the protocols presented in Williams et al. (2006). Specific conductivity, pH, and ANC were measured within one week of collection. Conductivity and pH were measured with temperature-compensated meters and ANC was measured using the Gran Titration method. The base cations Na^+, Mg^{2+}, K^+, and Ca^{2+} were analyzed using a Perkin Elmer Analyst 100 Atomic Absorption Spectrometer with detection limits of 0.07, 0.04, 0.04, and 0.26 μeq L^{-1} respectively. NH_4^+ and Si were measured on an OI Analytical Spectrophotometric Flow System IV Analyzer with a detection limit of 0.13 μeq L^{-1} for ammonium and 0.23 μmoles L^{-1} for silica. Nitrate, SO_4^{2-}, and Cl^- were measured on a Metrohm 761 Compact Ion Chromatograph with detection limits of 0.02, 0.04, and 0.14 μeq L^{-1} respectively.

Total Dissolved N (TDN) concentrations on filtered samples were determined by using potassium persulfate digestion to oxidize all forms of N into nitrate. The digested samples for TDN were then measured on an OI Analytical Spectrophotometric Flow System IV Analyzer with detection limit of 0.45 μmoles L^{-1} and precision of 1.39%. DON was calculated by subtracting measured total inorganic N from TDN. Samples for DOC were filtered through pre-combusted Whatman GF/F filters with a nominal pore size of 0.7 μm. DOC was determined by high-temperature catalytic oxidation using a Shimadzu Organic Carbon Analyzer at the Institute of Arctic and Alpine Research (INSTAAR) in Boulder, CO. Three replicate analyses yielded standard deviations of about 0.06 mg C L^{-1}, with a range of 0.01 to 0.22 mg C L^{-1}.

Analytical bias was assessed through charge balance calculations using calibrated standards. Split samples were analyzed in parallel with NADP/NTN Central Analytical Laboratory in an ongoing inter-laboratory comparison study effort. An Ecosystem Proficiency Blind Survey was performed June and July 2004 through Environment Canada to assess the accuracy of the anion and cation methodologies. Analytical precision for all solutes was less than 2% and assessed with spikes, blanks, and replicates.

Samples for stable water isotopes were stored in 30-mL borosilicate vials with airtight caps. Isotopic analyses of ^{18}O and ^{2}H were conducted using the CO_2-H_20 equilibration technique at the Stable Isotope Laboratory at the Institute of Arctic and Alpine Research in Boulder, CO. The ^{18}O and ^{2}H values are expressed in conventional delta (δ) notation in units of per mil (‰) relative to Vienna Standard Mean Ocean Water (V-SMOW):

$$\delta^{18}O = \frac{\left(^{18}O/^{16}O\right)_{sample} - \left(^{18}O/^{16}O\right)_{VSMOW}}{\left(^{18}O/^{16}O\right)_{VSMOW}} \times 1000$$

Precision for $\delta^{18}O$ was ±0.05‰.

Tritium was analyzed at the USGS Tritium Laboratory in Menlo Park California by electrolytic enrichment and liquid scintillation counting. Distilled sample water was reduced electrolytically in electrolysis cells to 10 mL from an initial 200 mL in a cooling bath. This increases the concentration of tritium by a factor of 16. The remaining liquid is mixed with a scintillation cocktail of known tritium concentrations to improve baseline values. The sample is then counted in a Packard scintillation counter. Tritium concentrations are reported in “tritium units,” or TU, with a precision of ±0.4 TU. 1 TU is defined as equal to 1 tritium atom per 10^{18} hydrogen atoms. The detection limit is reported as twice the precision. Samples with tritium values less than 0.8 TU were considered to have no tritium, or be "tritium dead."

RESULTS

All Water Bodies

This section discusses isotopic and geochemical results for each of the seven categories of water sources sampled in the study area: precipitation, surface water sources (rivers and irrigation ditches), and subsurface sources (CBM wells, springs, piezometers, and domestic wells). First, I present an overview of the isotopic and geochemical results. Secondly, to capture spatial variation, results from the seven types of water bodies listed above are divided based on their location. The sampling sites are inside one of two counties: La Plata County or Archuleta County. I then consider them to be within one of three clusters inside these counties: 1) the Florida River drainage in La Plata County, 2) the Basin Interior, which straddles the line between the two counties and includes the Pine River drainage, and 3) the Piedra River drainage inside Archuleta County. I present the results from west to east based on these spatial categories. The field team sampled 67 sites, with the majority of sites sampled twice, during baseflow conditions in the fall of 2008 and during snowmelt in the spring of 2009.

The precipitation input values provide the starting point in the hydrologic cycle, and I will therefore present them first. As would be expected, winter precipitation (snow) samples produced the most depleted values of $\delta^{18}O$ and were -18.4 ‰ at the Beaver Meadows meteorological site from 11/21/08-12/28/08, and -17.0 ‰ each from two depth-integrated snowpack samples collected at maximum accumulation near Cascade Creek on 3/16/09. The precipitation sample collected in May was less depleted in the heavy oxygen isotope, at -13.0 ‰. Together, the

$\delta^2H/\delta^{18}O$ relationships between the four precipitation samples produce a LMWL with the equation:

$$\delta^2H = 3.8 + 7.0\ \delta^{18}O$$

The slope of seven is slightly less than the slope of eight for the GMWL. However, interpreting these results requires caution, as the four-sample dataset is limited. Two precipitation samples, both collected on the same day in March 2009, produced a mean tritium value of 6.6 TU, which serves as an estimate of the average the tritium input to the hydrologic system, to be discussed in further detail below. (For a summary of isotopic values for precipitation, please refer to Table 3.3)

Across all of the sampled water bodies, $\delta^{18}O$ values ranged from a low of -18.3 ‰ to a high of -10.3 ‰, with a mean of -13.1 ‰ (n = 120) (Figure 3.12). The $\delta^{18}O$ values for the major water types all clustered around the overall mean: -12.9 ±1.24 ‰ for surface waters, -12.7 ±0.98 ‰ for domestic wells, -13.0 ± 1.06 ‰ for springs, and -13.5 ±0.92 ‰ for piezometers (for a comparison of isotopic and solute values by water body, please refer to Table 3.4). In contrast, the four CBM wells ranged from -15.5 ‰ to -14.3 ‰, with a mean of -14.6 ‰. There was no significant difference in the $\delta^{18}O$ values among rivers, piezometers, springs, and domestic wells, though the p-value of 0.06 was quite close to the significance level of 0.05.

Tritium values for all surface waters, piezometers, springs, and precipitation were in the very narrow range of 4.5 to 7.5 TU (Figure 3.13). In contrast, tritium values for domestic wells ranged from below detection limits to 8.2 TU. The tritium values for the major water types all clustered around the overall mean: 5.8 ±0.81 TU for surface waters, 5.1 ±1.97 TU for domestic wells, 5.2 ±0.55 for springs, and 5.8 ±0.80 TU for piezometers (Table 3.4). Tritium values for the four CBM wells were all below detection limits. There was a significant difference in the tritium values among rivers, piezometers, springs, and domestic wells (p = 0.01). Note that tritium values consistent with the transient peak in atmospheric tritium in the 1960s (water samples found today with tritium values greater than 60 TU) were not found in any water sample.

CBM wells generally show a unique chemical signature due to the formation water they hold, which is high in total dissolved solids, particularly salts. A Piper diagram shows the chemical nature of water samples in a graphic, and also provides information on the relationships between samples. For example, classifying samples on a Piper diagram (Figure 3.14) makes it possible to distinguish waters from CBM wells from that of surface waters and/or groundwater. CBM waters plot as high sodium (Na^+) and bicarbonate (HCO_3^-) and low calcium (Ca^{2+}) and low magnesium (Mg^{2+}) waters. Surface waters generally plot opposite from production water collected from CBM wells. Domestic wells tend to plot on a mixing line between that of surface waters and the CBM wells, with several of the domestic wells plotting near the CBM wells.

Sodium and chloride concentrations may be considered indicators of interaction with the Fruitland Formation to some degree, based on known trends in CBM-related waters as being high in both major ions. Sodium concentrations in the present study ranged widely, from a low of 4 μeq L^{-1} to a high of about 30,000 μeq L^{-1}; mean concentrations for all samples (n = 120) was 2,300 μeq L^{-1} (Figure 3.15). Similarly, chloride concentrations showed a wide range, from a low of 3 μeq L^{-1} to a high of about 5,200 μeq L^{-1}; the mean chloride concentration was 330 μeq L^{-1}. In contrast to the stable water isotopes, mean sodium concentrations for the major water types differed significantly with high variance ($p << 0.001$): 689 $\pm$462 μeq L^{-1} for surface waters, 3,627 $\pm$3,247 μeq L^{-1} for domestic wells, 820 $\pm$407 μeq L^{-1} for springs, and 1,248 $\pm$1475 μeq L^{-1} for piezometers; chloride showed a similar pattern by water type (Table 3.4). Sodium and chloride concentrations in precipitation were quite dilute, with concentrations always below 10 μeq L^{-1} (n = 4). In contrast, our four CBM wells had sodium concentrations greater than 10,000 μeq L^{-1} and chloride concentrations greater than 1,000 μeq L^{-1}. Several of the domestic wells, piezometers, springs, and surface water sites had elevated sodium and chloride values similar to those of our CBM wells (Figure 3.15).

Water from coal beds typically is high in sodium and low in calcium and magnesium, as shown in Figure 3.15, resulting in a high sodium-adsorption ratio (SAR) (Nimick 2004). Thus, elevated levels of SAR may provide another index of waters that have had some interaction with the Fruitland Formation. Generally, SAR is calculated as:

$$\mathrm{SAR} = \frac{\mathrm{Na}^+}{\sqrt{1/2\left[(\mathrm{Ca}^{2+}) + (\mathrm{Mg}^{2+})\right]}}$$

where $[Na^+]$, $[Ca^{2+}]$, and $[Mg^{2+}]$ are the concentrations in meq L^{-1} of sodium, calcium, and magnesium ions. SAR values ranged from less than 0.1 to more than 20, with only CBM wells having values greater than 20 (Figure 3.16). Most water samples had SAR values below 1. However, there were several wells and piezometers with SAR values above 1, suggesting possible interaction with the Fruitland Formation. The SAR values for the major water types showed statistically significant differences ($p << 0.001$): mean values were 0.48 ±0.26 for surface waters, 3.7 ±4.92 TU for domestic wells, 0.50 ±0.21 for springs, and 0.9 ±1.02 for piezometers (Table 3.4). It is worth noting that when the SAR rises above 12 to 15, serious physical soil problems arise and plants have difficulty absorbing water (Munshower, 1994).

La Plata County: Florida Drainage

Surface Water: Florida River, Irrigation Ditches

The $\delta^{18}O$ values for the Florida River ranged from -15.5 ‰ to -12.6 ‰, with a mean $\delta^{18}O$ value of -14.0 ± 1.35 ‰ (n = 10) (Table 3.5) (Figure 3.17). There was a significant difference between spring and fall values (n = 5, p = 0.007), with the spring mean value of -15.2 ‰ about 2.5 ‰ more depleted than the fall average of -12.7 ‰. The Florida River generated a $\delta^{2}H/\delta^{18}O$ slope of 7.5, which is between the LMWL slope of 7.0 and the GMWL slope of 8 (Figure 3.18). Tritium values ranged from 6.4 to 7.8 TU, with mean of 6.9 ± 0.47 TU (n = 10) (Table 3.5) (Figure 3.19). The fall mean of 6.7 TU was slightly less than the spring mean of 7.2 TU, but the difference is close to the laboratory measurement precision of 0.4 TU. The average tritium values for the Florida River were close to the 6.6 TU in precipitation.

Sodium and chloride concentrations in the Florida River were dilute, with sodium concentrations ranging from 39 to 126 μeq L^{-1} and chloride concentrations ranging from 14 to 47 μeq L^{-1}. Concentrations of these ions thus showed only a slight increase when compared to concentrations in precipitation. The SAR values were quite low, ranging from 0.04 to 0.11.

Three irrigation ditches were sampled in the Florida drainage in May of 2009. The irrigation ditches' mean $\delta^{18}O$ concentration was -12.8 ‰ ± 0.05 and mean tritium concentration was 6.1 TU ± 0.49 (Table 3.5). Thus, the irrigation ditches had a mean $\delta^{18}O$ value about 2.4 ‰ more enriched then the mean the $\delta^{18}O$ value for the Florida River in May 2009. Moreover, the $\delta^{2}H/\delta^{18}O$ slope was 4.9, much less than the slope of 7.5 for the Florida River. Similarly, the mean tritium values were less than that of the Florida River. The sodium and chloride concentrations for the irrigation ditches were similar to that of the Florida River, all less than 90 μeq L^{-1}. The SAR values were similar to those of the Florida River, ranging from 0.06 to 0.11.

Groundwater: Coalbed Methane Wells

The four CBM wells were each sampled once, during the fall sampling period. To broaden the analysis of water collected from CBM wells, I incorporated legacy CBM well data from the 3M Project, for which 109 CBM wells provided water chemistry information (3M Project 2000). The $\delta^{18}O$ values for the four CBM wells sampled for the present study ranged from -15.5 to -14.3 ‰, with a mean of -14.6 ±0.58 ‰ (Table 3.4), compared to the mean of -10.5‰ for the 3M Project CBM wells (n = 109). The slope of the $\delta^{2}H/\delta^{18}O$ relationship from the 3M Project CBM wells track the GMWL, with a slope of 7.6 (n = 109) (Figure 3.20).

There was no measurable tritium in the four CBM wells sampled, indicating that recharge of the water in these CBM wells predates the 1950s (Figure 3.19). Refering to the 3M Project data for CBM wells, six of those wells were tested for tritium, with five of the wells having no measurable tritium. The Southern Ute well 12U–2, located in the Indian Creek area, contained 134 TU, however. The water produced by this well was approximately 45 years old and has been isolated from the atmosphere since that time (SJPLC, 2006).

The average sodium and chloride concentrations of our four CBM wells were about a quarter of those from the 3M CBM wells. Mean sodium concentrations for the four CBM wells were 26,033 ±5,075.10 μeq L^{-1}, compared to mean sodium concentrations of 107,269 ± 62,914 μeq L^{-1} for CBM wells from the 3M Project. Mean chloride concentrations for our four CBM wells were 3,101 ±1,761.37 μeq L^{-1}, compared to mean chloride concentrations of 21,559 ± 29,683 μeq L^{-1} for CBM wells in the 3M study. SAR values for our four CBM wells were the highest of our study, at 69.9 ±10.6.

Groundwater: Domestic Wells, Piezometers, Springs

One spring, three piezometers, and seven domestic wells were sampled near the Florida River (Table 3.1). The single spring shows a mean $\delta^{18}O$ concentration of -12.6 ‰ (Figure 3.17) and tritium concentration of 5.9 TU (Figure 3.19). Piezometers were slightly more depleted in $\delta^{18}O$ than the spring at -13.9 ± 1.14 ‰, much like domestic wells, which measured -13.3 ± 1.15 ‰. Mean tritium values of 6.3 ± 0.80 TU for the piezometers were slightly higher than the mean value of 5.8 for domestic wells. The slope of the $\delta^{2}H/\delta^{18}O$ relationship did vary among the subgroups. Piezometers produced a slope of 7.5 that matches that of precipitation and of CBM wells, while the slope of 6.3 from domestic wells was below that of both precipitation and piezometers (Figure 3.21).

Sodium content of the domestic groundwater wells was elevated compared to the Florida River, ranging from 175.1 to 3901.7 μeq L^{-1}; chloride concentrations followed a similar pattern (Table 3.6). Piezometer FR2 was characterized by elevated sodium concentrations of near 4,500 μeq L^{-1}, while the other piezometers had sodium concentrations more than an order of magnitude lower that more closely matched river water concenrations. The SAR value of 3.2 for piezometer FR2 was much greater than that of the other piezometers, which were all below 0.2. SAR values for the domestic wells ranged widely, from 0.2 to 3.6

Somewhat surprisingly, the nitrate content of the wells was elevated. Nitrate concentrations ranged from less than 0.2 to 218.8 μeq L^{-1}, with a mean of 55 μeq L^{-1}. In contrast, nitrate concentrations in surface waters were always less than 5.1 μeq L^{-1}.

La Plata/Archuleta Counties: Basin Interior

Groundwater: Domestic Wells, Springs

The $\delta^{18}O$ values for the four domestic wells sampled in this geographic area were tightly clustered around a mean of -12.5 ±0.29 ‰ and ranged from -13.1 ‰ to -12.1 ‰, with little seasonal variation (Table 3.6) (Figure 3.17). The $\delta^{18}O$ values for the four springs were slightly more depleted, with a mean of -13.6 ± 0.79‰ and ranged from -14.8 ‰ to -12.4 ‰, again with little seasonal variation. The domestic wells sampled toward the interior of the basin, produced a low $\delta^{2}H/\delta^{18}O$ slope of 4.6 (n = 8) compared to the slope of 6.3 for the springs (n = 8) (Figure 3.22). It is worth noting that both the $\delta^{18}O$ values and the slope of the $\delta^{2}H/\delta^{18}O$ relationship for the domestic wells was similar to that of the irrigation ditches.

The tritium values for domestic wells ranged from 4.1 to 8.2 TU, with a mean of 6.3 ± 1.4 TU (Table 3.5) (Figure 3.19). The tritium values for springs sampled in the area ranged from 4.3 to 6.1 TU, with a mean of 5.2 ±0.65 TU. Somewhat surprisingly, several of the wells showed notable seasonal differences in tritium values. For example, tritium values for well PA1 ranged over almost 3 TU, from 5.4 to 8.2 TU.

Sodium and chloride concentrations from the domestic wells were elevated, as was SAR. Sodium concentrations from the wells ranged from 735 to 11,831.3 μeq L^{-1}, with a mean of 6,122 μeq L^{-1} (Table 3.6). Similarly, chloride concentrations ranged from 142 to 2,151 μeq L^{-1}, with a mean of 677 μeq L^{-1}. SAR values ranged from 0.54 to 19.3, with the higher SAR values associated with higher sodium and chloride concentrations. Waters from springs were more dilute, with mean sodium concentrations of 671 μeq L^{-1} and mean chloride concentrations of 33 μeq L^{-1}. SAR values for springs were also much lower than for domestic wells, and ranged from 0.13 to 0.90.

Similar to domestic wells in the Florida drainage, nitrate values were elevated, ranging from 6.1 to 537 μeq L^{-1}. In contrast, nitrate values for springs were always less than 15 μeq L^{-1}.

Archuleta County: Piedra Drainage

Surface Water: Piedra River and Tributaries (Stollsteimer Creek, Archuleta Creek, Squaw Creek, Little Squaw Creek, Fossett Gulch, and Peterson Gulch)

The $\delta^{18}O$ values for the Piedra River and its tributaries (18 sampling sites) ranged from -10 ‰ to -14 ‰, with a mean of -12.6 ± 1.04 ‰ (n = 34) (Table 3.5) (Figure 3.17). $\delta^{18}O$ values for the Piedra River were thus 1.4 ‰ more enriched than the Florida River mean of -14.0 ‰, though the difference was not statistically significant (p = 0.07). The $\delta^{18}O$ values in the Piedra River showed little seasonal change: spring samples showed a mean value of -12.8 ‰, while fall values had a mean value of -12.3 ‰ (Figure 3.17). The $\delta^{18}O$ values did vary between the main channel of the Piedra River and its tributaries, with the mean $\delta^{18}O$ value of -13.2 ± 0.53 ‰ for the main channel more similar to that of the Florida River while the mean $\delta^{18}O$ value of -12.3 ± 1.09 ‰ for the tributaries was almost one per mil more enriched than the main stem. The Piedra River and its tributaries generated a $\delta^{2}H/\delta^{18}O$ slope of 4.3, much lower than the slope of 7.5 for the Florida River (Figure 3.18). The tributaries of the Piedra River primarily drove the lower slope for the $\delta^{2}H/\delta^{18}O$ relationship in the Piedra drainage. The Piedra's tributaries combined to produce one of the lowest $\delta^{2}H/\delta^{18}O$ slopes in the study at 4.1 (Figure 3.23). In contrast, the main channel of the Piedra River (n= 10) had a slope of 6.3, still lower than the 7.5 for the Florida River.

Tritium concentrations showed more variation in the Piedra drainage than they did in the Florida drainage, with a range of 5.5-7.2 TU in the Piedra's main channel and 4.6-7.2 TU when including tributaries (Figure 3.19). The mean tritium value of 6.4 ± 0.61 for the main stem of the Piedra River (Table 3.5) was similar to and not significantly different than that of the Florida River ($p = 0.15$). However, the Piedra River and its tributaries had tritium values significantly lower than that of the Florida River (mean of 5.7 TU; $p = 0.002$), driven by the lower tritium values of the Piedra River tributaries. The mean tritium value for the Piedra River tributaries of 5.4 was one tritium unit lower than the mean value of 6.4 for the main channel.

The main stem of the Piedra had elevated sodium and chloride concentrations relative to the Florida River. Sodium concentrations ranged from 174 to 1,039 $\mu eq\ L^{-1}$ and chloride concentrations ranged from 21 to 190 $\mu eq\ L^{-1}$. The Piedra's tributaries were also characterized by elevated concentrations of salts, particularly Squaw Creek and Stollsteimer Creek. Both creeks produce elevated sodium and chloride concentrations as compared to the other surface water sources we sampled, with sodium concentrations ranging from 450-1,000 $\mu eq\ L^{-1}$ and chloride concentrations ranging from 400-1,000 $\mu eq\ L^{-1}$. SAR values for the Piedra River and its tributaries were also elevated relative to the Florida River, ranging from 0.27 to 0.88. The lowest SAR value for the Piedra River system of 0.27 was more than twice that of the maximum SAR value of 0.11 for the Florida River.

Groundwater: Domestic Wells, Springs, Piezometers

Mean $\delta^{18}O$ values were -12.0 ± 0.47 ‰ for domestic wells ($n = 10$), -12.6 ±1.15‰ for springs ($n = 10$), and -13.2 ± 0.63‰ for piezometers ($n = 7$) (Table 3.5) (Figure 3.17). Subsurface samples from the Piedra drainage all plotted below the GMWL and LMWL's (Figure 3.24), with a $\delta^2H/\delta^{18}O$ slope of 6.6 for domestic wells, 5.8 for springs, and 4.0 for piezometers.

Tritium values for groundwater were also lower in the Piedra drainage than in the Florida drainage, particularly in domestic wells, where tritium concentrations showed the most variance of all sources we sampled. Tritium values for the domestic wells ranged from below detection limits to 5.4 TU, with a mean of 3.2 TU (Figure 3.19). Springs in the Piedra averaged 5.1 TU, while the mean tritium value for piezometers was 5.4 TU (Table 3.5).

Domestic wells, springs, and piezometers all showed elevated solute concentrations. For domestic wells, sodium concentrations ranged from 1,831 to 8,200 μeq L^{-1} and chloride concentrations ranged from 64 to 726 μeq L^{-1}, SAR values ranged from 0.90 to 12.11 (Table 3.4). For piezometers, sodium concentrations ranged from 622 to 1,096 μeq L^{-1} and chloride concentrations ranged from 47 to 65 μeq L^{-1}, SAR values ranged from 0.38 to 0.67. For springs, sodium concentrations ranged from 392 to 1,674 μeq L^{-1} and chloride concentrations ranged from 28 to 555 μeq L^{-1}, SAR values ranged from 0.31 to 0.82.

Similar to domestic wells in the Basin Interior, domestic wells in the Piedra drainage at times exhibited elevated nitrate content, with concentrations ranging from below detection limits to 726 μeq L^{-1}. Domestic wells with tritium content below detection limits had nitrate values below or near detection limits and elevated SAR and solute values (SAR values for well MA2 were as high as 12.1 and 2.1 for well GAR1). In contrast, well HD3433 had nitrate values of 444 and 726 μeq L^{-1}, tritium values of 4.9 and 5.2 TU, and SAR values of 2.6 and 2.9.

DISCUSSION

Precipitation

Current meteoric water – i.e., precipitation – marks the beginning of the hydrologic cycle as it is commonly defined. As such, the isotopic and geochemical content of precipitation make the best place to start in discussing the results of a hydrologic investigation. The San Juan Mountains typically receive moisture from the Gulf of Mexico or the Pacific Ocean. Our relatively enriched $\delta^{18}O$ values and low tritium levels suggest Gulf of Mexico waters as a primary precipitation source for the samples we collected. The high-elevation snowpack values of -17 ‰ are more enriched than depth integrated $\delta^{18}O$ values of about -21 ‰ from the Colorado Front Range (Williams et al. 2009). More enriched $\delta^{18}O$ values in snow in the San Juan Mountains are consistent with the latitudinal differences between the San Juan and Front Range mountains, as well as with warm southerly air masses meeting the San Juan Mountains and, by association, the range's orographic effect. Tritium values in precipitation show a similar latitudinal difference. The average of 6.6 TU in depth-integrated snowpack samples is much lower than the 10 TU typically found roughly 200 mi to the northeast, near Leadville, CO (Wireman et al. 2006; Manning & Caine 2007). Tritium concentrations of precipitation increase with latitude in the northern hemisphere because of the latitudinal gradient in tritium concentrations in the atmosphere, and the results of the present study fit this pattern (Michel 2005).

To properly interpret tritium values in precipitation – and the ages they reflect – the data must be placed in the proper context. That context is a tritium input function, computed from tritium values measured over long periods of time in the precipitation of a given area. Because one would expect the tritium values in the precipitation samples to follow the latitudinal gradient described above, a long-term meteorological station just to the south of the Fruitland Outcrop research area would provide us with the most representative baseline precipitation data for use in a tritium input function. One such station exists in Albuquerque, New Mexico (Michel 2004) (for long-term tritium measurements from this station, please refer to Figure 3.25). Therefore, to estimate ages for all of the water samples collected for this study, I relied on an input function developed from tritium values measured at the Albuquerque station and buttressed by additional tritium values estimated from correlation with long-term tritium measurements made by the International Atomic Energy Agency in Vienna, Austria.

Applying the tritium input function to the present data set makes it possible to derive approximate ages of water from tritium concentrations (Revelle & Suess 1957; Michel 2004), as shown in (Figure 3.26). In doing so, it becomes apparent that nearly all of the groundwater and surface water sampled for this study fall into an age range of less than 15 years. Not counting deep CBM wells, which are expected to contain older water, only three of the water bodies we sampled exceeded 15 years of age. In fact, the vast majority of the water samples were less than 10 years old, according to tritium concentrations – a very young age for most of these waters, all of which would fall into the "modern" category as per Clark and Fritz (1997). Based on the input function and the precipitation tritium mean of 6.6 TU as a starting point, one can use the tritium half-life of 12.3 years and a simple decay function to calculate tentative ages. Assuming that there is no mixing of older or younger waters, one can estimate that:

- 5.5 TU = 3 years old,
- 4.5 TU is 6.5 years old, and
- 3.5 TU is 11 years old.

These isotopic results for precipitation are critical for characterizing the surface water and groundwater systems evaluated in this study, since precipitation both recharges groundwater systems and supplies surface water systems with run-off. As such, it would have been ideal to perform a more comprehensive evaluation of the isotopic content of precipitation in the study area. An evaluation on that scale was beyond the scope of the current project, however. Because only four precipitation samples were collected, the values are too sparse to determine absolutely the current isotopic values of recharge, but they provide a good starting point for analysis.

The Southern Rockies show strong seasonality to $\delta^{18}O$ values in precipitation: summer precipitation values near Buena Vista, Colorado can be as enriched as -2 ‰ at high elevations (Hazen et al. 2002). (For comparison, wintertime precipitation values mentioned above were much more depleted, at -17 ‰.) The results of the present study, combined with literature values, suggest that the annual volume-weighted mean value of $\delta^{18}O$ in precipitation in the Fruitland Outcrop research area is probably in the range of -12 to -13 ‰, with average winter values near -17 ‰ and summer rains averaging about -5 ‰. Tritium values in precipitation are more consistent throughout the year than stable water isotopes, however (Michel 2004; Manning & Caine 2007). I therefore assume that our measured tritium values in snow of 6.6 TU are close to what we would find had we the luxury of a volume-weighted annual mean.

Additional measurements to constrain the seasonal and annual values of water isotopes in precipitation would be extremely helpful in interpreting the isotopic record in water collected for this project, as well as that of other San Juan Basin studies. An increased focus on precipitation inputs is one area of suggested future work.

Rivers

The most striking aspects of the isotopic and geochemical results of this study are the statistically significant differences in water chemistry between the Florida River and Piedra River surface waters, which heretofore have been assumed to share similar hydrogeologic characteristics (Questa, 2001; Papadopulos, 2006). The data suggest that the Florida River and Piedra River contain very different source waters that have followed very different flowpaths to arrive in these rivers. The disparities between drainages that these results suggest may provide important insights into future CBM development in the less-studied Piedra River area of Archuleta County as well as important empirical points (or counterpoints) against which to check surface depletion models and the assumptions behind them.

Source waters for the Florida River appear to be recent snowmelt and rainfall from higher elevation areas of the catchment. The slope of 7.5 for the $\delta^2H/\delta^{18}O$ relationship is very close to the LMWL slope of 7 and the GMWL slope of 8, and is therefore consistent with meteoric water that has experienced little if any evaporation or other processes that may cause fractionation of the stable water isotopes. The Florida River's $\delta^{18}O$ values also show the seasonality one would expect in a river sourced by snowmelt and rainfall. The more depleted $\delta^{18}O$ values in May indicate snowmelt as the dominant water source at that time, whereas the significantly more enriched $\delta^{18}O$ values collected in the fall during baseflow conditions suggest that the primary water source in the autumn was some combination of summer rains and/or groundwater discharge. Tritium values ranged mostly between 6.5 and 7.0 TU, correlating with the precipitation average of 6.6 TU, suggesting that most of the water in the Florida is modern, with a residence time on the scale of months to only a few years. The low values for sodium, chloride, and SAR in the Florida River suggest that there is only limited groundwater input. Groundwater from the Fruitland Formation would contribute higher solute content because of increased residence time and geochemical weathering.

In contrast, isotopic results from the Piedra River suggest that its source waters have undergone different environmental interactions than waters the Florida River. The $\delta^{2}H/\delta^{18}O$ relationship produces a slope of 4.3, which is consistent with water that has experienced large amounts of evaporation or geochemical processes that may cause fractionation of the stable water isotopes. The cause of these evaporative or geochemical effects is not known and should be considered in future fieldwork in the Piedra River region. A number of potential processes could be at play. For example, the water table in the Piedra River drainage might be relatively high and subject to heightened evapotranspiration. On the other hand, the low $\delta^{2}H/\delta^{18}O$ slope of 4.3 could signal a large amount of return flow from agricultural activities in the Piedra River drainage. In an example from the literature on this topic, return flow from irrigation in the Euphrates River system decreased $\delta^{2}H/\delta^{18}O$ slopes from 7.52 in local precipitation to 5.33 in the river (Kattan, 2008). This hypothesis does not fit with the fact that the land above the Piedra sampling points is primarily forested USFS land, however, and while the Piedra and its tributaries do travel through some agricultural land near our sampling points, to the best of my knowledge, they are primarily ranching operations that do not perform the kind of large-scale irrigated agriculture that would produce return flows with an evaporated isotopic signature.

Hot springs could be another cause of the low $\delta^{2}H/\delta^{18}O$ slope for the Piedra River and its tributaries. Unmarked hot springs exist on the Piedra River upstream from our study area by approximately 16 km (10 mi). Little is known about the hot springs' geochemistry, temperature, or flow volumes, though guidebooks suggest that the the Colorado Geological Survey has measured the springs' temperature at 107 °F (~41 °C) and that pools built there by hot springs aficionados have dried up in recent years (Frazier & George, 2000). Unverified reports also claim that the spring water is effervescent with gas. Stable isotope and fluid chemistry investigations of thermal waters in Utah (Cole, 1982) show similar evaporation trends similar to those found in the Piedra caused by shifts in $\delta^{18}O$ with little change in $\delta^{2}D$, which grew more pronounced as waters approached 30–60 °C. Other potential influences on the Piedra's isotopic trends could be water infiltrating from holding pits at a small gravel extraction operation on a ranch upstream, which has been the site of river restoration activities. The potential isotopic and geochemical influences of these activities cannot be known without collecting samples of water upstream and downstream of these point sources.

Yet another possible evaporative influence on the $\delta^{2}H/\delta^{18}O$ relationship in the Piedra River could be contributions of water from spring-fed wetlands that exist along the Piedra River and its tributaries. The $\delta^{18}O$ and solute values for the Piedra River suggest a larger component of groundwater to the Piedra River when compared to the Florida River, which could partly be attributed to spring flow. The $\delta^{18}O$ value of -12.6 ‰ for the Piedra River and its tributaries was 1.4 ‰ more enriched than the Florida River mean of -14 ‰, and did not show the variation with seasons found in the Florida River. Furthermore, the mean $\delta^{18}O$ value of -12.6 ‰ for the Piedra River is similar to the mean $\delta^{18}O$ values of -12.6 ‰ for springs, -13.2 ‰ for piezometers, and -12.0 ‰ for domestic wells, in the Piedra drainage. The similar $\delta^{18}O$ values between the Piedra River surface water and the regional shallow groundwater systems suggest a large groundwater contribution to the Piedra River at all times of year. In keeping with this trend, sodium and chloride concentrations in the Piedra River were as much as an order of magnitude higher than the Florida River. Groundwater in domestic wells of the Piedra drainage had sodium concentrations as high as 8,000 μeq L^{-1}, and chloride concentrations as high as 700 μeq L^{-1} (Table 3.6). The elevated sodium and chloride concentrations in the Piedra

River and its tributaries are consistent with dilute river water from higher elevation mixing with local groundwater that has high solute content.

The difference in tritium values and the slope of the $\delta^2H/\delta^{18}O$ relationship between the main stem and the tributaries of the Piedra River suggest that the tributaries account for much of the evaporation and groundwater input to the main stem of the river. The $\delta^{18}O$ vs. D slope of 4.1 for the tributaries compared to the $\delta^2H/\delta^{18}O$ slope of 6.3 for the main channel suggests that much of the evaporation in the Piedra may occur in the tributary regions, perhaps in spring-fed wetlands along tributaries such as Peterson Gulch. The mean tritium value of 5.4 TU for the tributaries suggest a longer residence time and, therefore, more of a groundwater contribution there than in the river's main stem, which had a mean tritium value close to that of precipitation (6.4 TU). Tributaries also showed higher levels of solutes, which also indicate a longer residence time and increased groundwater contribution. For example, stream samples from Stollsteimer Creek on the east side of the Piedra River (ST1, ST2, ST3), produced elevated levels of sodium (from 1,060 to 1,290 μeq L^{-1}) and chloride (306 to 406 μeq L^{-1}).

Isotopic and solute signals therefore suggest that the channel waters are a combination of recent meteoric water mixed with older, groundwater-dominated flow from tributaries. Given our understanding of the Fruitland Formation's role of receiving recharge from precipitation and then discharging it via shallow flowpaths at lower-elevation river cuts at the Outcrop (AHA, 2000), the groundwater signal in the Piedra and its tributaries may be a direct signal of Fruitland/Pictured Cliffs Sandstone groundwater. The Fruitland/Pictured Cliffs Sandstone dips at a very low angle in the Piedra drainage (5-12°) and is broadly exposed at widths of up to 1.4 km (or 2 mi) (Carroll et al., 2009), providing ample surface area for groundwater-surface water interactions. This is in contrast to the steeply dipping regions at the Florida River that provide only 65 m (0.1 mi) of Outcrop exposure. The groundwater signal is apparent enough to call into question modelers' conclusions that Fruitland Formation discharge to rivers is less than one percent of baseflow in NSJB streams (AHA, 2000). Stream depletion modeling projects have not paid close attention to the intricacies of the Piedra River drainage. Moreover, modeling studies have assumed similar hydrogeologic characteristics between the Animas, Pine, Florida, and Piedra rivers, and have even gone so far as to suggest that the Piedra is only weakly connected to the Fruitland, is less dependent on discharge, and would be depleted by CBM development at a much lesser rate than the other rivers (maximum of 15-60 af/y versus 140 af/y for the Animas, Pine and Florida by 2050 in Questa's 2001 model). The empirical results presented here suggest important differences in the hydrogeologic dynamics of these drainages, however – complexities that should be considered in future monitoring and management decisions as CBM production moves into Archuleta County and the Piedra River drainage.

The strong groundwater signal in the Piedra River is also interesting for what might indicate about the Florida River drainage, which did not show a groundwater signal despite conclusions of previous studies that the interconnection between the river and the aquifer system is "very high" (Questa, 2001). The absence of extra solutes, lower tritium concentrations, and $\delta^{2}H/\delta^{18}O$ relationships off the LMWL in the main channel of the Florida River suggest that the Florida is not receiving groundwater to the same degree as the Piedra River. For example, in breaking out sodium data for the Florida and Piedra rivers and in-Outcrop piezometers (Figure 3.27), one finds a marked difference between the two drainages. Aside from a single outlier piezometer in the Florida River (FR2, which had a sodium concentration of 4,500 μeq L^{-1}), the piezometers in the Florida produced low-sodium water similar to that found in the river above. In the Piedra River, sodium concentrations were also similar between piezometers and the river, but they were much higher. Piedra sodium concentrations also closely matched spring sodium data. Spring water can be considered a good indicator of Fruitland Formation groundwater chemistry, since the near-Outcrop springs we sampled are known to be sourced from the Fruitland. It would follow, then, that if the Piedra River and piezometers demonstrate spring-like sodium levels but the Florida River and piezometers do not, then the Florida River may not be receiving much, or any, groundwater from the Fruitland Formation.

In interpreting these differences, one should take into account that the topography and structural geology of the Florida drainage differs considerably from the Piedra drainage. The Fruitland Formation dips steeply at the Florida River cut (at approximately 53°) and the Outcrop is only exposed for a width about 65 m there (Carroll et al., 2009). The river crosses the Outcrop at an elevation of about 2,100 m (7,000 ft) in a relatively narrow river valley between high points of Fruitland/PCS at 2,750 m (9,000 ft) nearby, however, providing more than enough topographic disparity to drive discharge from the Fruitland/Pictured Cliffs Sandstone to the river. Taking this interpretation a step further, one could surmise that the Florida River lacks a groundwater signal because it has become a losing reach at the Outcrop instead of a gaining reach. One of the great fears of resource managers in the NSJB is that CBM development's reduction of artesian pressures on a regional scale might eventually reverse the hydraulic relationship between the Fruitland aquifer and rivers (Questa, 2001). While the results of this isotopic and geochemical investigation cannot ascertain with certainty whether that is in fact occurring in the Florida River, they are cause for concern that it might be. Collecting water samples from CBM and domestic wells near the Outcrop in the Florida River drainage would provide a method to test this hypothesis.

Piezometers and springs

The springs and piezometers sampled for the present study were all selected because SJPLC field staff presumed them to be sourced by or drawing from Fruitland Formation waters at the Outcrop. In regard to springs, all of which were on private land, these presumptions were based on fieldwork performed by resource managers as part of the SJPLC's environmental impact assessment (SJPLC 2006), previous hydrogeologic studies, and anecdotal information from landowners. As for piezometers, SJPLC field staff installed them at the Outcrop and screened them in the Fruitland Formation with the intent of measuring Fruitland water. Isotopic and geochemical results for these water bodies confirm that presumption, and also suggest that springs and piezometers are drawing Fruitland Formation discharge from the same shallow groundwater flowpaths. Compared categorically and regardless of drainage, springs and piezometers did not show a statistically significant difference from each other in terms of ^{18}O, tritium, or SAR content.

The young recharge waters of the Fruitland Formation at the Outcrop therefore appear to be characterized by moderate solute concentrations, with slightly elevated SAR values (0.38 to 0.67). The waters are modern, with mean tritium values of 5.4 TU and a possible tritium age of about 3 years. Springs and piezometers appear to be recharged by waters that similar to that found in the Piedra tributaries, with mean $\delta^{18}O$ values near -13‰ and mean tritium values of about 5.4 TU. The similar values for tritium, solute content, and SAR between piezometers, springs, and that of the Piedra River tributaries further suggests a hydrologic connection between surface water and shallow groundwater in the Piedra drainage.

Piezometers show a large contrast in the slope of the $\delta^{2}H/\delta^{18}O$ relationship by geographic area. The $\delta^{2}H/\delta^{18}O$ slope of 7.5 for piezometers in the Florida River basin mirrors that of the Florida River. This suggests either that there is a strong hydrologic connection between the Fruitland Formation and the Florida River, or that the piezometers were not properly installed and are drawing river water instead of shallow groundwater. The direction of that potential hydraulic relationship cannot be known for sure, either it has indeed reversed itself and the Fruitland is being recharged by surface water at the Outcrop, or Fruitland Formation water near the Florida has an extremely short residence time in the subsurface and discharges into the river without gaining any of the groundwater signals we have identified. Springs near the Florida indicate a longer residence time, with tritium concentrations of 5.9 TU versus 6.9 TU found in the river. The $\delta^{2}H/\delta^{18}O$ slope of 4.0 for piezometers in the Piedra River basin is similar to that of the tributaries of the Piedra River, and suggests a strong hydrologic connection between the piezometers and the groundwater that may be feeding the tributaries. Tritium values also matched between these piezometers (5.4 TU) and the Piedra River tributaries (5.4 TU), consistent with hydrologic connectivity between the tributaries and shallow groundwater. The piezometers of the Piedra drainage have elevated sodium, chloride, and SAR values that are very similar to those of the Piedra River tributaries.

Domestic Wells

Domestic well owners rely on several aquifers in the NSJB. As described earlier, the most important of these are the alluvial aquifers around the major rivers, the sandstone bedrock aquifers of the Animas Formation, Mesa Verde Group, Dakota Sandstone, and Morrison Formation (Topper et al., 2003). Near the Fruitland Outcrop, the alluvium and Animas Formation are the most commonly tapped aquifers, though the SJPLC has identified approximately 40 domestic wells completed in the Fruitland Formation and two completed in the Pictured Cliffs Sandstone (Papadopulos, 2006; SJPLC, 2006).

The isotopic and geochemical results from the 16 domestic wells sampled for this study are difficult to interpret primarily because we do not know which of the several potentially water-yielding formations they are drawing water from. As can be seen in Figure 3.28, other sedimentary formations outcrop in the NSJB as one moves southward into the basin from the northern rim of the Fruitland Outcrop. Domestic wells could be completed in any of these formations, or in hydrostratigraphic units below them (Figure 3.29). Depth of wells and formation-of-completion data was not collected during 2008-2009 fieldwork and it cannot be accurately ascertained by public drilling records retrieved from the Colorado Division of Water Resources (www.dwr.state.co.us). The only helpful information that public drilling records provide is well depth, casing depth, and static water level at the time of drilling (see Table 3.2) – and this information is available only haphazardly in public documents and may not be accurate to begin with. Gathering what data is available (depths for 13 of 16 wells), the domestic wells sampled ranged from 27–122 m deep (90 to 400 ft), with a median depth of 47 m (155 ft) and the vast majority (10 of the wells) exceeding 30 m (100 ft) in depth. The deepest well, WI1 in an irrigated agricultural area to the east of the Florida River, measured 122 m (400 ft) deep with a static water level at the time of drilling at 98 m (320 ft) below ground surface.

Without structural geologic data that provides the depth of the Fruitland Formation at each sampling area, it is impossible to truly evaluate whether domestic wells are in hydrologic contact with the Fruitland. We know that the 40 domestic wells completed in the Fruitland Formation near the Outcrop are less than 90 m (300 ft) deep (SJPLC, 2006). A general rule of thumb then, would be that wells shallower than 90 m (300 ft) are less likely to draw Fruitland waters moving basin-ward from the Outcrop, because the Fruitland's depth increases going south. Such generalizations do not account for preferential flowpaths such as natural fracture or joint systems, however. Based on a visual inspection of satellite imagery alone, only four of the 16 wells we sampled are definitely completed in the immediate vicinity of the Fruitland Outcrop. The remaining dozen wells are down-gradient of the Outcrop. Moreover, all but five of the wells sampled are close enough to the Florida, Pine, and Piedra Rivers that they could be completed in alluvium.

Domestic well chemistry can at the very least provide indicators to strengthen hypotheses about Fruitland interaction or suggest new ones, as well as generally providing windows into shallow groundwater systems in the NSJB that can help to characterize them. For example, all but two domestic wells sampled contained very young groundwater – the majority of which was less than three years of age, based on estimates derived from tritium concentrations (Table 3.6). Furthermore, age of groundwater did not correlate with well depth. For example, the 122 m (400 ft) WI1 well produced tritium concentration of 6.0 TU, similar to precipitation's 6.6 TU, despite being the deepest well sampled. In a different case, two wells near each other in the Basin Interior – PA1 and YE1 – are both about 84 m (275 ft) deep and differed in tritium concentration by 2.1 TU. Based on the age estimates derived from the tritium input function, a difference of 2.1 TU indicates an age difference of approximately seven years between the groundwater drawn by these neighboring wells.

The prevalence of young water in domestic wells in the study area suggests that groundwater is not being drawn at a sustainable rate in the area, resulting in overdrafted conditions. In an overdrafted groundwater system, water wells create cones of depression around them with steepened hydraulic head gradients, capable of quickly drawing in any new infiltration or other available water. Overdrafted conditions speed groundwater movement and could be the cause of the very young groundwater found in NSJB domestic wells. Along these lines, wells that show a significant difference in tritium concentration throughout the year might indicate a significant seasonal difference in water demand and/or water source. For example, the 1.2 TU difference between sampling dates for well YEI (5.3 TU in December 2008 and 4.1 TU in May 2009) is not consistent with a well-mixed groundwater reservoir with a long residence time and sustainable yields.

If overdrafting is related to agricultural activities, it might also help explain the high nitrate concentrations found in many domestic wells. Agricultural and ranching activities often lead to elevated nitrate concentrations in groundwater recharge, as do septic systems. There is an extensive literature on the use of nitrate as an index of ecosystem perturbation (Townsend & Riley 1999). Pristine waters generally have nitrate concentrations less than 10 $\mu eq\ L^{-1}$ (Williams & Tonnessen 2000), while increasing concentrations of nitrate are consistent with increasing perturbations (Aber et al. 1989). All springs, piezometers, and Florida River waters produced nitrate concentrations below 15 $\mu eq\ L^{-1}$, and all but four of the surface water sites in the Piedra River drainage have nitrate concentrations below 15 $\mu eq\ L^{-1}$. In contrast, nitrate values in domestic wells were as high as 726 $\mu eq\ L^{-1}$.

Two domestic wells produced older waters with tritium at or below the detection limit of ±0.8 TU. The wells are within 1.5km of each other along the Piedra River, downstream of the Fruitland Outcrop. One of the wells, MA2, is a mere 92ft deep. The depth of the other, GAR1, is not recorded. In addition to a lack of tritium, MA2 was characterized by a SAR of 12.1, significantly higher than the mean SAR value of 3.7 for domestic wells (Table 3.4). The Piper diagram (Figure 3.14) shows that domestic wells plot on a geochemical trajectory between that of surface waters and CBM wells. Further, the low tritium and high salinity of MA2 water suggest a potential hydrologic connection to the Fruitland Formation at this well, however it is difficult to ascertain the potential mechanisms for this kind of connection without knowing the depth of the Fruitland at MA2, and whether it is shallow enough to put it in the range of a domestic well completed at a depth only 28 m (92 ft). Estimating from a map view of MA2, the well is within a mile of the Outcrop in a region where the Fruitland Formation dips gently, so shallow contact is certainly not out of the question. However, given our understanding of Fruitland Formation recharge and discharge dynamics in the Piedra drainage, I would not expect Fruitland water to be tritium dead in this region. Moreover, assumptions that MA2 and GAR1 must be drawing Fruitland water are confounded by the fact that a well directly in between them, MA1 at 18 m (60 ft) deep, contains modern water with 5.1 TU.

Addressing Management Concerns

In summary, I will discuss the specific SJPLC management questions that drove this study. The current study design adequately addressed several of these questions, but others require additional work.

1. Is the Fruitland Outcrop an area of active recharge and discharge area?

Groundwater at the Fruitland Outcrop – as measured via springs and piezometers sourced by the Fruitland – is characterized by meteoric stable isotope concentrations and tritium concentrations that indicate young water. These data suggest that the Fruitland Formation is indeed recharged at the Outcrop where it is exposed as a topographic high point and unconfined by shale layers. Recharge moves from areas of higher hydraulic head to areas of lower hydraulic head. The young recharge waters of the Fruitland Formation at the Outcrop thus appear to be characterized by moderate solute concentrations, with slightly elevated SAR values (0.38 to 0.67). The waters are quite modern, with mean tritium values of 5.4 TU and a possible tritium age of about three years. The Piedra River and its tributaries, the Piedra piezometers, and springs across the Outcrop demonstrate similar isotopic and geochemical patters and therefore suggest that the Fruitland Outcrop is also an active discharge area at the Piedra crossing. This trend is not uniform across the NSBJ, as isotopic and geochemical results for the Florida River do not suggest a strong groundwater component.

2. *Will CBM-related groundwater withdrawals from the Fruitland Formation cause declines in groundwater levels near the Outcrop that could impact domestic water wells?*

This management question is perhaps the most difficult to answer of all. SJPLC staff have identified 40 domestic wells near the Fruitland Outcrop that they consider to be vulnerable to potential groundwater declines (SJPLC, 2006). Based on a visual inspection of satellite imagery alone, only four of the 16 wells we sampled are definitely completed in the immediate vicinity of the Fruitland Outcrop. The remaining dozen wells are down-gradient of the Outcrop. Moreover, all but five of the wells sampled are close enough to the Florida, Pine, and Piedra Rivers that they could be completed in alluvium. Without knowing what formations these wells are completed in, it is difficult to assess whether high solutes (and/or low tritium in a few cases) indicates interaction with Fruitland Formation waters. To truly address this management question, future fieldwork should focus on determining the stratigraphy at sampled domestic wells, the formations that they draw from, as well as monitoring for changes to the static water level at each well in addition to isotopic and geochemical parameters. An effort to improve geologic data could begin with interviewing the well owners and analyzing personal well completion records, if they are available, followed up with borehole geophysical methods to characterize stratigraphy. Speaking generally, based on the data available, however, the domestic wells sampled for this study shared a unique trend of producing very young water – groundwater often less than three years of age based on tritium estimates. Such quickly circulating groundwater suggests overdrafted shallow groundwater systems, which would exacerbate the long-term impacts of Fruitland Formation dewatering and depressurization from CBM development, if they occur. So while the current study does not directly answer the question of whether groundwater withdrawals from the Fruitland will impact domestic wells near the Outcrop, it suggests a need for extra vigilance regarding what could be particularly sensitive groundwater systems.

3. *Will CBM-related groundwater withdrawals from the Fruitland Formation intercept groundwater that would normally discharge via springs, thereby decreasing spring flow?*

Spring water and piezometer water at the Outcrop do not differ from each other in a statistically significant way based on any of the primary isotopic and geochemical metrics, which suggests that springs are fed by Fruitland Formation recharge. This finding corroborates earlier studies. Therefore, to the extent that CBM-related withdrawals may reduce the potentiometric surface of groundwater and groundwater storage near the Outcrop, springs will be effected. Springs with elevated solute content and SAR values above 0.3 – 10 of the 19 sampled – may have had the most interaction with the Fruitland Formation and its high-sodium characteristics and could be particularly vulnerable to groundwater declines. These springs are: TC2 in the Florida drainage; RS, VS1, VS2 in the Basin Interior; PG4, PG5, PG6, SC2, ST4, ST5 in the Piedra drainage.

4. *Will CBM-related groundwater withdrawals from the Fruitland Formation intercept groundwater that would normally discharge to rivers and streams, thereby decreasing baseflow to those rivers?*

The Fruitland Formation may already be intercepting groundwater that would normally discharge to the Florida River, based on the lack of an isotopic or geochemical groundwater signal in this river. If the Florida has indeed become a losing stretch in the vicinity of the Outcrop, it may be because groundwater withdrawals near the Outcrop have created a cone of depression and a hydrologic gradient that is driving water from the Florida River and into the Fruitland Formation, instead of the reverse. To evaluate this potential in the Florida drainage one could apply a tritium time series and convolution algorithm for $\delta^{18}O$ in near-River/near-Outcrop CBM wells that may be pumping young water, as well as in precipitation and an index site on the Florida River. Additionally, river flows could be measured at points immediately above and immediately below the Outcrop with the goal of monitoring baseflow levels at both places over the long term.

The Piedra River, on the other hand, appears to be very dependent on groundwater as a component of flow, year-round, which could mean higher sensitivity than other regional surface water systems to future CBM-related depletions. Because CBM development is moving into Archuleta County and the Piedra Drainage, it would be interesting to collect tritium and other isotope and geochemistry data from just-drilled CBM wells before they start producing. The results could be compared to current samples from the Piedra drainage, and monitored for changes over time. It would also be worthwhile to investigate whether the isotopic and geochemical differences between the Florida and Piedra drainages can be partly attributed to: 1) Piedra drainage being a lower elevation headwater catchment, perhaps resulting in more infiltration and a longer transit time for groundwater flow than in the Florida headwaters, and 2) if the Piedra drainage might also have a higher water table, subject to more evaporation as compared to the Florida drainage.

At the very least, the high degree of groundwater-surface water interaction in the Piedra River and its tributaries, as suggested by isotopic and geochemical data, calls into question modelers' conclusions that baseflow in NSJB rivers is less than 1 percent Fruitland Formation water, as well as their assumptions of similar hydrogeologic conditions between the Animas, Florida, Pine, and Piedra drainages. The uniqueness and complexities between these rivers that empirical data reveal should be considered in future monitoring and management decisions. In dealing with stream depletions in particular, a "one size fits all" management approach will likely not prove to be effective across the NSJB. For example, the SJPLC's current no-drilling buffer distance of 1.5mi may need to be adapted in different areas.

Reevaluating Conceptual Models

The dueling conceptual models of the NSJB merit reevaluation based on the results of the present study, though, true to scientific form, the new results primarily generate more questions than answers. In my opinion, the process of characterizing near-Outcrop groundwater and surface water, as well as their interactions, has not necessarily ruled out one conceptual model or another. I have not, with this dataset, explicitly proven or disproven that a Hydraulically Connected Basin or a Compartmentalized Basin exists. It does appear that the Fruitland Outcrop serves as a recharge area, and that Fruitland Formation groundwater travels shallow flowpaths that discharge via springs and rivers in regions of lower hydraulic head along the Outcrop. Both conceptual models could be supported by this data, however, since both presume that Outcrop recharge sources springs. The Compartmentalized Basin model does not directly posit Fruitland discharge to rivers, however, which our data suggests is occurring in the Piedra River drainage.

The conceptual models primarily differ over whether additional groundwater moves into the central San Juan Basin via deeper flowpaths, ultimately discharging at the San Juan River in New Mexico. The present sampling design could not address this "deeper question," due to lack of access to a representative sample of CBM wells, despite good faith efforts to gain industry permission for such a sampling effort. Among other things, it is impossible to perform more advanced hydrologic analyses, such as Principle Component Analysis (PCA) and End-Member Mixing Analysis (EMMA), without properly characterizing CBM waters, and potential variation in those waters, as an end member in a hydrologic mixing model. Because of this, it is impossible to speculate on the ultimate fate of Fruitland Outcrop recharge beyond reinforcing others' conclusions that some of the groundwater feeds springs and rivers.

The four CBM wells sampled were clustered together approximately 1.6-4.8 km (1-3 mi) from the Outcrop and contained no measurable tritium, suggesting low to no contact with modern recharge. In contrast, piezometers in the Fruitland Outcrop at the Florida River produced modern tritium concentrations. The Fruitland Formation near the Outcrop therefore appears to contain modern water and be in contact with the shallow aquifers. At 1.6 km away from the Outcrop and beyond, however, Fruitland Formation waters are sub-modern. This is not surprising, due to the slow movement of groundwater – hydraulic conductivity of 0.0055-0.055 ft/day, according to Norwest (2009) – and the probable depths of the CBM wells and Fruitland Formation at these distances. (Exact depths of the CBM wells were not provided; the possible range is 550-4,000 ft.) We may be missing important hydrologic activity in the intervening kilometers, however, as indicated by an increasing trend in SAR values with distance from the Outcrop. Sampling of CBM wells nearer the Outcrop would provide helpful information about the potential hydrologic interactions between waters in the Fruitland Formation and nearby domestic wells and springs. It was also impossible to sample CBM wells in the Piedra drainage for the current analysis, which precludes comparisons between CBM wells in La Plata and Archuleta counties.

To truly target the question of the degree of hydrologic interconnection between Fruitland Outcrop flowpaths and the deeper basin, one could sample CBM wells along a transect perpendicular to the Outcrop and look for changes in isotopic and geochemical traits with distance from the recharge zone. To grasp the differences that may occur along the breadth of the Outcrop, such as the presence of preferential flowpaths or interactions between rivers and the Fruitland Formation, one could also sample a transect of CBM wells running parallel to the Outcrop rim through La Plata and Archuleta counties. The SJPLC appears to be moving forward on just this kind of sampling design in a later phase of this study. SJPLC has identified CBM wells near the Outcrop and near area rivers that are drawing as many as 120 gallons per minute of water, which based on volume alone, would suggest a hydrologic connection between groundwater and surface water systems (SJPLC, personal communication, 2010). A unique identifier of Fruitland Formation waters, or a suite of isotopic and geochemical parameters that provide such an identifier, would greatly contribute to this effort. Potential options include: 1) fluorescence measurements of dissolved organic carbon (DOC) from CBM wells, along with UV absorbance techniques; 2) Alkaline and rare-earth elements from CBM wells (for example, barium is characteristic of CBM waters in the Powder River basin); 3) Strontium concentrations and isotopes from CBM wells.

The empirical results here, therefore, do not definitively prove that one conceptual model or another is at play in the Northern San Juan Basin. Instead, the data add complexity to the margins of these conceptual models – namely, that groundwater-surface water interactions, however they may be changed by CBM development, currently are not the same in each river drainage along the Fruitland Outcrop. These results dash the assumptions of hydrogeologic similarity and consistency behind stream depletion models and should be taken into account in future modeling and monitoring projects by resource managers. One of the problems with regional-scale questions, such as those about groundwater depletion in the NSJB, is that investigators attempt to address them with regional-scale answers. Potential impacts to groundwater systems near the Fruitland Outcrop may in fact be localized, based on variation in the characteristics of different near-Outcrop environments. Monitoring of water features becomes even more important (and even more difficult to do well) in a hydrogeologically diverse setting such as the Fruitland Outcrop.

In a promising development, monitoring activity has been increasing steadily in the SJB in recent years. Since 2000, CBM operators in the San Juan Basin have been required to collect baseline water quality data in two water wells within 0.25 mi of a new CBM well before drilling and then at 1-, 3-, and 6-year intervals after drilling completion (COGCC Rule 608). In 2008, this rule was applied to other CBM basins in the state, such as the Raton Basin, subject of the next chapter. Baseline analytes required by the rule include all major cations and anions, total dissolved solids, iron, manganese, selenium, nitrates and nitrites, dissolved methane, field pH, sodium adsorption ratio, bacteria (iron related, sulfite reducing, slime, and coliform), specific conductance, and hydrogen sulfide. Beginning in 2010, COGCC had enough data from operators to commission a trend analysis of 12 parameters across domestic wells in NSJB (alkalinity, calcium, chloride, carbonate, bicarbonate, potassium, methane, magnesium, sodium, pH, sulfate, and total dissolved solids). These trend analyses are now being performed annually using a Mann-Kendall approach. The 2011 results suggest statistically significant increasing trends in these parameters in 166 wells, statistically significant decreasing trends in 265 wells, and trends that are not statistically significant in the remaining 1,607 wells analyzed (Geomatrix, 2011).

Basin-wide domestic well monitoring and trend analyses are an important contribution to our understanding of NSJB groundwater dynamics. However, the regional approach may be missing important localized patterns that could be examined using spatial statistics, for example. Moreover, the fact that certain parameters are decreasing or remaining the same in the majority of domestic wells in the NSJB does not discount the fact that some wells are seeing increasing trends. It is also difficult to gain meaningful insights from the domestic well monitoring as currently required by the COGCC because the rules do not require measurement of static water level, which would address groundwater depletion questions and the uncertainties that arise from dueling NSJB conceptual models far more directly than geochemical measurements. Solute concentrations could also be more meaningfully interpreted if they could be correlated with changes to static water level. In addition, sampling for water's stable isotopes and tritium concentrations, while expensive, would also add a helpful dimension to these monitoring efforts by providing tools to source and age groundwater.

In a recent report on management of groundwater resources in CBM basins, the National Academy of Sciences recommended that resource managers and regulators "require or continue to require collection of baseline groundwater level and quality information for domestic water wells in advance of new CBM drilling activities to protect well operators and residents," for comparison against measurements made during and after CBM development (NRC 2010, p. 182). The present study has contributed to this effort in the NSJB via a neutral fact-finding endeavor designed to gather essential baseline isotopic and geochemical information for specific portions of the Florida and Piedra River drainages, as well as a limited area within the Basin Interior. But that does not mean that work in the NSJB is done: baseline information is only as good as the long-term monitoring that follows it. Continued long-term monitoring of isotopic and geochemical characteristics at the 67 stream, domestic well, piezometer, and spring sites sampled here – or a subset of these sites – should be conducted seasonally for the 50-plus additional years of CBM production estimated for the NJSB. There is no other empirical way to comprehensively evaluate if – and if so, how – current and future CBM activity may change shallow groundwater hydrology and surface–groundwater interactions near the Fruitland Outcrop.

This approach has its own problems, of course, and I would be remiss not to mention them here. Because subsurface cause-and-effect relationships are often decoupled until they manifest somewhere that we can see, smell, or taste them, and because adverse impacts to groundwater systems often do not manifest in the short-term at all, by the time a groundwater problem is detected by monitoring efforts, it is often too late to reverse the harms. This is the grim reality of the Hydraulically Connected Basin conceptual model, in particular. I would argue that lessons learned in the NSJB are valuable regardless, however, if only because they can, at the very least, guide development in other CBM basins in the West. The San Juan Basin shares many characteristics with the Powder River, Uinta, Piceance, and Green River basins. All are in semi-arid to arid environments with low and sporadic recharge, low permeability coal beds, fracture-controlled permeability and porosity (Questa, 2001). And all face similar potential environmental consequences and conflicts. The San Juan Basin is by far the most mature CBM play of the Western basins, and may serve as a harbinger of the effects of high-volume, long-term groundwater withdrawals in other places.

CHAPTER 4

THE CURIOUS INCIDENT OF THE WELL IN THE RATON

INTRODUCTION

The Controversy over Hydraulic Fracturing

In December 2007, a geologist at Pennsylvania State University named Terry Engelder made a quick calculation on a piece of scrap paper at his desk, a calculation that would change national awareness of natural gas – and the ways it is extracted – in ways he could not then have imagined. Engelder was trying to take a rough stab at a question that somebody had asked him in passing not too long before: how much methane is in the Marcellus shale? It just so happened that nobody – at least nobody in the public domain – had tried very hard to make the calculation up to that point (Glass, 2011). The deep Marcellus Shale stretches from the middle of New York state, through Pennsylvania, Ohio, and West Virginia into Kentucky and even Tennessee. The USGS had long estimated that the Marcellus held 2 trillion cubic feet (TCF). Engelder's result? About 25 times the USGS figure: 50 TCF of natural gas[12].

The new Marcellus estimate came at a good time for the natural gas industry. New capabilities in horizontal drilling (also called directional drilling) combined with increasingly effective hydraulic fracturing technology were then uniting to make it technically and economically feasible to tap previously inaccessible unconventional

---

[12] The 50 TCF figure has since been revised upward to 262 TCF by the Department of Energy (DOE, 2009).

plays, such as deep Marcellus Shale gas. With the right technology, and promising reservoir estimates behind it, a drilling boom took hold in an area that also happens to be the watershed to New York City, among other major East Coast population centers. People started to pay attention, and a national debate over hydraulic fracturing as an extraction mechanism in natural gas development emerged.

As an industry practice, hydraulic fracturing has become a potent symbol of the era of extreme energy extraction, or "tough fossil fuels" (Klare, 2009), though it is an old technique in the petroleum industry. The first commercial hydraulic fracturing job dates to 1948, according to the American Petroleum Institute (API, 2011). The practice is used to coax oil and natural gas from rock formations with low porosities and permeabilities – more than would emerge unassisted. It involves forcing at high pressure large amounts of water, a proppant (usually sand), and chemicals through perforations in the production casing inside a wellbore, with the intention of cracking open tiny fissures in the reservoir rock so that gas can flow to the wellbore and on to the surface.

Considerable controversy surrounds the current implementation of hydraulic fracturing in the United States, and the related environmental safety concerns are being debated and studied at state and national levels. Foremost among them is concern about potential harm to drinking water sources (primarily aquifers, but also surface water systems) by way of contamination or dewatering. A nationwide study launched by the Environmental Protection Agency in 2010 is examining this particular subject (EPA, 2011). The EPA's 2010 study follows on the heels of a similar 2004 study, which concluded that hydraulic fracturing posed no threat to groundwater (EPA, 2004b). Unfortunately, the 2004 study was widely discredited by EPA scientists and other researchers for methodological shortcomings and conflicts of interest by peer reviewers (UCS, 2006). In an effort to improve upon the mistakes of the 2004 study and design the second investigation in a publicly accountable and unbiased way, the EPA arranged a series of public comment sessions in natural gas states in the early stages of the research project. EPA held one of those hearings in Denver, CO on July 13, 2010, and I went to listen to the remarks.

More than 250 people attended the public meeting, which ran for several hours (EPA, 2010). The EPA, and the mediators hired to run the meeting, tried mightily to keep the hall focused on how EPA could most effectively design its scientific study, but it was clear from the outset that the room was full of strong opinions about the virtues and vices of natural gas development, in general, and hydraulic fracturing, in particular. A number of commenters did provide relevant research suggestions and insights, however. One of them was a landowner from a place called North Fork Ranch in the Raton Basin in southeast Colorado, a major coalbed methane-producing region of the state that has seen sharp increases in production in recent years – tripling to 1,543 wells and 80 Bcf in 2004 from about 478 wells and 28 billion cubic feet (Bcf) in 1999 (Watts, 2006). The landowner approached the podium carrying a mason jar of brown water and told the room that his well water had deteriorated just two weeks before. Citing previous drilling impacts to groundwater near his home, he asked that EPA use his neighborhood as a case study. His name was Tracy Dahl.

When next I heard Tracy Dahl speak to a roomful of people about his well water, it was February 22, 2011 at the Colorado Oil and Gas Conservation Commission (COGCC) headquarters in Denver. Curious about what had transpired with Dahl's well water, I had looked up his name in the EPA's public comment report from the Denver meeting and found his email address a few weeks before. When I reached Dahl, he informed me that he was soon to present his case in a public COGCC hearing and encouraged me to attend, which I did. The Dahl well incident began with sudden turbidity on June 30, 2010, to be explained in detail below. Dissatisfied with the COGCC staff investigation, the Dahls took their case before the

Commission, asking the panel to designate North Fork Ranch a sensitive area and to issue an Order Finding Violation against the operator in question, again Pioneer. They requested the hearing pursuant to COGCC Rule 510, which allows any person to make a statement to the Commission, as well as Rule 522.a(4), which allows a complaintant to file an application for an Order Finding Violation against an operator.

FACT-FINDING OBJECTIVES AND QUESTIONS

In trying to understand the factual dispute dynamics of local scale coalbed methane-groundwater conflicts, the Dahl well case is uniquely instructive, and for several reasons. First, the Dahls have personally collected semi-annual groundwater quality data for the past eight years, providing a robust baseline for investigation and interpretation. Second, the Dahls took their groundwater case further than any I have encountered in the state regulatory arena, and were closely and proactively involved in its development, providing an important example for an institutional analysis of the COGCC's response. The analysis of the Dahl well case that follows here is built upon information gleaned from the February 22, 2011 public hearing, as well as close examination of testimony, analytical results, and drilling records publicly available online in the COGCC docket for the Dahl case (complaint #200258755). The overall objectives of this analysis are the following:

1. To better understand the factual dispute dynamics of local scale groundwater conflict in Colorado's Raton Basin by performing a critical analysis of an alleged hydraulic fracturing impact to a domestic well that considers both the scientific and regulatory aspects of the case.
2. To then use this improved understanding to consider how academic researchers might productively engage in this type of factual dispute.

Specifically, to propose a joint fact-finding strategy in the form of groundwater monitoring guidance for domestic well owners.

RATON BASIN HYDROGEOLOGY

Geographic and Geologic Setting

Covering 10,360 km^2 (4,000 mi^2) in southeastern Colorado and northeastern New Mexico, the Raton Basin is made up of 3,000-7,600 m (10,000-25,000 ft) of sedimentary rocks that range in age from Pennsylvanian to Eocene (Figure 4.1). Locally, the geologic region is more likely to be known as Trinidad, Walsenburg, or Las Animas or Huerfano counties, to the west of the I-25 corridor as it crosses the state line into Raton, New Mexico. The Sangre de Cristo Mountains and the Wet Mountains bound the Raton Basin to the west and north, respectively, and the Las Animas and Apishapa arches mark its eastern boundaries. The basin's eastern edges tilt gently toward the west, while the Sangre de Cristo uplift has generated a flank of steep dips and thrust faults on the western side, producing an asymmetric synclinal basin that dips to a fold in the middle and curves upward at the edges (Geldon, 1990; Johnson & Finn, 2001). (For a geologic cross-section of the Raton Basin, please refer to Figure 4.2.)

The Vermejo and Raton Formations are the primary coal-bearing strata in the Raton Basin, overlying the Trinidad Sandstone, which was deposited during the final retreat of the Western Interior Seaway during the Late Cretaceous (Pillmore, Flores, & Fleming, 1988). The Trinidad Sandstone sits atop the confining layer of the Pierre Shale. The Cretaceous sedimentary layers of the Raton Basin generally correspond to those of the San Juan Basin, discussed in the previous chapter, though they are slightly younger in the Raton Basin. The Western Interior Seaway receded to the east and, therefore, withdrew from the Raton Basin after it had left its mark in the San Juan. (For a schematic that displays Cretaceous and younger strata in Colorado's coalbed methane regions, please refer to Figure 4.3.)

Deltaic lower coastal plain and fluvial environments produced the Vermejo and Raton Formations, as well as the organic matter that ultimately became their coals. The Raton Formation ranges from about 335-580 m thick (1,100-1,900 ft), and is composed of interleaved sandstone, siltstone, mudstone, and carbonaceous shale, with two major coal layers (Watts, 2007). The Raton Formation interbeds with the Poison Canyon Formation above it, and the two sedimentary layers are considered to be hydraulically connected (Flores, 1987). The case study that follows here focuses on that connection. Starting from the bottom, the stratigraphic sequence of Cretaceous-era sedimentary layers discussed in this chapter are as follows: the Vermejo Formation conformably overlies the Trinidad Sandstone, while the Raton Formation unconformably overlies the Vermejo, and the Poison Canyon Formation unconformably overlies and is interbedded with the Raton (Flores & Bader, 1999; Johnson & Wood, 1956). All of these sedimentary layers are considered to be the principal water-bearing rocks in the Raton Basin. (For a schematic of the major hydrogeologic units of the Raton Basin, please refer to Figure 4.4.)

It has long been known that the Raton and Vermejo coals contain large amounts of methane. Southern Colorado colliers of the late 1800s and early 1900s – the miners of the Ludlow Massacre and the Great Coalfied War – called it "firedamp" or "swamp gas." In mines that produced considerable amounts of methane, such as the Jokerville Mine in Las Animas County, gas was said to hiss out of the earth and even burst forth from the mine face on occasion. Between methane and coal dust explosions, Colorado's coal mines more than tripled the national average for mine fatalities to more than 10 deaths per thousand workers in the early 1910s (Andrews, 2008). In more recent history, Jurich and Adams (1984) reported 2 million cubic feet (MMcf) of methane per day escaping from just three mines in the west-central part of the Raton Basin (Jurich & Adams, 1984). In the early 1990s, the Gas Research Institute estimated natural gas resources in the Vermejo and Raton formations at 10.2 trillion cubic feet (Tcf) (Stevens et al., 1992). More recent geologic investigations have suggested that the Raton may hold a basin-centered gas accumulation, inhibited from migrating upward by a capillary seal of groundwater rather than a structural or stratigraphic trapping mechanism (Johnson & Finn, 2001).

Coalbed methane abundance has been assured by numerous gas reservoir investigations in the Raton Basin, but the geologic heterogeneities of the region are less understood. Igneous rocks in the form of dikes, sills, and stocks intrude upon the sedimentary layers in various parts of the Raton (Figure 4.5). Igneous bodies are particularly prevalent near the Huerfano-Las Animas County line, where dike swarms radiate from the Spanish Peaks and cut across sedimentary bedding to intersect a set of subparallel dikes that trend east (Carter, 1956). Igneous sills, which run parallel to bedding, intrude in the middle part of the Raton Basin and emerge in the Purgatoire River Valley northwest of Trinidad (Watts, 2007). In addition to these complexities, the pressure regime in the basin is poorly understood. The sandstones and interbedded coals of the Trinidad, Vermejo, and Raton Formations, contain significant underpressured gas accumulations at shallow depths (< 1,000 m, or 3,500 ft). As a result, pressures in parts of deeper formations are lower than those in the formations above them (Johnson & Finn, 2001; Tyler et al., 1995).

Groundwater Hydrology and Aquifer Use

The sandstone aquifers of the Raton Basin are unconfined, unlike the Fruitland Formation discussed in the previous chapter, which is confined by shale layers above and below it and unconfined only at its outcrop. In keeping, precipitation infiltrates the Raton's aquifers more readily than the San Juan Basin's, though recharge still occurs primarily at outcrops and in upland areas at elevations greater than 2,300 m (7,500 ft). Regional groundwater flow generally moves west to east, guided by the downward slope of the Sangre de Cristos. In the northern part of the basin, however, groundwater flows radially away from the Spanish Peaks, and along the eastern margin, where sediments dip to the west, groundwater moves down-dip to the west (Geldon, 1990). Groundwater flows laterally and parallel to bedding for the most part, but where fractures connect permeable rocks, it may move vertically. Most flow occurs in sandstones and coal seams, but fractured siltstone and shale also transmit groundwater. Igneous intrusions, on the other hand, typically block flow (Geldon, 1990). Complex geology and topography make flow-paths complex within the Raton-Vermejo-Trinidad aquifer and overlying aquifers such as the Poison Canyon (Watts, 2007). Streams intercept much of the regional groundwater circulation, and evapotranspiration accounts for the remainder of discharge (Watts, 2007). (For a map of the regional water table, please refer to Figure 4.6).

Deep bedrock aquifers and shallow formations demonstrate large differences in hydraulic head in the Raton Basin, which would suggest that that they are not in hydraulic communication with one another. The regional freshness of produced waters indicate meteoric circulation, however (Stevens et al., 1992; Tyler et al., 1995). Produced water from coalbed methane wells is characterized by low total dissolved solids (TDS) – all of it less than 10,000 mg/l, which is the national water quality criterion for an underground source of drinking water (USGS, 1985). More than half of produced waters in the Raton Basin are actually below 1,000 mg/l in TDS, which is one of the reasons that produced water is often discharged to surface streams in the Raton Basin rather than being disposed of by injection, as is common in the San Juan Basin.

CBM-related groundwater withdrawals more than tripled in the Raton Basin from 1999-2004 and continue to climb alongside increasing CBM development. The volume of groundwater withdrawals increased from about 3,000 af/y in 1999 (which at that point, were roughly equivalent to San Juan Basin averages), to about 8,900 af/y in 2004 (Watts, 2007). In 1996, average water production was 0.7 acre-feet of water (700 barrels) per million cubic feet (Mcf) of gas. In the center of the Raton Basin, where coalbeds are deeply buried, fluid pressure must be reduced by as much as 250–300 pounds per square inch to make way for gas flow – equivalent to a groundwater level reduction approximately 600-700 feet (Watts, 2007). Groundwater produced by CBM wells is generally not returned to the intervals from which it was pumped. Several methods are used to dispose of produced water in the Raton Basin: re-injection into deep geologic units, discharge to surface drainages, and discharge to lined (evaporation) or unlined (recharge) pits (COGCC, 2000).

Potential CBM Development Impacts to Water Wells

An estimated 1,500 domestic water wells are also located in the Raton Basin (Figure 4.7). About 90 percent of these water wells are less than 450 feet deep and are completed in the sandstone and conglomerate associated with – and hydraulically connected to – the coalbeds targeted by CBM development (Watts, 2007). Concerns about the potential impacts of CBM development to water wells in this hydraulically connected system are driving closer study of the Raton's hydrogeologic dynamics. (For a schematic of possible connections between CBM and water wells, please refer to Figure 4.8). In 2001, the U.S. Geological Survey (USGS), in cooperation with the Colorado Water Conservation Board (CWCB), began a study to better understand the hydrostratigraphic framework of the Trinidad, Vermejo, and Raton Formations. The USGS/CWCB research aims to better elucidate the internal and external geometry of the Raton Basin, as well as discharge and recharge conditions, and groundwater levels and fluid pressures in the principal hydrostratigraphic units (Watts, 2007).

Recent USGS/CWCB work has also focused on the vertical separation between water wells and CBM wells in the Raton Basin. CBM wells are relatively shallow in the basin, with maximum depths[13] of 732 m (2,400 ft) (Johnson & Finn, 2001). In most places, the bottoms of water wells are separated from the top of CBM production intervals by significant depths; the top interval of 90 percent of the CBM wells in the basin (for which data are available) are deeper than 206 m (675 ft) (Watts, 2006). In some places, however, the vertical separation between water and gas wells is less than 30 m (100 ft). Hydrogeologists reason, sensibly, that these water wells have greater potential for interruption from CBM drilling and hydraulic fracturing. (For a map of vertical separation between water wells and CBM wells in the Raton Basin please refer to Figure 4.9). Researchers are unable to estimate the risk the water wells may be exposed to because of their close proximity to CBM completions, however. According to Watts (2006),"More detailed geologic and hydrologic information is needed in these areas to quantify the potential effects of coalbed-methane production on water levels and the availability and sustainability of groundwater resources."

While hydrogeologists do not always associate hydraulic fracturing with shallow CBM plays, the practice has been key to the increase in production in the Raton. According to the EPA, "coalbed methane well stimulation using hydraulic fracturing techniques is a common practice" there (EPA, 2004a). When hydraulic fracturing began in the Raton, operators initially assumed that large stimulations were necessary to link the sometimes thin and disjointed coal seams in the basin. They found, however, that high-volume fracturing increased unwanted water

[13] Minimum depths for CBM wells are rarely published, which makes them much more difficult to come by.

production from associated sandstones, sills, and water-bearing faults. In most CBM wells, water yield decreases dramatically as gas production increases, but some wells in the Raton do the opposite. Two causal factors have been suggested in the literature: 1) hydraulic fracturing may have increased the CBM well's zone of capture to include adjacent water-bearing sills or sandstones that were hydraulically connected to recharge areas, or 2) fracturing crated a connection between coal seams and the underlying water-bearing Trinidad Sandstone (Hemborg, 1998). Some of these dynamics could be at play in the hydraulic fracturing case study that follows here.

THE CASE OF THE DAHL WELL

Introduction

Tracy and Amy Dahl live in the uplift of the Sangre de Cristo Mountains of Las Animas County, in the Culebra Range of the western Raton Basin, atop a five-acre mesa. Their self-built, off-grid home is located in the North Fork drainage, a tributary to the Purgatoire River, outside of the town of Weston (Figure 4.10). Tracy Dahl is president of the North Fork Ranch Landowner's Association, and in this role, he has witnessed several CBM-related impacts to domestic water wells and surface water in the North Fork Ranch area and has actively participated in Colorado Oil and Gas Conservation Commission and Colorado Division of Water Resources rulemakings on these subjects. Much has changed in the area since the Dahls began building on their mesa in 1995, which now provides a view of 15 CBM wells. Uniquely, the residents of North Fork Ranch have gathered baseline water quality data in their neighborhood for the past seven years – before and after CBM development began in earnest – thanks in part to a Colorado State University extension program. In the process, North Fork Ranch landowners have reported changes in their water composition, including elevated chloride and pH level in several springs.

North Fork Ranch residents have filed complaints of drilling impacts to surface water and groundwater systems with COGCC in the years since CBM development began, some of which have resulted in fines to operators. In 2006, a drilling team from Pioneer Natural Resources Co. (Pioneer) shot high-pressure air into the Molokai well borehole in North Fork Ranch in an attempt to dislodge a stuck drill bit, and caused two nearby domestic wells to spurt water out of their standpipes like small geysers for days afterward (COGCC, 2006). The impact led to a temporary moratorium on new drilling in the area, as well as the installation of five monitoring wells, three of which have been producing methane at or above the Interior Department's 10 mg/l explosion threshold since 2008, according to testimony by Dahl submitted to the COGCC (Dahl, 2011; Eltschlager, 2001). Pioneer drilled new wells and built new cisterns for the two landowners affected by the Molokai. In the years since, one of the old domestic wells, which was still in use, saw a significant increase in its Sodium Adsorption Ratio (SAR) and dissolved methane, and COGCC issued an Order of Violation to Pioneer in 2009 (COGCC, 2009).

The Dahl Water Well, the Alibi 23-2 CBM Well, and the Incident

The Dahls have been using their well for over eight years under an adjudicated groundwater right. The Dahl well is 137 m (450 ft) deep and is completed in the Poison Canyon Formation, at an elevation of approximately 2,330 m (7,640 ft) above sea level (Boday, 2003). The well is approximately 15 cm (6 in) in diameter, and was completed in 2002 with a cable tool drill. In the process, the driller hit water-bearing zones at 175 ft, 350 ft, and 450 ft below ground surface. The top of the well is cased with 12 m (39 ft) of steel surface casing, and approximately 137 m (450 ft) of PVC plastic casing that is 11.5 cm (4.5 in) in diameter. Three 6 m (20 ft) sections of the plastic casing are perforated in the water production zone with slots 0.3 cm (0.125 in) wide. The well is not screened or packed with sand or gravel around the perforated casing; this is said to be a typical well construction method in the Raton Basin, however. The Dahl well operates by way of a solar-powered pump, which moves well water to a 1,250 gal cistern near the Dahls' house at a rate of approximately 1-1.5 gpm on clear days. From the cistern, the water is pumped to a second, smaller cistern located inside the house. The Dahls spent about $25,000 developing the system. At the time of drilling, depth to water was 62 m (205 ft) below the ground surface. In the ten times that the static water level has been measured between 2008 and 2010, the water level has ranged from 180-220 ft below ground surface.

The Dahl well is approximately 363 m (1,190 ft) away from the Alibi 23-2 CBM well, which is the closest CBM well to the Dahls (for a schematic of the horizontal plane, please refer to Figure 4.11). The bottomhole elevation of the Dahl well is approximately 468 ft above the uppermost perforated and stimulated zone in the Alibi 23-2 well, according to calculations made by COGCC staff (COGCC, 2010) (Figure 4.12). According to Pioneer's records, as submitted to COGCC, drilling began on the Alibi 23-3 on April 27, 2010 (Pioneer, 2010). Pioneer's team drilled a 28 cm (11 in) borehole to 236 m (775 ft) below ground surface and installed 22 cm (8.625 in) steel surface casing to a depth of 233 m (765 ft). The drilling team used 468 sacks of cement to secure the surface casing, but had problems during the cement job. According to drilling records, the cement stopped circulating up from the bottom of the well, which forced the Pioneer team to fill the annulus of the well from the top in two remedial cement jobs that left the top of the surface casing cement 64 m (210 ft) below ground surface. By the time the team deemed the job complete, they had pumped 40 percent more cement into the annulus than true hole volume (49 barrels), though the drilling superintendent said the unexplained lost cement was "pretty much normal" in the drilling completion report (Pioneer, 2010). After the surface casing cement set up, the team drilled a 20 cm (7.87 in) borehole to a depth of 782 m (2,565 ft), installed production casing to 760 m (2,491 ft) and cemented it with 382 sacks of cement. COGCC deemed the well in compliance with Rule 317, designed to protect groundwater resources during exploration, development, and production operations.

A Bradenhead test on the annular space between the surface casing and production casing showed zero lbs/in^2 of pressure on May 28, 2010, a month before Alibi 23-2's perforation and fracturing. Pioneer's well completion team used 240 shots to perforate the production casing and cement along coal zones. Once perforated, the well could be hydraulically fractured, and this was accomplished in 14 stages. According to Pioneer's drill completion report (2010), two deep perforated zones absorbed four of these fracture treatments and the shallowest perforated zone took the remaining ten treatments. The deepest fracturing zone was 704-711 m (2,310-2,334 ft) below ground surface and the shallowest was 232-239 m (760-784 ft) below ground surface. The top of the uppermost fracture zone, at an elevation of approximately 7,172 feet above sea level, was 468 ft below the bottom of the Dahl water well. The diagonal distance between the top of the fracture zone and the bottom of the Dahl well, as calculated using the Pythagorean Theorem and horizontal/vertical distances of 468 and 1,190 ft , respectively, is 1,279 ft. The fracturing mixture Pioneer used was 99.7 percent (by weight) recycled produced water from a nearby CBM well, guar gel, nitrogen in gas form, and silica sand. Other constituents included a biocide and gel breakers, according to the COGCC investigator in his final report, and likely additional agents not released publicly. The Alibi 23-2 first produced gas on July 22, 2010. Total production in August 2010 was 295,000 cubic feet of gas and 1.3 acre-feet (13,753 barrels) of water.

Before detailing the events related to the hydraulic fracturing of the Alibi 23-2, it is important to pause and mention Tracy Dahl's maintenance of his domestic water well. Dahl chlorinates his well roughly every two years with a mix of Chlorox bleach and water, as recommended by the Colorado Department of Public Health. In eight years, Dahl has disinfected his well following roughly the same procedure four times. On previous occasions the Dahls did not purge their well of bleach solution, but left it standing in the well in order to ensure the greatest efficacy, relying upon an activated charcoal filter in the house to remove any additional chlorine and byproducts such as trihalomethanes (THMs). According to Dahl's testimony before the COGCC, this strategy had always worked with no trouble. On May 25, 2010, Tracy Dahl premixed about 1.4 gal of bleach with 10 gal of water and poured it down his well bore; he then cycled the water between an outside hydrant and his well casing in a closed loop for 6 hours. Dahl let the bleach solution sit in the wellbore until the next afternoon. Then, for about half a day each on the following three days (May 26, 27, 28), Dahl purged the well of the disinfecting solution, pumping an estimated 405 gal of water onto the ground until all trace of chlorine odor had dissipated. Two days later, on May 30, Dahl began to filled his cistern with about 1,000 gal of water. All together, Dahl had purged roughly 1,400 gal of water – all of it clear – from his well after the chlorination treatment. Based on COGCC staff calculations, this was approximately seven well volumes of water.

The 1,000 gal of water in the cistern was enough to last the Dahls for the next month. Tracy Dahl next attempted to pump water on June 28 and June 29, when he had an estimated 50-100 gal left in his cistern, but could not due to overcast conditions. June 30 was clear, however, and Dahl began to pump his well at mid-day. Meantime, hydraulic fracturing operations had been underway at the nearby Alibi 23-2 for at least 24hrs. At 6:00 p.m. that evening, Dahl peered in his cistern to check on progress, and encountered quite a surprise. According to Dahl's testimony, he found it half full of about 400 gal of "grey/brown, very turbid water." (For photographs, please refer to Figure 4.13). "Since our water well had never produced anything but clean, clear water prior to this day, I can tell you that it was very shocking to see," he added. Dahl immediately called the operator, Pioneer, as well as the COGCC's environmental protection specialist for the Raton Basin region. He told them what had happened and asked them to come the following day.

Investigation

COGCC's environmental protection specialist arrived the next morning, July 1, as did two representatives from Pioneer Natural Resources and two representatives from Norwest, contracted by Pioneer. Accompanied by Pioneer staff, the COGCC investigator and Norwest. representatives sampled water from the Alibi 23-2 well site first, according to the investigator's final report (COGCC, 2010). There, they collected water from one of the two fracturing fluid tanks on the pad. The frac tank had been treated with a biocide, but all other products were added in a blender just prior to fracturing, according to Pioneer. The COGCC investigator measured gas venting from the flowback pipe using a portable meter, recording 20 percent methane (CH_4), 2.9 percent oxygen (O_2), 4.5ppm hydrogen sulfide (H_2S), and 125ppm carbon monoxide (CO). He also collected yellow quartz proppant sand from a pile on the well pad and samples of the flowback fracturing fluids as they cycled back from the well and ran out of a pipe into a lined pit. Norwest staff collected the same samples (Figure 4.14).

At the Dahl well, the COGCC investigator measured gasses from the vent hole in the sanitary cap on the Dahl well casing. He did not detect any combustible gasses and measured oxygen at 20.9. The COGCC investigator visually inspected the water in the cistern, which he wrote "appeared clear" and without any sheens on the water. Dahl said he thought he did see a sheen on the water. Neither Dahl nor the COGCC investigator noted any odors coming from the cistern or effervescence in the water. Dahl had begun pumping water from the well into buckets shortly beforehand, as per instructions from the COGCC investigator, and reported that it was initially cloudy and turbid but becoming less so with each bucket pumped (for pictures of the Dahl water on July 1, please refer to Figure 4.15). The COGCC investigator stirred the water in the cistern to re-suspend sediment and took a sample.

The COGCC investigator sent samples collected for general water quality to the Fort Collins lab of ALS Environmental, a full-service commercial laboratory. Water samples collected for isotopic analysis were shipped to Isotech Laboratories, Inc. in Champaign, IL, also a commercial lab. The investigator sent both sets of samples on July 1 and both labs received them the following day. The COGCC investigator accidentally forgot the samples that were supposed to be sent off for inorganic analyses at the Dahl home, however, and made an appointment to return a week later (July 8) to collect new ones. Norwest's representatives did not forget any samples. Norwest sent samples from the fracturing tank, flowback pit, Dahl cistern, and Dahl well to the commercial TestAmerica Laboratories, Inc. in Denver for a full organic and inorganic chemical analysis, and to Isotech Laboratories, Inc. in Champaign, IL for isotopes.

The COGCC investigator returned on July 8 and collected water samples directly from the Dahl well for analysis of general inorganic parameters and bacteria. He also collected sediment from bottom of the cistern. By this time, Dahl had purged another four well volumes of water since the impact at roughly 150 gal per day in an effort to clear his water. The COGCC investigator measured gas at the wellhead for a second time and the results matched those from July 1. He immediately sent water samples for inorganic chemistry analysis to ALS in Fort Collins. The sediment samples went to ALS in Fort Collins for metals analysis and DCM Science Laboratory, Inc. in Wheat Ridge, CO for mineralogical analysis. The investigator ran bacterial tests himself using a bacterial activity reaction test kit (BART). On this day, the investigator said the water was "relatively clear with no odors or effervescence." (For pictures of the Dahl water on July 8, please refer to Figure 4.15)

It is difficult to ascertain from the case docket what analytical tests the COGCC ordered and when. Between the first and second sampling events, the investigator ordered different parameters tested for (and between) the cistern and the well. In the final results, he shows COGCC samples for the cistern on July 1 and for the water well on July 8. Norwest's data is consistent for July 1, however. Norwest got well and cistern samples to the laboratory on the first try and ordered the same tests for both the cistern and well. The COGCC investigator and Norwest ordered the similar tests from the two Colorado-based commercial labs, which have comparable reporting limits. Norwest tested for a handful of parameters that COGCC did not, however, including: inorganic parameters including bromide, coliform bacteria, hydroxide as Caco3, mercury, slica, sulfide, temperature (field), Total Suspended Solids (or TSS); and organic parameters including volatile BTEX compounds (benzene, ethylbenzene, toluene, xylenes), ethane, ethane, diesel range organics, and oil and grease. The COGCC investigator ordered two tests that Norwest did not, for radioactive lithium and uranium. Separately, the Dahls also sampled their water for turbidity. When the Dahls realized the COGCC investigator had not ordered a turbidity test on 7/1, they sent a sample they had collected themselves on June 30 to Energy Laboratories in Casper, WY for turbidity analysis. They also did this for a second sample collected on July 2.

In his written case analysis, the COGCC investigator reported results from Dahl's water for the following:

- General Water Quality — Conductivity, Bicarbonate Alkalinity, Carbonate Alkalinity, Total Alkalinity, pH, Total Dissolved Solids, Total Suspended Solids
- Nutrients and Bacteria — Nitrate, Nitrite, Total Nitrite/Nitrate, Iron-reducing Bacteria, Sulfate-reducing Bacteria, Slime-forming Bacteria
- Metals — Aluminum, Antimony, Arsenic, Barium, Berylium, Boron, Cadmium, Chromium, Cobalt, Copper, Iron, Lead, Lithium, Manganese, Molybdenum, Nickel, Selenium, Silver, Strontium, Thallium, Uranium, Zinc

•	Major Ions	Bromide, Calcium, Chloride, Fluoride, Magnesium, Potassium, Sodium, Sulfate
•	Organics	Dissolved Methane
•	Other	Glycols, methanol, ethelyne glycol monobutyl ether
•	Gas Composition	Nitrogen/Argon ratio
•	Stable Isotopes	^{15}N, ^{18}O, ^{2}H
•	Minearology	Composition of frac sand, well cuttings, suspended sediment in Dahl cistern

The parameters not presented – namely, the volatile organic compounds that Norwest ordered – were all below detection limits.

The COGCC investigator returned a third time, on July 14, with a consultant from Environmental Alternatives, Inc., based in Cañon City, CO, to measure depth to groundwater in the well, two weeks after the turbidity event.

Assumptions of the COGCC Investigation

The COGCC investigator presented the analytical results from his investigation of the Dahl well according to two major themes based on the assumptions guiding his work. First, the COGCC investigator assumed that the Dahl's well water chemistry would change due to the June 30 turbidity event, departing from baseline water quality conditions. Second, the COGCC investigator assumed that, if the Alibi 23-2 fracturing was the cause of the turbidity, then some amount of the Alibi 23-2 fracturing fluid would have to end up in Dahl's well – and that, in the process, Dahl's domestic well water would pick up the chemical signature of CBM produced water and/or any fracturing chemicals used. Following these assumptions, the COGCC investigator compared and contrasted Dahl's well water from before June 30, 2010 to that sampled on July 1 and July 8, 2010, as well as to the chemistry of the Alibi 23-2 fracturing fluid. Following this logic, the Alibi 23-2 and the Dahl well would represent end members on a hypothetical "mixing line" representing different combinations of the two water sources. The mixing line model and hydrograph separation as a methodology are established concepts in hydrologic and hydrogeologic investigations (Liu, Williams, & Caine, 2004). Following this idea, the COGCC investigator was therefore looking for signs of "frac water" in Dahl's water chemistry, and did so by comparing before and after chemistry in the Dahl while keeping in mind the chemical signature of the frac water.

The COGCC investigator's comparisons were possible only because the Dahls had quite proactively been collecting baseline data on their groundwater quality going back to 2004, two years after the well was drilled. Dahl's baseline testing far exceeds that of your average domestic well owner; the wealth of data that resulted gave both parties a strong starting point for analysis and interpretation. The Dahls' first set of baseline data dates to October of 2004. After that, the Dahls tested their water twice in 2006, twice in 2008, twice in 2009, and twice in 2010 prior to the June 30 incident, for a total of nine sampling events. Dahl collected six of those samples collected during baseflow conditions (Sept-Feb) and three during snowmelt conditions (April-Aug). On most occasions, Dahl had his water tested for metals, major ions, nutrients, general water quality parameters, and methane. Testimony suggests that he also tested for bacteria occasionally. The COGCC investigator presented a summary of the Dahl 2004-2010 results in a table attached to his final report (Figure 4.16), in addition to a table of COGCC and Norwest results from the July 1 and 8 sampling events (Figure 4.17). In addition COGCC sampling, Dahl tested his well seven months later, on February 3, 2011, and presented those results in his testimony to COGCC. In addition to testing for the usual parameters, he added volatile organic compounds and turbidity to the 2011 analysis.

It is impossible to directly compare the hydrologic end members in the investigation because Pioneer, Norwest and COGCC did not reveal all of the hydraulic fracturing fluid chemistry. Pioneer is required to furnish this information to COGCC upon request, but the data is not made public. In his final report, the COGCC investigator presented major ion chemistry of the Alibi 23-2 flowback water and produced water from two nearby CBM wells in a series of Stiff diagrams, but the raw data is not provided. In the analytical reports in the docket, one can find raw data for bicarbonate, carbonate, total alkalinity, pH, conductivity, total dissolved solids (TDS), major anions, nitrogen-to-argon ratio, and stable isotopes. No data is available for volatile and semi-volatile organics, metals, glycols, or other parameters that could be considered proprietary; some information in Norwest's analytical reports is redacted. As one might expect, the fracturing and flowback fluids are high in chloride (140–170 mg/l), TDS (2,400–3,000 mg/l), conductivity (2,540–2,980 umohs/cm), pH (8.29–8.3), total alkalinity as $CaCO_3$ (1,100–760 mg/l), carbonate as $CaCo_3$ (50 mg/l), and bicarbonate as $CaCo_3$ (760 mg/l–1,100 mg/l).

Tracy Dahl approached the analytical results with a different set of starting assumptions. Dahl's starting assumptions included those of the COGCC investigator, but went slightly further. According to testimony, Dahl also assumed that there did not have to be fracturing fluid or CBM produced in his well for a causal connection to be established between the fracturing and his change in water quality. Dahl based this assumption on tacit experience with his well water – which had been clean every day for eight years. He also based the assumption on the timing of the turbidity in his well – which was the same day as the fracturing of the Alibi 23-2. Lastly, he built his assumptions upon scientific literature indicating that hydraulic fracturing can create or increase the hydraulic connection between formations, particularly in complex and poorly understood hydrogeologic circumstances like those of the Raton Basin (Hemborg, 1998).

Results of the COGCC Investigation

When the analytical results came in, they did not demonstrate the trends the COGCC investigator assumed would link Dahl's turbidity event to the hydraulic fracturing of the Alibi 23-2. First, Dahl's well water did not show significant differences in chemistry before and after June 30. A few minor differences were apparent, however. In terms of general water quality, the largest before-and-after difference came in the form of turbidity, which was 15.2 ntu on June 30 and had reduced by more than half to 7.1 ntu in 48 hours, on July 2. (For reference, the World Health Organization recommends turbidity levels of 1 ntu in drinking water.) Total Dissolved Solids increased slightly with turbidity, to 350 mg/l from a baseline range of 306-324 mg/l. Conductivity went up slightly along with TDS, to 551 umohs/cm from a historical range of 500-520 mg/l. The static water in Dahl's well did not change significantly from baseline – it was 67 m (219.5 ft) below ground surface as compared to a historic range of 51-65.5 m (181-215 ft). This measurement must be interpreted with caution, however, since the COGCC investigator did not measure depth-to-water until two weeks after the turbidity event.

The major ion chemistry of Dahl's well water did not change significantly either (for Stiff Diagrams, please refer to Figure 4.18). Dahl's sodium-calcium-bicarbonate-sulfate character water remained largely the same, with a noticeable change only to chloride, which rose to 17 mg/l in the cistern from a baseline range of 4-5.7 mg/l[14]. Stable isotopes of water did not show marked differences either. The COGCC investigator plotted the $\delta^2H/\delta^{18}O$ relationship, with the Global Meteoric Water

[14] Chloride measured 22 mg/l in the well on July 1, but this was measured only by Norwest because the COGCC investigator forgot the samples for inorganic analysis and had to resample them on July 8, by which time the chloride level in the well was down to 3.6 mg/l.

Line as a reference. The plot shows no change in the isotopes in Dahl's water between a sample from February 2010 and investigation samples on July 1, 2010. For comparison, the stable isotope plot shows the isotopic signature of the Alibi 23-2 flowback water, which plotted at a different place on the GMWL with slightly more depleted results ($\delta^{18}O$ of -11 ‰ for the Alibi 23-2 versus -10 ‰ for the Dahl well water) (Figure 4.19). The nitrogen-to-argon ratio of the well water matched atmospheric conditions (Figure 4.20). The stable isotope signatures of inorganic carbon were very different between the two water sources (-15 ‰ for the Dahl well and +8 ‰ for the Alibi 23-2), with the Dahl water holding at -15 ‰ before and after June 30.

As for metals, trace amounts of arsenic, antimony, aluminum, molybdenum and uranium were present in Dahl's well on July 1. Each of these metals had appeared in scattered traces in prior years, however, though none of them had been present in 2010. All appeared in slightly higher trace amounts on and after July 1, but those amounts were all below health standards. A few volatile and semi-volatile organics (VOCs and SVOCs) appeared in Dahl's well in trace amounts after the fracturing job. Methane, which had never been detected in Dahl's water, came in just above the reporting limit at 0.0054 mg/l. Four trihalomethanes (THMs) were present; all of them were relatively low, but two were measured at concentrations above drinking water standards. All of the THMs had been detected before, however. One phthalate was detected, but its result was below reporting limits. Traces of toluene, chloroform and chloromethane were apparent in water sampled by Dahl seven months after the incident (in February 2011) and tested by Energy Laboratories in Casper, WY.

The July 1 samples from Dahl's well (taken by Norwest) contained no bacteria, according to the ALS results. The COGCC investigator found iron-related bacteria in the samples he took on July 8, however, cultured using the BART kit. On a scale from one to four (not aggressive, moderately aggressive, very aggressive, extremely aggressive), Gintautas determined that the iron-related bacteria to be a "two," or "moderately aggressive." DCM Laboratories performed mineralogical identification and compositional analysis of the sediment in Dahl's cistern and the fracturing proppant sand. The proppant was almost pure quartz, well-rounded and well-sorted "silica sand" with a grain size between 0.5 mm and 1 mm. The particles filtered from the cistern show more varied minearology, including quartz, feldspars, micas, and clay, all indicative of the Poison Canyon Formation, which originated as fluvial and deltaic sedimentary deposits. The particles were primarily made of iron, aluminum, calcium, and silicon, in that order.

COGCC Investigator's Interpretation

After analyzing all of the available information, the COGCC investigator concluded "no data or observations available indicated the presence of any impacts to groundwater or [the Dahl] water well from the fracture treatment of the nearby Alibi 2302 Well." To arrive at this conclusion, the investigator reasoned that Dahl's well water chemistry would have to show a significant increase in at least one of the primary constituents of Alibi 23-2 fracturing chemicals or CBM produced water – i.e., nitrogen gas, silica sand, guar gel or surfactants, sodium, bicarbonate, TDS, total alkalinity, methane – in order to be considered "impacted" by the Alibi 23-2 fracturing job.

The COGCC investigator repeated that Dahl's well did not appear effervescent, which one would expect to see in the presence of escaping methane gas, or with a sheen, which one would expect to see in the presence of guar gel or surfactants. Dahl's well did not contain excess nitrogen or sand from the fracturing fluid either. The COGCC investigator concluded that the particles making Dahl's water turbid were mineral particles of the aquifer materials present in the rocks that the well was drilled and completed in. Moreover, water chemistry showed no significant changes to stable isotope concentrations or major ions, no change to pH, no meaningful trends in TDS concentration, total alkalinity, no appreciable change in static water level, and no major increase in methane concentration.

The COGCC investigator then offered an alternative hypothesis for the June 30 turbidity event. He quoted a book on well chlorination as recommending purging 10 well volumes after a chlorination event[15], and proceeded to make an argument that Dahl had not effectively purged his well after chlorination because he stopped at seven well volumes. The COGCC investigator interpreted the increased chloride concentration in the July 1 samples as evidence that the well had not been effectively purged prior to July 8, noting that that chloride concentration dropped to 3.6 mg/l after Dahl purged an additional 3.5 well volumes by July 8. "The continued presence of a strong oxidant in [the Dahl] well during the month of June 2010 allowed continued oxidation of biofilms in the well bore," the COGCC investigator wrote in his final report. According to the investigator, typical byproducts of chlorination with a sodium hypochlorite bleach such as Chlorox are sediment, trihalomethane (THM) organic compounds, and particulate iron oxides as well as chloride if the well contains active colonies of iron-related bacteria, which Dahl's did. Since frac fluid chloride could not have migrated into Dahl's well without other constituents such as sodium, the slightly elevated chloride levels could not be considered an impact from the Alibi 23-2, the investigator reasoned. The particles filtered from Dahl's water were high in iron, which he interpreted as indicating amorphous iron oxide particles, and which he concluded must have been formed by the colonies of iron-related bacteria present in Dahl's well.

[15] The COGCC investigator did not include written references for his citations, so it is difficult to know from what sources he gathered information.

The COGCC investigator did not address the toluene in Dahl's water in February, 2011, other than to say during the hearing before the COGCC that it could be "naturally occurring," when asked by Dahl during the hearing. The investigator also read and interpreted the pressure records from the 14-stage Alibi 23-2 fracture treatment, focusing on the Bradenhead annulus pressure, which must be monitored during fracturing under COGCC Rule 341. He said he did not observe any pressure increases during 9 of the 14 stages, and observed only minor pressure fluctuations (10-20 psig) during 5 of the 14 stages. (Operators are required to notify the COGCC within 24-hours if pressure increases by more than 200 psig during fracture treatments.) Neither did the investigator find any sudden decrease in pressure. He interpreted this as indicating that the fracturing stages could not have broken out of zone into an unconfined zone such as Dahl's well bore. Cement bond logs were also up to COGCC regulations, the investigator said.

Dahl Interpretation

Dahl read the COGCC report in the form of a letter sent to him on December 1, 2010, exactly six months after the impact (COGCC, 2010). Building from a different set of starting assumptions, Dahl came to different conclusions after looking at the COGCC data. In his response prepared for the COGCC hearing, Dahl called the well chlorination conclusion by the COGCC investigator "a red herring," and he attempted to disprove it in his written testimony. Dahl began by pointing out that the turbidity in his well had reduced by half in 48 hrs; to him, this drop suggested an acute impact beginning on or around June 30. "I maintain that there is no way that this level of sediment could have remained suspended In the water column in our well for over a month, then settled out in a few days' time," Dahl stated. Dahl also questioned why the COGCC investigator did not address this quick drop in turbidity in his report, and challenged the investigator's description on July 1 that the water "appeared clear" in the cistern.

Dahl argued that he had adequately purged the Chlorox solution from his well at the end of May by pumping until all trace of chlorine odor was gone, and then pumping another 1,000 gal to fill the cistern. He noted that in the four times that he had chlorinated the well in the previous eight years, he had not purged it all and no turbidity had resulted. Dahl quoted a hydrogeologist from Ottawa, Kansas-based Water Systems Engineering, Inc. named Michael Schneiders, as saying that sodium hypochlorite is the recommended disinfecting solution for water chemistry such as Dahl's because it is less likely to cause turbidity. Dahl also cited an instructional booklet by the Michigan Department of Environmental Quality as stating that sodium hypochlorite is the preferred disinfectant for domestic wells because it creates less precipitate than other types. He then quoted a Clorox company spokesman as stating that the company is unaware of its products causing turbidity when used properly as a well disinfectant. In short, Dahl argued that he had used the correct disinfectant at the proper ratio and purged the well in excess of the Colorado Department of Public Health's recommendations.

Further, Dahl argued that shock chlorination activities are typically less effective in well water like his, which is of a high pH (around 8.5) that subdues reduction reactions. The persistence of a low-level iron-related bacteria infection was evidence of this, he argued. "I will stop short of saying that biological activity couldn't have been responsible for any turbidity, but to ascribe it wholly to this is completely unsupportable," Dahl argued. Addressing the slightly elevated (17 mg/l) of chloride in the well, Dahl said that it might have come from the small amount of bleach he adds to his cistern as an extra measure to prevent the growth of algae or bacteria. Dahl argued that the COGCC investigator's "statements on shock chlorination were taken out of context and the entire argument smacks of an attempt to create plausible deniability.”

He then presented quotes from personal correspondence with Schnieders and other experts in an effort to offer a new interpretation of the data and a new model of causality. The experts Dahl had communicated with acknowledged that the water chemistry as presented did not show a direct influence of fracturing chemicals or CBM produced water on the well, but they challenged the assumption that those fluids would have to appear in the Dahl well in order to prove causality. All of the experts suggested that the high pressures of the fracturing job may have caused a physical disturbance to the Poison Canyon aquifer that manifested in Dahl’s well as turbidity. According to Schnieders: “The COGCC Summary Report does not address the physical impact of the fracing operations on the formation… the energy employed in the fracing of the Alibi 23-2 may have influenced the formation your well draws water from.”

Ernest Williams, PhD, chairman of the American Water Works Association Wells Committee said that chlorination could discolor water, but only temporarily. Williams added: “Drilling a nearby oil or gas well could easily cause turbidity to show up in this water well, especially if the water well and gas well are both in fractured rock formations. There are plenty of documented instances of this occurring, particularly if the gas well was hydraulically fractured as part of the completion.” Glenn C. Miller, PhD, Professor of Natural Resources and Environmental Science at the University of Nevada also challenged the COGCC investigator’s interpretation. “I agree with your argument that the chlorination of your well is very likely not associated with the turbidity,” Miller said. “The COGCC argument does not make much sense, particularly given the time frame between the chlorination and the observed turbidity.”

The Dahls' pump failed in October after weeks of pumping turbid water, which the COGCC investigator also did not address his report. A well technician – Fred Baros of WaterWorks Plus LLC, based in Las Animas County – removed the well pump in January 2011, at which time he said he found no evidence of biofouling or deposits left from bacterial colonies. The COGCC investigators and two Norwest employees were present for the removal. The pump's rotor shaft was marked with striations, indicating time spent running with abrasive material passing through. The motor spun easily when it was tested, showing that the pump had not failed for electrical reasons. Baros concluded that the pump seized due to high levels of particulates in the water. Baros performed a drawdown test the following day, January 19, which showed the well producing 2.25 gpm, up slightly from 2 gpm estimated by the well driller eight years earlier. Turbidity remained high in January, according to Baros. At this point, more than 5,000 gallons had been purged from the well since July 1. Baros interpreted this as evidence that the turbidity "stems from the aquifer in which the water well draws from as opposed to what one typically experiences following standard chlorination procedures."

Tracy Dahl represented himself at the COGCC hearing on February 22, 2011, in part because he and his wife had already spent $10,000 trying to rehabilitate their well and replace their pump, according to testimony. Because Dahl represented himself, he relied on statements from his expert witnesses instead of presenting them in person. Pioneer's attorneys challenged Dahl's use of the witnesses because they were not there in person to be cross-examined, in addition to challenging their credentials. Dahl was permitted to present his case to the COGCC, but his expert testimony was not considered and he was not permitted to discuss the previous drilling impacts on North Fork Ranch. Pioneer's attorneys challenged the background information and it was excluded from the hearing on legal grounds.

COGCC Order

On February 22, 2011, the COGCC panel of commissioners considered Dahl's case as presented by Dahl, the COGCC investigator, Pioneer's attorneys, and company drilling experts presented by Pioneer. The commission denied Dahl's request for an Order Finding Violation. "Based on a preponderance of evidence, the hydraulic fracture treatment of the Alibi 23-2 well did not cause chemical, gaseous, physical, or other adverse impacts to the Dahl domestic water supply well," the Order read when it was published a few weeks later (COGCC, 2011d). Two of the COGCC commissioners expressed sympathy toward Dahl, but all said they could find no evidence that Pioneer's fracturing of the Alibi 23-2 had been the cause of Dahl's ongoing turbidity problems.

As one commissioner put it: "There is no question that there is something going on with your water well. The big question here is did you prove to us that your water well was impacted by fracturing?" Dahl had not proven a causal connection to the commissioners' satisfaction, they said. One commissioner expressed "some residual doubt" about the circumstances, but added that "it was too far a stretch to find Pioneer as the cause." Most of the commissioners cited lack of a plausible mechanism for the fracturing to reach Dahl's well at a distance of 390 m (1,279 ft) away from the Alibi 23-2, particularly with no unexplained pressure losses from Pioneer. One commissioner seemed to be considering Dahl's hypothesis of damage done to the aquifer, but said that Dahl "did not adequately develop the shock wave theory."

DISCUSSION

The Question of Causality

Cause-and-effect relationships have long employed scientists, and also confounded them. The philosophical treatment of causality extends over millennia – in Western philosophy, it goes back at least to Aristotle and forward to the present, where it remains a staple in contemporary scholarship. Determining causality in a system as concealed as an aquifer is no small task, as demonstrated on the regional scale in the Northern San Juan Basin. The uncertainties and complexities involved in understanding hydrogeologic dynamics are no simpler at the local scale. To the detriment of those who rely on domestic wells, cause-and-effect relationships can be decoupled in groundwater systems on the geographic scale of 1,190 ft – or even on the scale of 100 ft, as conceded by Watts (2006). We know this to be true not just from the uncertainties involved in a case like the Dahls, but also from a history of hazardous waste contamination cases that stretch to the pre-Superfund era (Eaton, 2010).

Understanding causality is a central concern of both science and law, as is the idea of burden of proof. In U.S. law, the burden of proof typically goes to the accuser, as it did in Dahl's case, following legal presumptions of innocence until proven otherwise. In science, the burden of proof similarly goes to the scientist attempting to falsify or expand existing theory. The standard by which evidence is judged, also known as the degree of certitude required in considering evidence, is another critical aspect of determining causal relationships. In the Dahl case, the COGCC made its decision "based on a preponderance of evidence." Legally, this standard means "the balance of probabilities" or that a proposition is "more likely to be true than not" (Hill, 2011). It is met, therefore, when the likelihood of something being true is greater than 50 percent. In a case like the Dahl's, then, the COGCC concluded that the likelihood of the Alibi 23-2 fracturing treatment impacting the Dahl well must have been 49 percent or less – or, in other words, that it was at least 51 percent likely something else caused the prolonged turbidity problems in Dahl's well, such as Dahl's well chlorination.

When a cause-and-effect relationship in a concealed system like an aquifer is decided based on "the balance of probabilities" – and when somebody's sole water source hangs on that balance of probabilities – the dynamics of the investigative and analytical process gain critical weight. What counts as a smoking gun in a hydraulic fracturing investigation, for example, and who gets to decide? And how does this figure into what we know about factual disputes and the obstacles that accompany scientifically complex environmental conflicts? In conducting the investigation of the Dahl well, the COGCC investigator made assumptions about water chemistry that served to structure the remainder of Dahl case. His assumptions did not stray from common hydrogeologic knowledge, but what if they excluded something important?

A Critical Evaluation of the Dahl Case

The Dahl case could easily lay claim to a number of problems in Adler et al.'s tally of "Rocks on the Road to Agreement" in scientifically complex environmental conflicts (2007). The Dahl conflict suffered from "Restricted Data" in the form of undisclosed fracturing fluid chemistry, for example. But data restrictions extend beyond fracturing fluid disclosures. The most critical information in a fracturing endeavor has more to do with the three-dimensional structure of the subsurface – the presence of natural aquifer heterogeneities, for example, which have not been defined even in a probabilistic fashion on the Raton (Watts, 2007). If Pioneer had developed a particularly nuanced understanding of the complex lithology, faults, fractures, intrusions, or pressure regimes known to exist in the Raton Basin, using advanced industry methods such as microseismic investigations combined with fracture modeling at a scale relevant to the Alibi 23-2 fracturing, that information is not publicly available or available to Dahl. The case also suffers from a situation of "Theory Unsupported by Research," on Adler et al.'s list, insofar as Dahl posited a "shock wave theory" of structural damage to the Poison Canyon aquifer that he could not verify empirically. In a related note, "Unclear Significance" could be at play if water chemistry alone were deemed insufficient to decide the case; in that situation, the significance of water chemistry data would be considered unclear in respect to overall conclusions.

Adler et al.'s overlapping categories could be collapsed in this case under the larger category of "Inconclusive Data." The authors defined the problem of "Inconclusive Data" as a situation where the scientific or technical information relied on by disputants "is spotty, does not show strong cause-and-effect relationships and does not invite an obvious decision." Certainly, the COGCC investigator on the Dahl case would not call the data he presented inconclusive, nor would most of the COGCC commissioners that ruled against Dahl's request for an Order Finding Violation. To those parties in this environmental conflict, the data sufficiently disproved a cause-and-effect relationship between the Alibi 23-2's fracturing and Dahl's domestic well turbidity. I, on the other hand, share the "residual doubt" expressed by the minority on the COGCC panel, and will parse that doubt in a critical reading of the Dahl incident as a case, not of disproven causality, but of "Inconclusive Data" that did not show a strong cause-and-effect relationship, but was limited in its ability to do so. As one commissioner said on February 22, 2011: "I can see no direct connection [between the Dahl turbidity and the fracturing of the Alibi 23-2]…. But there is that wiggle room there, because I don't know for sure. It would be nice if someday in the future there is a direct connection made and proven. I hope scientists are looking at that." We are.

Considering Additional Pathways

The water chemistry data gathered and presented by the COGCC investigator is extremely valuable for establishing or eliminating one cause-effect pathway – that of the Alibi 23-2 fracturing fluids, mobilized by stimulation pressures, traversing the 1,279-ft distance to the bottom of the Dahl wellbore via induced or natural fractures. But it is of no value in establishing or eliminating other potential pathways. Water chemistry data, therefore, is a critical component of an investigation such as the Dahl case, but it is limited by the assumption that the direct contact pathway is the only pathway possible. The cause-effect relationship posited by Dahl and Dahl's experts – that hydraulic fracturing caused a physical shock to the structural integrity of the Poison Canyon/Raton Formation aquifer system, which manifested in Dahl's well – is not considered under this assumption. When limitations such as this one are made explicit, the data as presented by COGCC begin to take on a more "inconclusive" character.

Hydraulic fracturing in CBM formations can cause turbidity in nearby domestic wells, as has been learned from decades of experience in the more mature CBM fields of the Northern San Juan Basin (NSJB). These turbidity events are described by the San Juan Public Lands Center (SJPLC) in their 2006 Environmental Impact Statement on reduced CBM well spacing in the NSJB as follows:

> Some landowners have reported that CBM development has affected the water supply during hydrofracturing or cavitation. It is likely that the local vibrations induced by these activities may loosen or suspend some of the fine-grained materials around the shallow domestic well bores, causing discoloration of the water from these wells. (p. 3-94)

The discoloration and turbidity of water in domestic wells that have, more or less, been "shaken" by nearby hydraulic fracturing tend to be temporary in the NSJB, according to the SJPLC (2006). Landowners report that discoloration or turbidity "clears up several days after the work at the CBM well is completed," the EIS states. There are major differences between the turbidity cases described in the NSJB and those that might occur in the Raton, however. The vertical separation between water and gas well completion zones is wider in the NSJB, and lithology is different between the two basins. In the NSJB, shale layers confine the CBM-bearing Fruitland Formation from above and below basinward from the Fruitland Outcrop and domestic wells are typically completed in overlying hydrogeologic units, such as the Animas Formation or alluvial aquifers (Topper et al., 2003). In the Raton Basin, domestic water wells and CBM wells may be completed in the same hydrogeologic unit, such as the Raton Formation, or in hydrogeologic units with strong hydraulic connections, such as the interbedded Raton Formation and Poison Canyon Formation (Watts, 2007). Similarly, in the NSJB, aquifer heterogeneities due to faulting, folding, and igneous intrusions are not as common as they are in the more complex Raton. As such, turbidity problems lasting beyond "several days" would seem more likely in the more interconnected and incongruous hydrogeologic scenario represented by the Raton Basin.

By definition, hydraulic fracturing directs focused pressure designed to overcome the in situ stresses in the targeted geologic unit. Applying pressure in the subsurface can sometimes have unintended consequences. In the Molokai case in 2006 – which was not a hydraulic fracturing case, but which incorporated the use of high-pressure air and water to free a drill bit – hydrogeologists from Norwest hypothesized that Pioneer's drillers "may have created a pressure wave or opened existing factures" in the Poison Canyon aquifer that may have disturbed a rare overpressurized zone in the Poison Canyon or Raton Formation (COGCC, 2006). Because the affected domestic water wells were down-gradient from the Molokai, and because their water chemistry changed in the expected ways (eg., increase in methane, dissolved metals, etc.), the hydrogeologists hypothesized that the overpressurized zone must have released gas and water that flowed into the domestic wells respective zones of capture. Dahl's well is up-gradient from the Alibi 23-2, but is it possible that the pressure surge from the fracturing job reached a similarly overpressured zone, or displaced water in the Raton-Poison Canyon aquifer via preferential flowpaths, or produced some other unexpected result?

No empirical link was made between the physical disturbances of the Alibi 23-3 fracturing and the turbidity in the Dahl well on or after June 30, 2011. But given the investigative focus on chemical fate and transport, nobody really investigated one either, which begs a more practical set of questions. How would one measure the structural integrity of the Poison Canyon aquifer in the region around the Dahl and Alibi 23-2 wells? Moreover, how would one measure physical changes to that structural integrity at the relevant geographic scale? These are the questions that I think should have been included in the Dahl investigation, and in the arranging of the assumptions that drove the Dahl investigation. Unfortunately, they are not as simple to answer as they might sound.

A hydrogeologist can at least begin to address questions about the structural integrity of an aquifer (and potential changes to it) by measuring water levels. If wellbores provide us windows into an aquifer, then water levels provide us with light enough to start seeing profiles through them. The Dahls' static water had ranged from 180-220 ft in the two years prior to June 30, 2010. That water level would likely have changed had the fracturing of the

Alibi 23-2 opened one of the Raton's underpressured areas, connected natural fractures that had not been connected before, created new fractures that approached the Dahl well, or otherwise rearranged preferential flowpaths within the Poison Canyon aquifer, to name a few potential physical changes to the aquifer's structural integrity. The COGCC investigator in Dahl's case did not measure depth to water in the Dahl well until two weeks after the turbidity event, however – time enough for water levels to perhaps recover, though that can never be known for sure.

Other, more advanced, measurements could also be made in a case like Dahl's, though most of them are only apparent in hindsight. To measure the propagation of a physical "shock" to the region in which Dahl's well is completed, one could set up an advanced microseismic array, or a simpler tiltmeter array, at the domestic well site and watch for changes during the Alibi 23-2 fracturing. Microseismic monitors and tiltmeters can be used to plot the positions of fractures during fracturing (Cipolla & Wright, 2000; Warpinski et al., 1998; Warpinski et al., 2008), though in the field the effort is made in only about three percent of fracturing jobs, primarily when a new area is being developed (Zoback et al., 2010). This strategy would only be effective before the fact, or during it, however. Similarly, one might perform a slug test on Dahl's well – quickly removing or adding water from the well and monitoring its response to determine near-aquifer properties such as transmissivity and storativity – but the test would only be effective if it could be conducted both before and after June 30, 2010. A more advanced pumping test could potentially be devised and monitored between the Dahl water well and the Alibi 23-2 in the after-impact environment. A spin on this would be to insert a tracer in the Dahl well and wait to see if it appears in the Alibi 23-2. Such an aquifer test would be interesting to perform, but could be inconclusive now, a year-and-a-half since the original incident, due to methane gas desorption from Raton coals, which changes the permeability of the formation.

Strategizing experimental possibilities makes apparent the basic problem with understanding potential hydraulic fracturing impacts to groundwater systems: there has been no independent, first principles research conducted on the topic and the many scientific questions it raises. First principles research is just as it sounds – research that starts from the very beginning. In the field, this would mean actually drilling natural gas wells in several different ways, hydraulically fracturing them in several different ways, and watching the changes at monitoring wells drilled nearby (as many of them as possible). It is the kind of fact-finding that the hydraulic fracturing debate desperately needs: research that avoids the confounding variables and interpretations that plague less direct studies. First principles research is the kind of work that elucidates underlying patterns that might be transferrable across locations, transforming existing theories and pushing the scientific envelope toward new paradigms and understanding.

First principles research would also make the perfect experimental platform for assessing the consequences of drilling mistakes, such as incidences of poor well casing. In the end, first principles research could provide insight on how to drill for natural gas safely, in a way that maximizes the economic upside of energy development while minimizing potential collateral damage to the environment or domestic well owners. Trouble is, that kind of first principles research would be incredibly expensive. It would also take profitable natural gas areas out of production. Taking these issues into account, Department of Energy scientists from Lawrence Livermore National Laboratory are proposing to run fracturing experiments in gas fields with dwindling resources that could stand the meddling (Friedmann, 2011). While this would not be true first principles research as defined above, because the researchers would build their experiment in an already disturbed environment, it could provide a big step in the right direction.

Meantime, the USGS and CWCB will be working toward a better understanding of the spatial distribution of heterogeneities and anisotropy in the hydrogeologic units of concern in the Raton Basin (Watts, 2007). The gains in our comprehension of the Raton's groundwater dynamics may come too late for Dahl's case, and may be based on probabilistic approaches irrelevant to the local well-to-well scale, but they will at least move in the direction of clarity. Until the basic physical characteristics of the subsurface between a CBM well and nearby domestic water wells can be determined quickly and cost-effectively, the great faith we put in confining layers and vertical separation between wells will always be in question.

Improving the Character of Domestic Well Conflicts

The Dahl case demonstrated for a second time that it is possible for opposing parties in a scientifically complex environmental conflict over a groundwater system to reach disparate conclusions about cause-and-effect relationships based on the same dataset. Parties shared the same data, for the most part, yet assigned different weight to available information and arrived at significantly different impressions. We saw this phenomena manifest in the NSJB because stakeholders entertained opposing conceptual models of regional groundwater flow. It reappears in the Dahl case because stakeholders approached the investigation and analysis with different starting assumptions about potential pathways for effects.

Simplified, these differing assumptions could be described in similar terms as the dueling conceptual models of the NSJB: that is, they also hinge on questions of hydraulic connectivity. In the NSJB case, some stakeholders backed the Hydraulically Connected Basin model, while others were behind the Compartmentalized Basin Model. In the Dahl case, the dividing line can also be drawn over hydraulic connectivity, only in a different way. First, the issue of hydraulic connectivity comes up in the Dahl case at the local, well-to-well scale, rather than at the regional scale, as in the NSJB. Perhaps more importantly, the issue of hydraulic connectivity matters in the Dahl case in two ways: 1) in the question of whether the Dahl well and Alibi 23-2 could be hydraulically connected, which is a similar question those raised about hydraulic connectivity in the NSJB, but also 2) in the question of whether hydraulic connectivity is the *only* potential pathway or mechanism for the turbidity in Dahl's well. Addressing the latter question, the COGCC investigator and commissioners did not find evidence for connectivity between the Alibi 23-2 and the Dahl well because they considered only hydraulic connectivity in their analysis. Dahl, on the other hand, gave credence to the potential for a physical connection between the two wells in the subsurface, and reached different conclusions.

Neutral fact-finders tread into this contested territory at their own peril. But again I will propose that Colorado's independent academic researchers and academic institutions can, at least in small measure, work to improve the dynamics of conflicts over potential impacts to groundwater quality from natural gas operations. Researchers can do so via carefully planned fact-finding efforts, or by providing guidance on scientific protocols for such endeavors. While aquifers are easy to disagree about, as we have seen, resolving factual disputes about groundwater systems is considerably more achievable when important baseline data has been collected and when technical and scientific resources are more evenly distributed between parties involved. Academic researchers can play a positive role on both these counts.

On June 30, 2010, when Dahl's well went suddenly turbid, he had thorough and consistently-collected groundwater quality data back to 2004 that he could use as a starting point in his (and others') efforts to understand what had happened to his water. Dahl ultimately did not agree with the COGCC's conclusions that his well had been damaged by a longstanding disinfection practice rather than hydraulic fracturing operations nearby, and I have discussed related knowledge gaps above, but that is not the primary concern of this portion of the discussion. The point here is that Dahl might not have gotten as far as he did in the COGCC hearing process, might not have been able to solicit the expert opinions he received from PhD hydrologists, and might not have had much of a case to make at all without baseline data. It is an extreme minority of domestic well owners that collect semi-annual water quality data, and for as many parameters as Dahl covered. For the majority of well owners who have not established the physical and chemical baseline of their groundwater supply, cause-and-effect relationships are even more difficult – sometimes impossible – to determine.

Concerned citizens of Colorado's "gas patches" are beginning to grasp the importance of gathering baseline groundwater quality data, however, as indicated by the number of phone calls the University of Colorado-Boulder's Office for University Outreach has begun to receive on the matter (Outreach staff, Personal Communication, 2011). Natural gas operators, the state oil and gas lobby, and the COGCC also understand the importance of establishing a groundwater quality baseline in domestic wells and monitoring it for changes. As I write, the Colorado Oil and Gas Association, backed by Governor John Hickenlooper, is in the final stages of developing a voluntary statewide monitoring program, for which they say they have achieved 90 percent industry participation (COGCC, 2011c).

The COGA monitoring program is a tremendous step in the direction of groundwater protection and socially responsible energy extraction. Going from the details that have been released about the monitoring program thus far, however, it will probably not be a big enough step. Among other things, the COGA requirements do not include measuring the static groundwater level in domestic wells during the sampling events conducted before and after a new natural gas well is drilled, a critical oversight in Dahl's case as well. The plan, as currently described, also does not require operators to sample every domestic well in the vicinity of a natural gas well, but two within 0.8 km (0.5 mi). For at least these reasons, and potentially more, it is important to educate domestic well owners on 1) the importance of gathering groundwater quality data, and 2) on the most thorough way(s) to go about it.

The monitoring guide that follows here is an effort to do just that. It is written for concerned domestic well owners who live in close proximity to natural gas operations or in areas that soon will be. Some citizens may use the guide to organize their own long-term groundwater-monitoring program. Others may simply learn from it and go into negotiations with operators on a stronger scientific footing, capable of asking for changes or improvements to operators' sampling programs. In the latter case, domestic well owners will be in a position to design a joint fact-finding program with willing operators, which could serve to establish important social baselines in addition to scientific ones, based on the positive dynamics that can accompany joint fact-finding efforts (Schultz, 2004). If operators are not willing to negotiate their baseline sampling designs, domestic well owners may use the guide to plan supplementary testing to cover the interstices between operator visits.

Under any of these circumstances, the groundwater monitoring guide will hopefully serve to improve the dynamics of the potential factual disputes of the future. The Office for University Outreach is funding the development of the guide under the auspices of the new Colorado Water and Energy Research Center (CWERC). After extensive peer review and beta testing, the monitoring guide will be published online at CWERC's forthcoming Website. (Guide is attached as Appendix C.)

CHAPTER 4

TOWARD ENERGY-WATER NEXUS CONFLICT TRANSFORMATION

CONCLUSIONS

Commonalities Between the Case Studies

The energy-water nexus case studies presented thus far are merely two of an inestimable number of situations in which Westerners attempt to understand and navigate trade-offs between scarce energy and water resources. In essence, these accounts grapple with *why* we fight over groundwater systems in areas of natural gas development – and, as importantly, *how* we do it – in an effort to better comprehend the dynamics of these conflicts and what stakeholders want from of them. The energy-water nexus implies conflict in its very definition – as a crossroads where energy and water resources intersect, where the extraction or use of one often calls for the use of the other. As Tracy Dahl puts it, when it comes to coalbed methane extraction, we are "walking the tightrope of development of one of Colorado's natural resources and the preservation of others." As demand increases for energy and water resources in a rapidly growing West, the intersection between them is likely to become one of increasing collisions, rather than orderly traffic flow. It behooves us to tune into to the crossroads: perhaps with a better understanding of these types of environmental conflicts we can grow more adept in our individual participation in them and collective handling of them.

The regional-scale example of conflict over groundwater withdrawals in the Northern San Juan Basin (NSJB) and the local-scale example of conflict over allegations of groundwater contamination by hydraulic fracturing in the Raton Basin share much in common. Structural geology, surface hydrology, and hydrogeologic dynamics are unique to each basin, of course, but the larger questions about hydraulic connectivity and groundwater protection apply across cases. It is not known, for example, what high-volume groundwater withdrawals from the Raton and Vermejo Formations in the Raton Basin will mean for domestic wells, springs, and streams there. By the same token, unknowns exist in the NSJB regarding potential impacts to domestic water wells from reservoir stimulation techniques used on the Fruitland Formation, such as hydraulic fracturing, cavitation, and water enhancement. The basins engage the same set of scientific questions, and they share broader themes as well.

Both the Raton and the NSJB present us with distributional conflicts tied to two important resources – coalbed methane and groundwater – that are high in both their stakes and in uncertainty regarding the impacts of their extraction. When stakes are high, willingness to lose or to compromise is correspondingly low – whether that be by BP in in the *Vance v. Wolfe* case, the ranchers in the State Engineer's tributary-nontributary rulemaking, the Dahls in the case of their domestic well's deterioration, or the COGCC investigator in his findings on the hydraulic fracturing of the Alibi 23-2. When uncertainty is high, disagreement over the facts surrounding the conflict often escalates with it, as we have seen in both the NSJB and the Raton. The natural traits of aquifers and gas reservoirs only exacerbate this phenomenon. The concealed and changing nature of groundwater systems makes scientific uncertainty somewhat irreducible, and makes causal relationships difficult to determine at all scales. The manifestation of effects through systems invisible to the eye and over long timeframes serves to decouple cause and effect in frustrating ways, confounded further by the vagaries of groundwater modeling and the expense of drilling "windows" into the system that provide only a partial view for empirical work. It is no surprise, under these limited circumstances, that we tend to fight about hydrogeologic systems at the points where we can see them: outcrops and wellbores, at the regional and local scales, respectively.

The NSJB and Raton Basin case studies are also both plagued by circumstances of dueling conceptual models, which make it possible (nay, likely) for stakeholders with different interests in, and experiences with, groundwater and natural gas resources to arrive at different interpretations of the available data. The primary point of contention between these conceptual models is the question of hydraulic connectivity. Is the confined aquifer of the Fruitland Formation hydraulically connected to shallow and surficial hydrologic systems where it is unconfined at the Fruitland Outcrop, and will CBM-related groundwater withdrawals therefore change hydraulic relationships there, intercepting water that would otherwise discharge to streams, source springs, and supply domestic water wells? Are the Alibi 23-2 and the Dahl domestic water well hydraulically connected enough that hydraulic fracturing could impact the region of the Poison Canyon aquifer from which the Dahl well draws water a thousand feet away, either by contamination or structural damage? Hydraulic connectivity is the central question and the most imposing unknown in both the regional and local scale examples presented by this thesis.

Hydraulic connectivity also happens to be a critical question in CBM basins all across the West. In its 2010 report on management of produced groundwater in Western CBM basins, the National Academy of Science (NAS) highlighted, as a major knowledge gap, determining the degree of connectivity among water-bearing coalbeds, other groundwater aquifers, and surface water (NAS, 2010, p. 50). In the words of the NAS panel charged with the assessment:

> Quantitative understanding of the degree and extent of connectivity between surface water and shallow groundwater systems and methane-producing coalbeds is important when evaluating the potential effects of CBM extraction… [Effective management] is contingent on establishing to

what degree surface water and groundwater resources may be depleted, degraded, supplemented, or enhanced and over what time periods.

A few helpful conclusions about hydraulic connectivity can be made for the NSJB and the Raton Basin based on the previous analyses. In the NSJB case, the isotopic and geochemical results suggest hydraulic connectivity between rivers, springs, and piezometers at or near the Fruitland Outcrop. However, the NSJB results also suggest that groundwater-surface water interactions vary between the two river drainages investigated, with the Piedra River exhibiting gaining-stretch characteristics and the Florida River possibly exhibiting losing-stretch characteristics. In the Raton Basin case, the presence of hydraulic connectivity between the Alibi 23-2 and the Dahl well is less clear. That uncertainty raises the importance of considering other pathways or mechanisms for well-to-well impacts. Taken together, the cases suggest the importance of more closely considering geographic scale as it relates to hydraulic connectivity.

In particular, the cases raise the possibility of a distance threshold for potential impacts to groundwater from CBM development. In the NSJB, the springs and piezometers that demonstrated a groundwater signal and contact with the Fruitland Formation were within 2 km (1.25 mi) of the Outcrop. That is within the CBM drilling buffer instituted in 2000 by the SJPLC at 1.5 mi down-gradient from the Fruitland Outcrop – in hindsight, a solid groundwater management decision given our isotopic and geochemical results. In the Raton Basin case, the Alibi 23-2 was within 366 m (1,200 ft) of the Dahl well. That distance is inside the distance of 1,000 m (3,281 ft) recently put forward by researchers from Duke University as a threshold for increased probability of methane contamination by shale gas extraction (Osborn et al., 2011). These scientific investigations all put connectivity within 1-2 km range of the feature in question, whether it be a formation outcrop or a natural gas well. Future research should focus this threshold.

Why Do Conceptual Models Differ and Why Does It Matter?

How can stakeholders in energy-water nexus conflicts harbor such vastly different ideas of the inner dynamics of groundwater systems? How can parties hold such divergent estimations of hydraulic connectivity, for example, or put such disparate degrees of faith in geologic confining layers? The challenge of illuminating answers to these questions through scientific study certainly sustains these competing conceptual models, but a quick look at another major environmental conflict of our day suggests that there is more at play than knowledge and data gaps. Climate scientist Mike Hulme, in his 2009 book entitled *Why We Disagree About Climate Change*, goes far in explaining why discord reigns when societies face questions as socially weighty, scientifically complex, and politically charged as those surrounding climate change. In Hulme's effort to re-situate the idea of climate change "as the subject of a more creative and less pejorative discourse," he attributes the many ways we disagree about climate change to our constantly evolving idea of climate change; to differences in our values; to diversity in our beliefs about ourselves, the universe, and our place in it; to the different risks we worry about; and to our different approaches to policy choices, among other factors (Hulme, 2009).

According to Hulme, it is easy to disagree about climate change because the *concept* of climate change is so malleable. Climate change means too many different things to too many different people. When it comes to the groundwater conflicts that surround natural gas development, perhaps it is easy to disagree because the *context* is so malleable. Concealed and marginally understood groundwater systems may serve as a void that parties, in turn, fill with their own ideas, their own assumptions, and their own aversions or assurances. For example, a collective fear of the unseen might account for the disproportionate focus on subsurface contamination within the national debate over natural gas development. Underground pollution is the dominant frame for anti-drilling rhetoric despite the grim reality that considerable damage is done to the environment above ground via spills and other mishaps that directly impact surface water resources and other aspects of the surface environment. In Colorado, for example, oil and gas operators reported 493 surface spills to state regulators in 2010 (COGCC, 2011a). While subsurface consequences of drilling should not be marginalized, it is worth noting that we do seem to fixate on the subsurface – perhaps because it is unknown, and perhaps because the chemicals being introduced into it via hydraulic fracturing are unknown, too.

In asking how it is that people can hold such different ideas of groundwater dynamics, one must look no further than the modern practice of water dowsing in the West for a very different take on conceptual model diversity. In discussing the conceptual models of groundwater systems held by three active Colorado-based water dowsers in April of 2010 as part of interviews conducted[16] for a qualitative methods course in the Geography Department, I discovered that mental representations of groundwater systems are as varied as the people that hold them. A longtime Denver-based dowser described to me a hydrogeologic cycle in which ocean water infiltrates to the earth's superheated core, reemerging as steam via tree-like systems of cracks that emanate from the earth's center all the way to shallow ground. Another dowser, based in Trinidad, described to me a more scientifically sound concept of a groundwater system made up of sandstone bedrock that allows for water movement via natural fractures that serve as preferential conduits. The third dowser, also in Denver, did not even envision groundwater during his dowsing practice and could not tell me how a Colorado groundwater

[16] GEOG 5722, Qualitative/Ethnographic Methods, Spring 2011. Interviews conducted under course-wide human subjects approval.

system might operate. The dowsers' mental pictures of groundwater dynamics differed in many different ways, based in large part on the dowsers' exposure to scientific descriptions, but also on other factors related to their personal beliefs and degree of trust in classical hydrogeology. As Tidwell and van den Brink put it in their work on collaborative groundwater modeling (2008): "The poorly informed may come with visions of underground rivers and lakes, as well as ideas of 'infinite ground water supplies.' While the better informed may hold more physically based mental models, their conceptualizations are often biased toward a particular interest" (p. 175). The central challenge, then, of collaborative groundwater modeling endeavors as Tidwell and van den Brink describe them, is guiding participants toward a shared view of a groundwater system that is also scientifically defensible.

The same could be said of the NSJB and Raton Basin examples. It is worth wondering if the realities of the regional groundwater dynamics of the Fruitland Formation and the local groundwater dynamics near the Alibi 23-2 and Dahl wells are not somewhere in between the dueling conceptual models proposed at each scale. A merging of the Hydraulically Connected Basin and Compartmentalized Basin conceptual models did begin to occur in the NSJB case, when Papadopulos (2006) and Norwest (2009) devised regional groundwater models premised on an idea of limited hydraulic communication that proposed connectivity in some places and not others. But by the time the State Engineer's tributary/nontributary rulemaking concluded in late 2009, the newly combined ideas were being challenged in Colorado courts by water rights holders who mistrusted the modeling and felt like they had been left out of the rulemaking deliberations (Klahn, 2010).

Establishing a shared vision of groundwater problems, or at least considering potential common ground between conceptual models, is critical for effective resource management. In her Nobel Prize-winning work on common pool resources, Elinor Ostrom addressed the topic of conceptual models while considering institutional responses to groundwater problems in California (Ostrom, 1990). In her studies of groundwater decline and saltwater intrusion, Ostrom came to the conclusion that sharing a single, authoritative "image of the problem faced" was critical for successful intervention. In Ostrom's words: "Individuals who do not have similar images of the problems they face, who do not work out mechanisms to disaggregate complex problems into subparts, and who do not recognize the legitimacy of diverse interests are unlikely to solve their problems even when the institutional means to do so are available to them" (p.149). In her extensive research on common pool resources, Ostrom has built a strong case for the importance of establishing the external boundaries and internal characteristics of a resource system as a prerequisite for effective management. For a fishery or a grazing range, this might come as a byproduct of careful observation and folk knowledge. "For a groundwater basin, on the other hand, the discovery of the internal structure may require a major investment in research by geologists and engineers," she adds (p. 33).

From Hulme's work, however, we learn that agreement on the internal structure of a groundwater system likely depends on a lot more than a major research investment by geologists and engineers. In his effort to re-situate climate change in a "more creative" discourse, the British climatologist confronts us with the reality that scientifically complex environmental disputes – even those framed as factual disputes, such as the cases presented here – are often "rooted in more fundamental differences between the protagonists." Science thrives on disagreement. Indeed, it progresses by disagreement. But, in Hulme's words, disagreements presented as disputes about scientific evidence may only be about science at the surface. At their core, factual disputes often have more to do with "differences about epistemology, about values, or about the role of science in policy making" (p. xxxv).

How Do We Arrive at Shared Visions of Groundwater Systems?

If establishing a shared vision of groundwater systems is critical for addressing groundwater problems, as per Ostrom, and if factual disputes over scientific evidence are not actually the root cause of many environmental conflicts, as per Hulme, then how do we arrive at common understandings of the groundwater systems in examples like the NSJB and the Raton Basin? We can start by acknowledging the complexities inherent in these environmental conflicts, the many factors that contribute to them, as well as some of the limitations of scientific knowledge in their resolution. In some cases, disputing the facts of an environmental conflict may merely serve as a proxy for (or a distraction from) what is really at issue: competition over interests; differing goals, values, ways of life; or unequal control, power, or authority to distribute or enjoy resources, according to Adler et al. (2007).

No doubt there is more to the environmental conflicts in the NSJB and Raton Basin than disagreements over data. Residents rely on groundwater and surface water resources to sustain their health and ways of life, while natural gas companies have made major outlays on drilling operations in both basins to meet market demand for fossil fuels, to name two cursory examples. Without performing detailed qualitative research on the additional sources of conflict that likely influence the factual disputes underway in the NSJB and the Raton, it is beyond the scope of this analysis to suggest what they might be exactly and how they might be shaping the conflicts. I will, for now, simply assume instead that unidentified value- and interest-based conflict sources are at play in these contexts and discuss them in the abstract. In scientifically intensive conflicts with value- and interest-based components, it is important to be realistic about the limitations of scientific knowledge in transforming or resolving the issues at stake. Environmental conflict mediators work to acknowledge the following points in these situations (Adler et al., 2007; Moestert, 1998; Schultz, 2004):

- Science is not the only way of knowing: traditional, cultural, and remembered knowledge all have a place at the negotiating table;
- Models are rarely fully predictive; they are best thought of as illustrative, and their limitations and uncertainties should be honestly communicated;
- All science is based on assumptions that are affected by culture, perspective, and prior experience. Reflexivity is important and scientists must be very explicit about the assumptions, approaches, and subjectivities that effect their work;
- Differences in assumptions are rarely the product of malice or ignorance. More often, they are the result of legitimate differences in professional experience, scientific judgment, and interests.

Noting these limitations is not to suggest that scientific contributions to factual disputes are irrelevant or useless. When real scientific questions exist in an environmental conflict, unbiased and carefully designed scientific investigations are of critical importance, as suggested in the previous chapters. Rather, noting the limitations of scientific studies is to suggest that fact-finding efforts can be more effectively orchestrated by keeping those limitations in mind. At decision time, scientific information cannot finesse value choices for the parties involved in a conflict. But if scientific information is collected and analyzed in a way that all parties can get behind, then it can at least inform the value choices that need to be made. At the end of a successful fact-finding effort one can find some hard, established facts, but also "a determination of how much agreement has been achieved, where facts remain in dispute, and where there are irreducible unknowns and uncertainties" (Schultz, 2004). Establishing what we do not know, and what we perhaps cannot know for sure, might be as powerful in conceptual model evaluation and negotiation as getting concrete answers.

Returning to the NSJB and Raton Basin, one might ask what else is gained from neutral or joint fact-finding efforts, besides facts, and whether these potential gains might get stakeholders any closer to a shared conceptual model of groundwater dynamics in each case? For starters, efforts to determine relevant facts can serve as a new paradigm for conflicting parties to work together, which may connect people who would not usually be eager for close contact. Our neutral fact-finding efforts in the NSJB did not necessarily accomplish this because they were not originally designed with that goal in mind, but sampling efforts did allow the study team to go between concerned domestic well and spring owners[17], the San Juan Public Lands Center (SJPLC), and, to some degree, the CBM industry. The joint fact-finding efforts proposed in this thesis for future cases like the Dahl well in the Raton Basin via the citizen groundwater monitoring guide could do a better job of uniting parties in shared investigative efforts. Boosting domestic well owners' scientific understanding and savvy regarding baseline data can aid in bringing citizens and natural gas operators together to negotiate sampling designs and protocols tied to surface use agreements or COGA's future statewide sampling efforts.

An important goal behind fact-finding efforts is an improved relationship between conflicting parties – one that transforms conflict dynamics by lowering the costs of conflict and improving the chance of reaching consensus (Schultz, 2004b). Ironically enough, this may not even require agreement over technical facts. What it does require, however, is agreement over the *process* of fact-finding. Conflict mediation puts strong emphasis on process and relationship management, and while the idea may be antithetical to traditional scientific thinking, which lofts the scientific

[17] I also spent a considerable amount of time interpreting and presenting each domestic well and spring owner's analytical results to them in a clear and coherent way, so that they could understand our findings.

method as both neutral and absolute, the process of implementing the scientific method in the real world is critical to the legitimacy of science in environmental conflict. The routes that scientific information takes into environmental conflict are as important as the information itself – particularly in instances when stakes and uncertainty are both high. The EPA recognized this in the design the hydraulic fracturing study it currently has underway. Before launching its investigation, the agency created opportunities for the scientific and lay public to contribute insight regarding research questions and the best ways to approach them.

In thinking about the groundwater conflicts of the NSJB and the Raton Basin, one might imagine long-term studies and monitoring programs designed around the questions that matter to all stakeholders, and which make alternative assumptions and approaches clear, provide some leveling of the technical playing field, allow for as much equal access to critical information as possible, and otherwise bring transparency to previously closed investigations or modeling projects. In a perfect world (and I realize I may already have been describing one), such a process needs also to provide a setting for all parties to voice their concerns regarding risks. People generally feel more inclined to work toward the transformation or resolution of conflicts when they feel their concerns have been heard or acknowledged (Schultz, 2004b). In the NSJB, such a project might take the form of long-term monitoring of all 40 domestic wells and the dozen or more springs near the Fruitland Outcrop that SJPLC has identified as being at risk from CBM-related groundwater withdrawals. The monitoring could be a joint effort between state and federal regulators, CBM operators, and domestic well and spring owners, conducted by an independent scientific entity with mutually agreed upon methods and data sharing. Long-term monitoring of domestic water wells in the Raton Basin could follow a similar strategy, with primary focus on wells considered to be "at-risk" of impacts by hydraulic fracturing due to slim vertical separation from CBM wells (Watts, 2006) or proximity to igneous intrusions and other known geologic heterogeneities. Under such circumstances, the variable of ultimate importance might end up being stakeholders' conceptual models of the groundwater systems in question – providing yet another critical candidate for long-term observation.

Moving Forward

It is easy to forget, in the throes of factual disputes and resource disagreements, that conflict has benefits in addition to costs. If conflicts had no upside, they would not be such a defining element of human relationships. Conflict provides a mechanism for addressing social issues of power, scarcity, inequality, and cultural or moral differences that, without conflict, might not be dealt with. In the words of Guy Burgess, co-director of the University of Colorado Conflict Information Consortium, conflict is actually "the engine of social learning" (Brahm, 2004). If, when they inevitably occur, conflicts are handled constructively, they can actually serve as positive forces in social change. The analysis presented here is an attempt to broaden our awareness of energy-water nexus conflict dynamics and engage constructively with them.

Factual disputes over the real and potential impacts of natural gas development on critical groundwater systems are not going away anytime soon. Western coalbed methane basins are at various stages of maturity from Montana to New Mexico – most of them have been in production only since the 1990s and have seen rapid development in recent years – and they share similar problems and scientific questions. Many of those problems and questions also extend to other types of unconventional natural gas development across the country, from shales to tight sands. In all cases, stakeholders are presented with institutional, scientific, and environmental complexities that make clear resource development answers and simple decisions difficult to come by.

Hulme and Lederach asks us, in these situations, to approach environmental quandaries not just as "problems" to be "solved," but as issues that we can engage with constructively to reflect on and confront even bigger questions about the human project. From this angle, the relationship between the development of scarce resources in the West and the prevalence of social conflict or collaboration could be considered a crucible for our beliefs, assumptions, and the ways we make individual and collective choices, among many other things. The links between water scarcity and human cooperation have been difficult for researchers to ascertain since the question gained academic prominence in the last decade. Some say water scarcity and cooperation are unrelated (Hensel et al., 2006), others argue that the two correlate linearly and inversely (Tir & Ackerman, 2009), and still others say the relationship is one of an inverted curve, such that cooperation is highest when scarcity is moderate rather than very low or very high (Dinar, 2009). What happens, I wonder, when we add energy development to the equation?

As a normative project, the field of Peace and Conflict Studies aims to prevent, manage, limit, and overcome social conflict through mechanisms of resolution and transformation. For our best teacher in this capacity, we need not look much further than water itself, which manages quite well in a polarized environment. More than just getting by in a charged setting, water's powers of cohesion can be credited to polarity at the molecular level. Interestingly enough, the H_2O molecule's slightly negative and slightly positive ends encourage it to interact with itself and with others on every side. In doing so, water molecules form elaborate networks of hydrogen bonds that are constantly breaking and reforming. Despite perpetual motion and changing circumstances, those bonds are strong enough to create the unique properties of water that make it integral to life – strong cohesion, adhesion, and surface tension, a remarkable ability to absorb heat and a correspondingly high boiling point, and an ability to play the role of "universal solvent." Properties, all, that the 40 percent of the human body that is not made of water might learn from by example.

REFERENCES

Aber, J.D., Nadelhoffer, K.J., Steudler, P.A., & Melillo, J.M. (1989). Nitrogen saturation in forest ecosystems, *BioScience*, 39, 378-386.

Adler, P. S., Barrett, R. C., Bean, J. D. M. C., Birkhoff, J. E., Ozawa, C. P., & Rudin, E. B. (2007). Managing scientific and technical information in environmental cases. *US Institute for Environmental Conflict Resolution*. Retrieved from http://www.resolv.org/wp-content/uploads/2011/02/Environmental_Cases.pdf

Applied Hydrology Associates, Inc. (AHA). (2000). *3M Project San Juan Basin, Colorado and New Mexico: Hydrologic Modeling Report.* Denver, CO: Applied Hydrology Associates, Inc.

AMEC Geomatrix, Inc. (2011). *Updated Trend and Data Analysis, San Juan Basin Water Quality Analysis Project, San Juan Basin, Colorado, Project No. 15244.*

Andrews, T. G. (2008). *Killing for coal: America's deadliest labor war.* Harvard Univ Pr.

American Petroleum Institute (API). (2009). Strategic Energy Resources: San Juan Basin. Retrieved from http://www.api.org/policy/exploration/energyresources/

API. (2011). Frac In Depth: History of Hydraulic Fracturing. Retrieved Oct. 25, 2011 from http://www.energyindepth.org/in-depth/frac-in-depth/history-of-hf/

Ayers Jr, W. B., Ambrose, W. A., & Yeh, J. S. (1994). Coalbed methane in the Fruitland Formation, San Juan basin: depositional and structural controls on occurrence and resources. *Coalbed methane in the Upper Cretaceous Fruitland Formation, San Juan basin, New Mexico and Colorado: University of Texas at Austin, Bureau of Economic Geology Report of Investigations*, *218*, 13–40.

Ayers, W.B. Jr., Ambrose, W.A., Kaiser, W.R., & Laubach, S.E. (1991). Geologic and hydrologic characterization of coalbed methane reservoirs, Fruitland Formation, San Juan Basin, Colorado and New Mexico, *AAPG Bulletin,* 75(3).

Hughes, B. (2011). North America Rotary Rights Count: U.S. Annual Average by State 1987-2010. Retrieved Nov. 1, 2011 from http://investor.shareholder.com/bhi/rig_counts/rc_index.cfm

Bureau of Land Management (BLM). (1999). Coalbed methane development in the northern San Juan Basin of Colorado – a brief history and environmental observations. Retrieved from http://cogcc.state.co.us/library/sanjuanbasin/blm_sjb.htm

Boday, A. (2003). Well Construction and Test Report, Permit #242925.

Bolin, B., Collins, T., & Darby, K. (2008). Fate of the verde: water, environmental conflict, and the politics of scale in Arizona's central highlands. *Geoforum*, *39*(3), 1494-1511. doi:10.1016/j.geoforum.2008.02.003

Brahm, E. (2004). Benefits of Intractable Conflict. *Beyond Intractability*. Conflict Research Consortium, University of Colorado-Boulder. Retrieved from http://www.beyondintractability.org/essay/benefits/

Burgess, G. & Burgess, H. (1997). Conflict Transformation Conflict Research Consortium, University of Colorado-Boulder*.* Retrieved from http://www.colorado.edu/conflict/transform/jplall.htm

Byrne, D. (2011). Fracking and the road to energy independence. *Chicago Tribune*,. Retrieved from http://articles.chicagotribune.com/2011-08-23/news/ct-oped-0823-byrne-20110823_1_fracking-energy-independence-natural-gas

Carroll, C. J., Gillam, M. L., Ruf, J. C., Loseke, T. D., & Kirkham, R. M. (1999). Geologic map of the Durango East quadrangle, La Plata County, Colorado—description of map units, fracture data and analysis, economic geology and references. *Colorado Geological Survey Open-file Report,* 99-96.

Carroll, C. J., & Kirkham, R. M. (1998). Geologic Map of the Ludwig Mountain Quadrangle, La Plata County, Colorado.

Carroll, C. J., Kirkham, R. M., & Wracher, A. (1997). Geologic map of the Rules Hill Quadrangle, La Plata County, Colorado—description of map units, economic geology and references. *Colorado Geological Survey Open-file Report,* 97-91.

Carter, D. A. (1956). Coal deposits of the Raton Basin. *Geology of the Raton Basin, Colorado: Rocky Mountain Association of Geologists Guidebook,* 89-92.

CDWR. (2010). Cumulative Yearly Statistics of the Colorado Division of Water Resources. Retrieved Oct. 31, 2010 from http://water.state.co.us/DWRDocs/Reports/Pages/CumStats.aspx

Chapelle, F. H. (1997). *The Hidden Sea: Groundwater, Springs, and Wells.* Tuscon: Geosciences Press, Inc.

Cipolla, C. L., & Wright, C. A. (2000). *State-of-the-Art in Hydraulic Fracture Diagnostics*. Proceedings from SPE Asia Pacific Oil and Gas Conference and Exhibition.

Clark, I.D., & Fritz, P. (1997). *Environmental isotopes in hydrology*. Boca Raton, FL: Lewis Publishers.

Colorado Oil and Gas Conservation Commission (COGCC). (2011a). *Report to the Water Quality Control Commission and Water Quality Control Division of The Colorado Department of Public Health and Environment.* Denver: COGCC.

COGCC. (2011b). Staff Report: Sept. 19, 2011. Retrieved Sept. 28, 2011 from cogcc.state.co.us

COGCC. (2011c). Colorado Oil and Gass Association, Governor John Hickenlooper, and the Department of Natural Resources Announces Voluntary Baseline Groundwater Quality Sampling Program. Retrieved Aug. 15, 2011 from http://newsroom.coga.org/pr/coga/news.aspx

COGCC (2011d). *Report of Commission and Order, Order No. 1V-363, Docket No. 1102-OV-04.*

COGCC. (2010). Response to Complaint #200258755 and Final Report on Investigation.

COGCC. (2009). Response to Complaint #200206880.

COGCC. (2006). Response to Complaint #1393114 Re: Molokai 13-36 Well.

Cohn, J. P. (2002). Environmental conflict resolution. *BioScience*, *52*(5), 400-404.

Cole, D. R. (1982). Tracing Fluid Sources in the East Shore Area, Utah. *Ground Water*, *20*(5), 586-593.

Coleman, P. (2000). Intractable Conflict. In M. D. a. P. T. Coleman (Ed.), *Handbook of Conflict Resolution: Theory and Practice* (pp. 428-450). San Francisco: Jossey-Bass Publishers.

Condon, S. M. (1988). Joint patterns on the northwest side of the San Juan basin (Southern Ute Indian Reservation), southwest Colorado. *Coal-Bed Methane in San Juan Basin, Colorado and New Mexico. Rocky Mountain Association of Geologists,* 61-68.

Coplen, T.B. & Kendall, C. (2000). Stable isotope and oxygen isotope ratios for selected sites of the US Geological Survey's NASQAN and Benchmark surface water networks: *U.S. Geological Survey Open-File Report 00-160*, 409.

Craig, H. (1961). Isotopic variations in meteoric waters, *Science*, 133, 1702-1703.

Craig, H., Gordon, L.I. (1965). Deuterium and oxygen-18 variations in the ocean and the marine atmosphere. In E. Tongiorgi (Ed.), *Stable Isotopes in Oceanographic Studies and Paleotemperatures*, 1-22. Pisa, Italy: Consiglio Nazionale delle Richerche, Laboratorio di Geologia Nucleare.

Craigg, S. D. (2001). *Geologic framework of the San Juan structural basin of New Mexico, Colorado, Arizona, and Utah, with emphasis on Triassic through Tertiary rocks* ((1420)). US Geological Survey.

Dahl, T. (2011). *Written Testimony of Tracy Dahl before the Colorado Oil and Gas Conservation Commission on Feb. 22, 2011, Complaint #200258755.* Denver.
Darcy, H. (1856). *Les fontaines publiques de la ville de Dijon.* V. Dalmont, Libraire des Corps imperiaux des ponts et chaussées et des mines. Retrieved from
Demissie, Y. K., Valocchi, A. J., Minsker, B. S., & Bailey, B. A. (2009). Integrating a calibrated groundwater flow model with error-correcting data-driven models to improve predictions. *J Hydrol*, *364*(3-4), 257-271. doi:10.1016/j.jhydrol.2008.11.007
Department of National Health and Welfare, Canada. (1978). Guidelines for Canadian drinking water quality. Ottawa, Canada: Health Canada. Retrieved from: http://www.hcsc.gc.ca/ewh-semt/pubs/water-eau/iron-fer/index-eng.php
Dinar, S. (2009). Scarcity and cooperation along international rivers. *Global Environmental Politics*, *9*(1), 109-135. Retrieved from http://www.mitpressjournals.org/doi/pdf/10.1162/glep.2009.9.1.109
Department of Energy (DOE). (2006). *Energy Demands On Water Resources: Report to Congress on the Interdependence of Energy and Water.* Washington, D.C.: U.S. Department of Energy. Retrieved from http://www.sandia.gov/energy-water/congress_report.htm
DOE. (2008). Energy Efficiency & Renewable Energy State Activities and Partnerships: Energy Consumption in Colorado Homes. Retrieved Oct. 31, 2011 from http://apps1.eere.energy.gov/states/residential.cfm/state=CO
DOE. (2011). *Improving the Safety and Environmental Performance of Hudraulic Fracturing: Ninety-Day Report.* Wasington, D.C.: U.S. Department of Energy. Retrieved from www.shalegas.energy.gov
DOE. (2009). Modern shale gas development in the United States: a primer. Retrieved Oct. 10, 2011
Domenico, P.A., & Schwartz, F.W. (1990). *Physical and chemical hydrogeology*. New York, NY: Wiley.
Dugan, M. A. (1989). Peace Studies: Past and Future. *Annals of the American Academy of Political and Social Science*, *504*, 72-79.
Eaton, J. R. (2010). The Sieve of Groundwater Pollution Protection: A Public Health Law Analysis. *Journal of Health & Biomedical Law*, *VI*, 109-146.
Energy Information Administration (EIA). (2007). U.S. Coalbed Methane Cumulative Production (BCF) By Basin to 12/31/06. Retrieved from ftp://ftp.eia.doe.gov/pub/oil_gas/natural_gas/analysis_publications/maps/maps.htm
EIA. (2009). Colorado Energy Profile. Retrieved Oct. 31, 2011 from http://www.eia.gov/state/state-energy-profiles.cfm?sid=CO
Ellis, A. J. (1917). *The divining rod: a history of water witching, with a bibliography* ((416)). US Govt. Print. Off.
Eltschlager, K. K. (2001). Technical measures for the investigation and mitigation of fugitive methane hazards in areas of coal mining. Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.130.2329&rep=rep1&type=pdf
Environmental Protection Agency (EPA). (1996). Ground Water Cleanup at Superfund Sites. Retrieved Sept. 10, 2011 from http://www.epa.gov/superfund/health/conmedia/gwdocs/brochure.htm
EPA. (2004a). Evaluation of Impacts to Underground Sources of Drinking Water by Hydraulic Fracturing of Coalbed Methane Reservoirs. Retrieved from http://www.worldcat.org/oclc/61739904
EPA. (2004b). *Study of Potential Impacts of Hydraulic Fracturing of Coalbed Methane wells on Underground Sources of Drinking Water.* Washington, D.C.: Office of

Ground Water and Drinking Water. Retrieved from www.epa.gov/ogwdw/uic/pdfs/cbmstudy_attach_uic_final_fact_sheet.pdf

EPA (2010, July 13). *Summary of Public Comments*. Proceedings from Hydraulic Fracturing EPA Public Informational Meeting., Denver, CO.

EPA. (2011). *Draft Plan to Study the Potential Impacts of Hydraulic Fracturing on Drinking Water Resources.* Washington, D.C.: U.S. Environmental Protection Agency. Retrieved from http://water.epa.gov/type/groundwater/uic/class2/hydraulicfracturing/index.cfm#curstud

Eriksson, E., & Khunakasem, V. (1969). Chloride concentration in groundwater, recharge rate and rate of deposition of chloride in the Israel Coastal Plain. *Journal of Hydrology*, 7, 178-197.

Fassett, J. E. (1997). Subsurface correlation of the Late Cretaceous Fruitland Formation coal beds in the Pine River, Florida River, Carbon Junction, and Basin Creek gas- seep areas, La Plata County, Colorado. in Geology and structure of the Pine River, Florida River, Carbon Junction, and Basin Creek gas seeps, La Plata County, Colorado.

Fassett, J. E. (2000). Geology and coal resources of the Upper Cretaceous Fruitland Formation, San Juan Basin, New Mexico and Colorado. *Geologic assessment of coal in the Colorado Plateau: Arizona, Colorado, New Mexico, and Utah: US Geological Survey Professional Paper,* Q1-Q131.

Fassett, J. E., & Hinds, J. S. (1971). Geology and fuel resources of the Fruitland formation and Kirtland shale of the San Juan Basin, New Mexico and Colorado. *US, Geol. Surv., Prof. Pap.;(United States)*, *676*.

Fetter, C. W. (2001). Applied Hydrogeology (4 th).

Flores, R. M. (1987). *Sedimentology of Upper Cretaceous and Tertiary silliciclastics and coals in the Raton Basin, New Mexico and Colorado*. Proceedings from Northeastern New Mexico: New Mexico Geological Society Annual 38 th Field Conference.

Flores, R. M., & Bader, L. R. (1999). A summary of Tertiary coal resources of the Raton Basin, Colorado and New Mexico. *USGS Professional Paper*. Retrieved from http://pubs.usgs.gov/pp/p1625a/Chapters/SR.pdf

Forsyth, T. (2003). *Critical political ecology: The politics of environmental science.* Psychology Press. Retrieved from http://www.worldcat.org/oclc/223349176

Frazier, D., & George, D. F. (2000). *Colorado's hot springs.* Pruett Publishing.

Friedman, I., Smith, G.I., Gleason, J.D., Warden, A., & Harris, J.M. (1992). Stable isotope composition of waters in Southeastern California: Modern precipitation. *Journal of Geophysical Research,* 97, 5795–5812.

Friedmann, J. (2011, Sept. 26). *Emerging and Future Technologies for Hydraulic Fracturing*. Proceedings from University of Wyoming Hydraulic Fracturing Forum, Laramie, WY.

Gaganis, P., & Smith, L. (2006). Evaluation of the uncertainty of groundwater model predictions associated with conceptual errors: A per-datum approach to model calibration. *Adv Water Resour*, *29*(4), 503-514. doi:10.1016/j.advwatres.2005.06.006

Geldon, A. L. (1990). Ground-water hydrology of the Central Raton Basin. *Colorado and New Mexico: US Geological Survey Water-Supply Paper*, *2288*, 81.

Glass, I. (2011, July 8). Game Changer, Episode #440. *This American Life*,.

Glover, R. E., Balmer, G. G., & Union, A. G. (1954). *River depletion resulting from pumping a well near a river.* American Geophysical Union. Retrieved from http://www.worldcat.org/oclc/184714544

Groundwater Protection Council (GPC). (2007). State Fact Sheets: Colorado Groundwater Conditions. Retrieved from http://www.gwpc.org/state_resources/state_resources_fact_sheets.htm

Guay, B. E. (2007). Tracking Groundwater Sources with Environmental Isotopes. *Southwest Hydrology*, 6(4), 18-19.

Guay, B., Eastoe, C., Bassett, R., & Long, A. (2006). Sources of surface and ground water adjoining the Lower Colorado River inferred by δ18O, δD and ^{3}H. *Hydrogeology Journal*, 14, 146-158.

Hanel, J. (2010a, Feb. 23). Senate gives drillers time. *The Durango Herald*,.

Hanel, J. (2010b, March 3). Water-rights owner sue state - again. *The Durango Herald*,.

Hazen, J.M., Williams, M.W., Stover, B., & Wireman, M. (2002). Characterisation of Acid Mine Drainage Using a Combination of Hydrometric, Chemical and Isotopic Analyses, Mary Murphy Mine, Colorado. *Environmental Geochemistry and Health*, 24(1), 1-22.

Hemborg, H. T. (1998). *Spanish Peak Field, Las Animas County, Colorado: Geologic setting and early development of a coalbed methane reservoir in the central Raton basin.* Colorado Geological Survey, Dept. of Natural Resources.

Hensel, P. R., McLaughlin Mitchell, S., Sowers, I. I., & Thomas, E. (2006). Conflict management of riparian disputes. *Political Geography*, *25*(4), 383-411.

Hilgartner, S. (1992). The social construction of risk objects: Or, how to pry open networks of risk. *Organizations, uncertainties, and risk,* 39–53.

Hill, G. (2011). Preponderance of the Evidence. Retrieved Sept. 12, 2011 from http://dictionary.law.com/

Hoefs, J. (1997). *Stable Isotope Geochemistry* (4th ed.). Berlin, Germany: Springer.

Holifield, R. (2009). How to speak for aquifers and people at the same time: Environmental justice and counter-network formation at a hazardous waste site. *Geoforum*, *40*(3), 363-372. doi:10.1016/j.geoforum.2008.02.005

Holland & Hart, L. L. P. (2009). Supreme Court Decisions: Vance v. Wolfe. Retrieved March 7, 2010 from www.westernwaterlaw.com/articles/Vance_v_Wolfe.html

Hulme, M. (2009). *Why we disagree about climate change.* Cambridge: Cambridge University Press.

Ivahnenko, T. (2005). Estimated Withdrawals and Use of Water in Colorado, 2005. *pubs.usgs.gov*,. Retrieved from http://pubs.usgs.gov/sir/2010/5002/

Jasanoff, S. (1986). *Risk management and political culture: a comparative study of science in the policy context* (12). Russell Sage Foundation. Retrieved from

Jasanoff, S. (1990). The Fifth Branch: Science Advisors as Policy Makers Cambridge.

Jasanoff, S. (1992). Science, politics, and the renegotiation of expertise at EPA. *Osiris*, *7*, 195. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/11615243 Johnsen, S.J., & White, J.W.C. (1989). The origin of arctic precipitation undepresent and glacial conditions. *Tellus,* 41B(4), 452–468.

Johnson, R. B., & Wood Jr, G. H. (1956). Stratigraphy of Upper Cretaceous and Tertiary Rocks of Raton Basin, Colorado and New Mexico. *Assoc. Petroleum Geologists Bull*, *40*(4), 707-721.

Johnson, R. C., & Finn, T. M. (2001). Potential for a basin-centered gas accumulation in the Raton Basin, Colorado and New Mexico. *Geologic studies of basin-centered gas systems: US Geological Survey, Bulletin,* 1-14. Retrieved from http://pubs.usgs.gov/bul/b2184-b/b2184-b.pdf

Jurich, D., & Adams, M. A. (1984). Geologic overview, coal, and coalbed methane resources of Raton Mesa region—Colorado and New Mexico. *Coalbed Methane Resource of the United States,* 163–184.

Kaiser, W. R., Hamilton, D. S., Scott, A. R., Tyler, R., & Finley, R. J. (1994). Geological and hydrological controls on the producibility of coalbed methane.

Journal of the Geological Society, *151*(3), 417. Retrieved from http://jgs.geoscienceworld.org/cgi/content/abstract/151/3/417
Kattan, Z. (2008). Estimation of evaporation and irrigation return flow in arid zones using stable isotope ratios and chloride mass-balance analysis: Case of the Euphrates River, Syria. *Journal of Arid Environments*, 72, 730-747.
Kaufman, S. & Libby, W.F. (1954). The natural distribution of tritium. *Physical Review*, 93, 1337-1354.
Kernodle, J. M. (1996). Hydrogeology and steady-state simulation of ground-water flow in the San Juan Basin, New Mexico, Colorado, Arizona, and Utah. *USGS Branch of Information Services, Box 25286, Denver Federal Center, Denver, CO.*
Kioprogge, P., van, d. S., JP, & Petersen, A. C. (2011). A method for the analysis of assumptions in model-based environmental assessments. *Environ Modell Softw*, *26*(3), 289-301. doi:10.1016/j.envsoft.2009.06.009
Klahn, S. (2005). *Plaintiffs' Complaint for Declaratory Judgment, Case No. 05CW63.* Durango, CO: District Cour, Water Division 7.
Klahn, S. (2010). *Plaintiffs' and Plaintiff-Intervenors' Opening Brief, Case No. 2010CW80.* Greeley: District Court, Water Division No. 1.
Klare, M. T. (2009). *Rising powers, shrinking planet: The new geopolitics of energy.* Holt Paperbacks.
Lederach, J.P. (1995). *Preparing for Peace: Conflict Transformation Across Cultures*. Syracuse University Press.
Libiszewski, S. (1991). What is an Environmental Conflict? *Journal of Peace Research*, *28*(4), 407-422.
Liu, F., Williams, M. W., & Caine, N. (2004). Source waters and flow paths in an alpine catchment, Colorado Front Range, United States. *Water Resources Research*, *40*(9), W09401.
Lyman, G. G. (2007). *Order. Motion for Stay, Motin for Clarification and Motion For Extension.* Durango, CO: District Court, Water Division 7.
Maest, A. (2011, Oct. 18). *Effects of Produced Waters on Surface Environments*. Proceedings from Scientific Workshop: Potential Impacts of Natural Gas Development to Water and Air in the West, Boulder, CO.
Martin, B., & Richards, E. (1995). Scientific knowledge, controversy, and public decision making. *Handbook of science and technology studies,* 506–526. Retrieved from http://www.bmartin.cc/pubs/95handbook.html
Manning, A.H., & Caine, J.S. (2007). Groundwater noble gas, age, and temperature signatures in an Alpine watershed: Valuable tools in conceptual model development. Water Resources Research, 43, W04404.
McCord, J., Reiter, M., & Phillips, F. (1992). Heat-flow data suggest large ground-water fluxes through Fruitland coals of the northern San Juan basin, Colorado-New Mexico. *Geology*, *20*(5), 419. Retrieved from http://geology.geoscienceworld.org/cgi/content/abstract/20/5/419
Michaels, D., & Monforton, C. (2005). Manufacturing uncertainty: Contested science and the protection of the public's health and environment. *Am J Public Health*, *95*, S39-S48. doi:10.2105/AJPH.2004.043059
Michel R.L. (2004). Tritium hydrology of the Mississippi River basin. *Hydrologic Processes,* 18, 1255-1269.
Michel, R.L. (2005). Tritium in the Hydrologic Cycle. In P.K. Aggarwal, J.R. Gat, & K.F.O. Froehlich (Eds.), *Isotopes in the Water Cycle: Past, Present, and Future of a Developing Science.* Dordrecht, Holland: Springer.
Miller, Z. C. (2006). *BP America Production Co. Motion for Summary Judgment, Case No. 05CW63.* Durango, CO: District Court, Water Division No. 7.
Mostert, E. (1998). A framework for conflict resolution. *Water Int*, *23*(4), 206-215.

Munshower, F.F. (1994). *Practical Handbook of Disturbed Land Revegetation*. Boca Raton, FL: Lewis Publishers.
Narasimhan, T. N. (2009). Groundwater: from mystery to management. *Environ Res Lett*, *4*(3), ARTN 035002. doi:10.1088/1748-9326/4/3/035002
National Groundwater Association (NGWA). (2010). Groundwater Use for Colorado. Retrieved Oct. 31, 2011 from www.ngwa.org/Documents/States/Use/co.pdf
National Academy of Science (NAS). (2010). *Management Effects of Coalbed Methane Produced Water in the Western United States.* Washington, DC: National Academies Press. Retrieved: http://www.nap.edu/catalog/12915.html
Nelkin, D. (1995). Science controversies: the dynamics of public disputes in the United States. *Handbook of science and technology studies,* 444–456.
Nimick, D.A. (2004). Monitoring Surface-Water Quality in the Tounge River Watershed. *U.S.Geological Survey Fact Sheet 2004-3011*. Retrieved from http://pubs.usgs.gov/fs/2004/3011/
Norwest Corp. (2009). *Northern San Juan Basin Groundwater Modeling Project Final Report.* Denver, CO: Norwest Corp. Retrieved from ftp://dwrftp.state.co.us/dwr/Produced_Nontributary.../digital_.pdf
Osborn, S.G., Vengosh, A., Warner, N.R., Jackson, R.B. (2011). Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. *Proceedings of the National Academy of Sciences.* doi: 10.1073/pnas.1100682108
Ostrom, E. (1990). *Governing the commons: The evolution of institutions for collective action.* Cambridge Univ Pr.
Papadopulos & Associates, Inc. (2006). *Coalbed Stream Depletion Assessment Study - Northern San Juan Basin, Colorado.* Boulder, CO: Papadopulos & Associates, in conjunction with Colorado Geological Survey. Retrieved from cogcc.state.co.us/Library/SanJuanBasin/CMSDA_Study.pdf
Peers, J. (2011, Oct. 18). *Natural Gas Development: Potential Contamination Sources, Pathways, and Monitoring*. Proceedings from Scientific Workshop: Potential Impacts of Natural Gas Development to Water and Air in the West. Colorado Water and Energy Research Center, University of Colorado., Boulder, CO.
Phillips, F.M., Peeters, L.A., Tansey, M.K. (1986). Paleoclimatic inferences from an isotopic investigation of groundwater in the central San Juan Basin, New Mexico. *Quaternary Research*, 26, 179–193.
Pillmore, C. L., Flores, R. M., & Fleming, F. (1988). *Field guide to the continental Cretaceous–Tertiary boundary in the Raton Basin, Colorado and New Mexico: in*. Proceedings from Geological Society of America Field Trip Guidebook, Centennial Meeting.
Pioneer Natural Resources. (2010). Drilling Completion Report, Alibi 23-2.
Questa Engineering Corp. (2000). *The 3M CBM Final Report, Volumes I and II.* Golden, CO: Questa Engineering Corp.
Questa Engineering Corp. (2001). *San Juan Basin Ground Water Modeling Study: Ground Water -- Surface Water Interactions Between Fruitland Coalbed Methane Development and Rivers.* Golden, CO: Questa Engineering Corp.
Richards, C., Axler, R. P., Gunderson, J. L., Hagley, C. A., & McDonald, M. E. (2002). Assessing and communicating risk: a partnership to evaluate a superfund site on Leech Lake tribal lands. Retrieved from http://www.csa.com/partners/viewrecord.php?requester=gs&collection=ENV&recid=6000995
Ridgley, J. L. (2002). *Assessment of Undiscovered Oil and Gas Resources of the San Juan Basin Province of New Mexico and Colorado.* U.S. Geological Survey Fact Sheet FS-147-02.

Riese, W. C., Pelzmann, W. L., & Snyder, G. T. (2005). New insights on the hydrocarbon system of the Fruitland Formation coal beds, northern San Juan Basin, Colorado and New Mexico, USA. *Coal systems analysis*, *387*, 73.

Rojas, R., Feyen, L., & Dassargues, A. (2008). Conceptual model uncertainty in groundwater modeling: Combining generalized likelihood uncertainty estimation and Bayesian model averaging. *Water Resour Res*, *44*(12), ARTN W12418. doi:10.1029/2008WR006908

Rozanski, K., Araguás-Araguás, L., & Gonfiantini, R. (2003). Isotopic patters in modern global precipitation, in Climate Change in Continental Isotopic Records, *Geophysical Monograph Series*, 78, 1-36.

San Juan Public Lands Center. (2006). *Final Environmental Impact Statement: Northern San Juan Coal Bed Methane Project.* Durango, CO: San Juan Public Lands Center.

SJPLC. (2007). *Record of Decision, Northern San Juan Coal Bed Methane Project*. Durango, CO: SJPLC. Retrieved from: http://www.fs.fed.us/r2/sanjuan/projects/ea/nsjb/nsjb.shtml

Schultz, N. (2003a). Factual Disputes. Conflict Research Consortium, University of Colorado-Boulder. Retrieved from http://www.beyondintractability.org/essay/factual_disputes.

Schultz, N. (2003b). Technical Facts. Retrieved from http://www.beyondintractability.org/essay/technical_facts

Schultz, N. (2003c). Distinguishing Facts from Values. Conflict Research Consortium, University of Colorado-Boulder. Retrieved from http://www/beyondintractability.org/essay/facts_values

Schultz, N. (2004a). The Role of Information in Disputes. Conflict Research Consortium, University of Colorado-Boulder. Retrieved from http://www.beyondintractability.org/essay/fact-finding

Schultz, N. (2004b). Fact-Finding. Conflict Research Consortium, University of Colorado-Boulder. Retrieved from http://www.beyondintractability.org/esasy/fact-finding

Silver, C. (1951). Stratigraphic Oil and Gas Possiblitities in San Juan Basin, New Mexico and Colorado. *Aapg Bull*, *35*(5), 1105-1106.

Skinner, A. C. (2008). Groundwater: still out of sight but less out of mind. *Q J Eng Geol Hydroge*, *41*, 5-19.

Snyder, G. T., & Fabryka-Martin, J. T. (2007). I-129 and Cl-36 in dilute hydrocarbon waters: Marine-cosmogenic, in situ, and anthropogenic sources. *Appl Geochem*, *22*(3), 692-714. doi:10.1016/j.apgeochem.2006.12.011

Southwest Ground-Water Consultants. (2004). *C.V./C.F. Ranch acquisition hydrology report. Prepared for the City of Prescott.*

Consultants, S. G. (2005). *Big Chino Ranch Hydrology Study. Prepared for City of Prescott Public Works Department.*

Stevens, S. H., Lombardi, T. E., Kelso, B. S., & Coates, J. M. (1992). A geologic assessment of natural gas from coal seams in the Raton and Vermejo Formations. *Raton basin: Gas Research Institute Topical Report GRI-92/0345*,.

Suthers, J. W. (2005). *Answer and Motion to Dismiss, Case No. 05CW63.* Durango, CO: District Court, Water Division 7.

Tidwell, V. C., & van den Brink, C. (2008). Cooperative modeling: linking science, communication, and ground water planning. *Ground Water*, *46*(2), 174-182. doi:10.1111/j.1745-6584.2007.00394.x

Tir, J., & Ackerman, J. T. (2009). Politics of formalized river cooperation. *Journal of Peace Research*, *46*(5), 623. Retrieved from http://jpr.sagepub.com/content/46/5/623.short

Topper, R., Spray, K. L., Bellis, W. H., Hamilton, J. L., & Barkmann, P. E. (2003). Ground water atlas of Colorado. *Colorado Geological Survey Special Publication*, *53*, 210.

Toth, J. (1962). A theory of groundwater motion in small drainage basins in central Alberta. *Journal of Geophysical Research*, 67, 4375-4387.

Townsend, C.R., & Riley, R.H. (1999). Assessment of river health: accounting for perturbation pathways in physical and ecological space. *Freshwater Biology*, 41(2), 393-405.

Tremain, C. M., Laubach, S. E., & Whitehead III, N. H. (1994). Fracture (cleat) patterns in Upper Cretaceous Fruitland Formation coal seams, San Juan basin. *Coalbed methane in the Upper Cretaceous Fruitland Formation, San Juan basin, New Mexico and Colorado: Bureau of Economic Geology Bulletin*, *146*, 87–102.

Tyler, R., Kaiser, W. R., Scott, A. R., Hamilton, D. S., & Ambrose, W. A. (1995). Geologic and Hydrologic Assessment of Natural Gas from Coal: Greater Green River, Piceance, Powder River, and Raton Basins, Western United States. *REPORT OF INVESTIGATIONS-UNIVERSITY OF TEXAS BUREAU OF ECONOMIC GEOLOGY*, *228*. Retrieved from http://direct.bl.uk/research/0C/1E/RN030362044.html?source=googlescholar

Union of concerned Scientists (UCS). (2006). EPA Findings on Hydraulic Fracturing Deemed "Unsupportable". Retrieved Nov. 1, 2011 from http://www.ucsusa.org/scientific_integrity/abuses_of_science/oil-extraction.html

Urbina, I. (2011). Regulation Lax as Gas Wells' Tainted Water Hits Rivers. *New York Times*,. Retrieved from http://www.nytimes.com/2011/02/27/us/27gas.html?ref=drillingdown

U.S. Geological Survey (2000). *Toxic Substances Hydrology Program: Tritium*. Retrieved http://toxics.usgs.gov/definitions/tritium.html

USGS. (1985). *National Water Summary 1984: Hydrologic Events, Selected Water-quality Trends, and Ground-water Resources.* US Dept. of the Interior, Geological Survey. Retrieved from http://www.worldcat.org/oclc/12335558

Van Voast, W.A. (2003). Goechemical signature of formation waters associated with coalbed methane. *AAPG Bulletin*, 87, 667-676.

Vance v. Wolfe. (2007). Order. Motions for Summary Judgment, Case No. 05CW63. Durango, CO.: District Court, Water Division 7.

Vance v. Wolfe. (2009). Colorado Supreme Court Case No. 07SA293, April 20, 2009.

Warpinski, N., Mayerhofer, M., Vincent, M., Cipolla, C., & Lolon, E. (2008). *Stimulating unconventional reservoirs: maximizing network growth while optimizing fracture conductivity*. Proceedings from SPE Unconventional Reservoirs Conference.

Warpinski, N. R., Branagan, P. T., Peterson, R. E., Wolhart, S. L., & Uhl, J. E. (1998). *Mapping hydraulic fracture growth and geometry using microseismic events detected by a wireline retrievable accelerometer array*. Proceedings from SPE Gas Technology Symposium.

Watts, K. R. (2006). … Separation between Production Intervals of Coalbed-Methane Wells and Water-Supply Wells in the Raton Basin, Huerfano and Las Animas Counties, Colorado, 1999 …. *ntis.library.gatech.edu*,. Retrieved from http://ntis.library.gatech.edu/handle/123456789/2421

Watts, K. R. (2007). Hydrostratigraphic Framework of the Raton, Vermejo, and Trinidad Aquifers in the Raton Basin, Las Animas County, Colorado. *ntis.library.gatech.edu*,. Retrieved from http://ntis.library.gatech.edu/handle/123456789/8868

Wirt, L., & DeWitt, E. (2005). Geochemistry of Major Aquifers and Springs. Chapter E: Geologic Framework of Aquifer Units and Ground-Water Flowpaths, Verde

River Headwaters, North-Central Arizona. United States Geological Survey Open-File Report 2004-1411-E, Reston, VA. Retrieved from http://www.google.com/webhp?hl=en&oe=ASCII&num=1" target="_top

Wirt, L., DeWitt, E., Langenheim, V. E., Commission, A. W. P. F., & (US, G. S. (2005). *Geologic framework of aquifer units and ground-water flowpaths, Verde River headwaters, north-central Arizona.* US Geological Survey. Retrieved from http://www.worldcat.org/oclc/62789652

Wray, L. L., Streufert, R. K., Morgan, M. L., & Survey, C. G. (2000). *Late Cretaceous Fruitland Formation Geologic Mapping, Outcrop Measured Sections and Subsurface Stratigraphic Cross Sections, Northern La Plata County, Colorado.* Colorado Geological Survey, Division of Minerals and Geology, Dept. of Natural Resources. Retrieved from http://www.worldcat.org/oclc/56532640

Yarn, D. (1999). Conflict. In *Dictionary of Conflict Resolution*. San Francisco: Jossey-Bass Publishers.

Yearley, S. (1995). The environmental challenge to science studies. *Handbook of science and technology studies,* 457-479.

Zoback, M., Kitasei, S., & Copithorne, B. (2010). Addressing the environmental risks from shale gas development. *Natural gas and sustainable energy initiative. Washington DC: Worldwatch Institute*,. Retrieved from http://efdsystems.org/Portals/25/Hydraulic Fracturing Paper - World Watch.pdf

APPENDIX A: TABLES

Table 2.1. Adapted from a SJPLC Environmental Impact Statement (2006) table comparing differing conclusions regarding impacts of CBM development derived from assumptions of the Hydraulically Connected Basin conceptual model, as proposed by AHA (2000) and interpreted by SJPLC) and the Compartmentalized Basin Conceptual model, as proposed by Riese et. al (2005).

Impact Issue	Hydraulically Connected Basin Model	Compartmentalized Basin Conceptual Model
Groundwater level declines near Fruitland Outcrop	CBM-related groundwater withdrawals from the Fruitland Formation can cause declines in groundwater levels near the Outcrop.	CBM-related groundwater withdrawals from the Fruitland Formation have no effect on groundwater levels near the Outcrop.
Reduction in groundwater discharge from the Fruitland Formation to area rivers and streams.	CBM-related groundwater withdrawals from the Fruitland Formation will intercept groundwater that would normally discharge to area rivers and streams, and will therefore decrease baseflow to those rivers.	CBM-related groundwater withdrawals from the Fruitland Formation have no effect on groundwater discharge to area rivers and will have no effect on baseflow in the rivers.
Declines in natural spring flow from springs sourced by the Fruitland Formation and issuing from the Outcrop.	CBM-related groundwater withdrawals from the Fruitland Formation may cause declines in natural spring flow or drying up of springs.	CBM-related groundwater withdrawals from the Fruitland Formation do not affect natural springs.
Methane seeps at the Fruitland Outcrop and related problems for residential areas and/or local vegetation.	CBM-related groundwater withdrawals from the Fruitland Formation allows gas desorption from the Fruitland coals which, in turn causes changes and increases in methane seeps at the Outcrop as well as increased areal extent of related problems.	CBM-related groundwater withdrawals from the Fruitland Formation have no effect on methane seeps. Vegetation impacts are caused by factors unrelated to CBM development, such as drought.

Table 3.1 – Sample sites divided in three geographic categories. Descriptions include relationship to the Fruitland Outcrop. Domestic wells' position relative to Outcrop is an estimate based on location.

	Sample Site ID	Location type	Hydrologic Feature	Relation to Outcrop	Elevation (ft)	Land Use	County
Florida Drainage							
	FL1	stream	Surface Water	Above Outcrop	7950	Residential	La Plata
	FL2	stream	Surface Water	Above Outcrop	7170	Agricultural - ranching	La Plata
	FL3	stream	Surface Water	In Outcrop	7080	Agricultural - ranching	La Plata
	FL4	stream	Surface Water	In Outcrop	7070	Agricultural - ranching	La Plata
	FL5	domestic well	Subsurface water	In Outcrop	7080	Residential	La Plata
	FL6	domestic well	Subsurface water	In Outcrop	7050	Agricultural - ranching	La Plata
	FL7	stream	Surface Water	Below Outcrop	7040	Agricultural - ranching	La Plata
	FR2	peizometer	Subsurface water	In Outcrop	7075	Agricultural - ranching	La Plata
	FR3	peizometer	Subsurface water	In Outcrop	7070	Agricultural - ranching	La Plata
	FR4	peizometer	Subsurface water	In Outcrop	7060	Agricultural - ranching	La Plata
	FC	Irrigation ditch	Surface Water	Below Outcrop	6800	Agricultural - ranching	La Plata
	RD	Irrigation ditch	Surface Water	Below Outcrop	6850	Agricultural - ranching	La Plata
	FFD	Irrigation ditch	Surface Water	Below Outcrop	6870	Agricultural - ranching	La Plata
	TC1	domestic well	Subsurface water	Below Outcrop	6880	Residential	La Plata
	TC2	spring	Subsurface water	Below Outcrop	6850	Agricultural - ranching	La Plata
	MY1	domestic well	Subsurface water	Below Outcrop	6900	Residential	La Plata
	WI1	domestic well	Subsurface water	Below Outcrop	6700	Residential	La Plata
	SH1	domestic well	Subsurface water	Below Outcrop	6830	Residential	La Plata
	HI1	domestic well	Subsurface water	Below Outcrop	6770	Residential	La Plata
	Davis	CBM Wells	Subsurface water	In Outcrop	6890	CBM	La Plata
	Huber-Flanagan	CBM Wells	Subsurface water	In Outcrop	6930	CBM	La Plata
	Huber-Federal	CBM Wells	Subsurface water	In Outcrop	7120	CBM	La Plata
	Huber-Nelson	CBM Wells	Subsurface water	In Outcrop	7100	CBM	La Plata
Basin Interior							
	MCD	Irrigation ditch	Surface Water	Below Outcrop	6700	Agricultural - ranching	La Plata
	HD147	domestic well	Subsurface water	Below Outcrop	6760	Residential	La Plata
	HD3488	domestic well	Subsurface water	Below Outcrop	6700	Residential	La Plata
	YE1	domestic well	Subsurface water	Below Outcrop	6720	Agricultural - ranching	La Plata
	PA1	domestic well	Subsurface water	Below Outcrop	6500	Agricultural - ranching	La Plata
	RS	spring	Subsurface water	In Outcrop	7060	Public Lands (forested)	Archuleta
	MS	spring	Subsurface water	In Outcrop	7630	Residential	Archuleta
	VS1	spring	Subsurface water	In Outcrop	7470	Agricultural - farming	Archuleta
	VS2	spring	Subsurface water	In Outcrop	7540	Agricultural - farming	Archuleta
Piedra Drainage							
	ST1	stream	Surface Water	Above Outcrop	6430	Agricultural - ranching	Archuleta
	ST2	stream	Surface Water	In Outcrop	6410	Agricultural - ranching	Archuleta
	ST3	stream	Surface Water	Below Outcrop	6330	Agricultural - ranching	Archuleta
	ST4	spring	Subsurface water	In Outcrop	6420	Agricultural - ranching	Archuleta
	ST5	spring	Subsurface water	Below Outcrop	6310	Agricultural - ranching	Archuleta
	ST6	stream	Surface Water	Above Outcrop	6550	Public Lands (forested)	Archuleta
	ST7	stream	Surface Water	Above Outcrop	6640	Public Lands (forested)	Archuleta
	AC1	stream	Surface Water	In Outcrop	7020	Public Lands (forested)	Archuleta
	MA1	domestic well	Subsurface water	In Outcrop	6410	Residential	Archuleta
	MA2	domestic well	Subsurface water	In Outcrop	6440	Residential	Archuleta
	GAR1	domestic well	Subsurface water	Below Outcrop	6360	Residential	Archuleta
	CC1	stream	Surface Water	In Outcrop	6820	Public Lands (forested)	Archuleta
	DE	domestic well	Subsurface water	In Outcrop	6290	Residential	Archuleta
	HD3433	domestic well	Subsurface water	In Outcrop	6310	Residential	Archuleta
	PG2	peizometer	Subsurface water	In Outcrop	6840	Public Lands (forested)	Archuleta
	PG3	stream	Surface Water	In Outcrop	7040	Public Lands (forested)	Archuleta
	PG4	stream	Surface Water	In Outcrop	6910	Public Lands (forested)	Archuleta
	PG5	stream	Surface Water	In Outcrop	6770	Public Lands (forested)	Archuleta
	PG6	spring	Subsurface water	In Outcrop	7000	Public Lands (forested)	Archuleta
	SC1	stream	Surface Water	Above Outcrop	7570	Public Lands (forested)	Archuleta
	SC2	spring	Subsurface water	In Outcrop	7420	Public Lands (forested)	Archuleta
	SC3	stream	Surface Water	In Outcrop	7430	Public Lands (forested)	Archuleta
	SC4B	stream	Surface Water	Below Outcrop	7120	Public Lands (forested)	Archuleta
	LS1	peizometer	Subsurface water	Below Outcrop	7030	Public Lands (forested)	Archuleta
	LS2	peizometer	Subsurface water	In Outcrop	7050	Public Lands (forested)	Archuleta
	LS4	peizometer	Subsurface water	Above Outcrop	7100	Public Lands (forested)	Archuleta
	LS5	stream	Surface Water	In Outcrop	7050	Public Lands (forested)	Archuleta
	PR1	stream	Surface Water	Above Outcrop	6580	Public Lands (forested)	Archuleta
	PR2	stream	Surface Water	Above Outcrop	6520	Public Lands (forested)	Archuleta
	PR3	stream	Surface Water	Above Outcrop	6390	Public Lands (forested)	Archuleta
	PR4	stream	Surface Water	In Outcrop	6370	Public Lands (forested)	Archuleta
	PR5	stream	Surface Water	Below Outcrop	6300	Public Lands (forested)	Archuleta
Precipitation							
	SHA	Precipitation	Surface Water	Above Outcrop	7770	Public Lands	La Plata
	CA1	Precipitation	Surface Water	Above Outcrop	8780	Public Lands	La Plata
	CA2	Precipitation	Surface Water	Above Outcrop	8780	Public Lands	La Plata

Table 3.2 – Depths (total and case) and static water levels of domestic wells, as per public drilling records (Colorado Division of Water Resources, http://www.dwr.state.co.us/, retrieved 12/10); depths of piezometers as reported by SJPLC (SJPLC field staff, personal communication 2010).

Sample_ID	Type	Static Water Level (ft)	Well Depth (ft)	Case Depth (ft)
HD147	Domestic Well	0	120	
MA1	Domestic Well	18	60	
MA2	Domestic Well	0	92	
GAR1	Domestic Well	0		
PA1	Domestic Well	20	275	275
YE1	Domestic Well	42	264	100
HD3488	Domestic Well	80	200	200
FL5	Domestic Well	60	200	200
FL6	Domestic Well	12	100	100
WI1	Domestic Well	200	400	320
MY1	Domestic Well	35	200	200
SH1	Domestic Well	0		
TC1	Domestic Well	38	155	
HI1	Domestic Well	20	90	90
DE	Domestic Well	0		
HD3433	Domestic Well	0	125	
FR2	Piezometer	--	7.18	--
FR3	Piezometer	--	7.29	--
FR4	Piezometer	--	7.29	--
PG2	Piezometer	--	5.10	--
LS1	Piezometer	--	9.09	--
LS2	Piezometer	--	9.10	--
LS3	Piezometer	--	9.29	--

Table 3.3 – Isotopic results for precipitation samples.

PRECIPITATION SAMPLES			
Date	**d^{18}O (‰)**	**d^{2}H (‰)**	**Tritium (TU)**
3/16/09	-17.0	-120.2	6.4
3/16/09	-17.0	-119.6	6.7
5/26/09	-13.0	-95.4	NP
12/28/08	-18.4	-134.7	NP
Mean	**-16.3**	**-117.5**	**6.55**

Table 3.4 – Summary table of mean isotopic and geochemical results, partitioned by water body (n=120). Analysis of variance was conducted among surface water, irrigation ditch, domestic well, piezometer, and spring sources using a Kruskal Wallis non-parametric ANOVA. CBM well data presented here is from the current study only (n=4).

	sample n	^{18}O ‰ d per mill	Tritium TU	Na^{+} uEQ/L	Cl^{-} uEQ/L	SAR
Surface Water	44	-12.90 ± 1.24	5.8 ± 0.81	689.0 ± 462.49	212.1 ± 285.64	0.48 ± 0.26
Irrigation Ditch	4	-12.86 ± 0.05	5.6 ± 1.06	71.3 ± 12.66	18.25 ± 2.75	0.1 ± 0
Domestic Well	32	-12.7 ± 0.98	5.1 ± 1.97	3,627.6 ± 3247.48	418.2 ± 463.27	3.7 ± 4.92
Piezometer	13	-13.5 ± 0.92	5.8 ± 0.8	1,248.6 ± 1475.89	79.0 ± 53.38	0.9 ± 1.02
Spring	19	-13.03 ± 1.06	5.2 ± 0.55	820.2 ± 407.55	177.1 ± 223.35	0.5 ± 0.21
Kruskal Wallis ANOVA		p=0.06	p=0.01	p=0.0000001	p=0.000006	p=0.0000004
CBM Well	4	-14.62 ± 0.58	0 ± 0.07	26,033.3 ± 5,075.10	3,101.0 ± 1,761.37	69.9 ± 10.6
Precipitation	4	-16.3 ± 2.31	6.6 ± 0.21	5.6 ± 2.89	4.0 ± 1.73	0 ± 0

Table 3.5 – Isotopic results divided by water body and drainage (precipitation was collected in the Florida drainage). 3M Project coalbed methane well data was provided by SJPLC. Deuterium-excess (D-excess) was calculated for individual samples following the protocol developed by Johnsen and White (1989) based on the equation for the GMWL: $d_{excess} = \delta^2H - 8\,\delta^{18}O$.

	sample n	^{18}O ‰ vs. ^2H ‰ slope	^{18}O ‰ d per mill	^2H ‰ d per mill	D-Excess d per mill	Tritium TU
Florida Drainage	**38**					
Florida River	10	7.5 R^2=0.98	-14.0 ± 1.35	-103.0 ± 10.11	8.7 ± 0.90	6.3 ± 2.18
Irrigation Ditch	3	4.9 R^2=0.86	-12.8 ± 0.05	-93.2 ± 0.39	9.5 ± 0.48	6.1 ± 0.49
Domestic Well	14	6.3 R^2=0.93	-13.3 ± 1.15	-97.1 ± 7.52	8.8 ± 2.84	5.8 ± 0.72
Piezometer	6	7.5 R^2=0.99	-13.9 ± 1.14	-102.5 ± 8.56	8.3 ± 0.74	6.3 ± 0.80
Spring	1	NA	-12.6	-92.8	7.85	5.9
CBM Well	4	5.5	-14.6 ± 0.58	-107.9 ± 3.17	9.0 ± 1.49	<1
Interior Basin	**17**					
Irrigation Ditch	1	NA	-12.9	-92.3	10.9	6.9
Domestic Well	8	4.6 R^2=0.40	-12.5 ± 0.29	-93.6 ± 2.13	6.4 ± 1.91	6.3 ± 1.4
Spring	8	6.3 R^2=0.85	-13.6 ± 0.79	-98.8 ± 5.40	9.8 ± 2.47	5.2 ± 0.65
Piedra Drainage	**61**					
Piedra River + Tribs	18	4.3 R^2=0.92	-12.6 ± 1.04	-93.3 ± 6.81	7.4 ± 4.03	5.73 ± 0.69
Main Channel	5	6.3 R^2=0.96	-13.2 ± 0.53	-96.2 ± 3.38	9.6 ± 1.16	6.4 ± 0.61
Tributaries	13	4.1 R^2=0.91	-12.3 ± 1.09	-92.1 ± 4.67	6.5 ± 4.45	5.4 ± 0.47
Domestic Well	5	6.6 R^2=0.72	-12.0 ± 0.47	-91.4 ± 3.65	4.3 ± 2.04	3.2 ± 2.25
Piezometer	4	4.0 R^2=0.79	-13.2 ± 0.63	-95.5 ± 2.86	10.1 ± 2.82	5.4 ± 0.62
Spring	6	5.8 R^2=0.98	-12.6 ± 1.15	-94.4 ± 6.81	6.7 ± 2.67	5.1 ± 0.44
Precipitation	**4**	7.0 R^2=1.00	-16.3 ± 2.31	-117.5 ± 16.3	13.2 ± 3.53	6.6 ± 0.21 (n=2)
3M Study CBM Well	100	7.6 R^2=0.88	-10.5 ± 3.98	-69.3 ± 27.92	14.5 ± 3.92	NA

Table 3.6 – Mean solute concentrations in domestic wells, which are divided by drainage and arranged in ascending order within each group based on tritium content. Mean values are used when n > 1. Bold wells are "tritium dead."

WELL	Na+ uEQ/L	Cl- uEQ/L	NO3- uEQ/L	^{18}O ‰ d per mill	TRITIUM tu
LA PLATA CO					
FL5	1746.4	75.4	4.8	-14.0	5.2
HI1	2988.3	344.9	29.3	-13.2	4.9
FL6	184.8	114.8	22.2	-14.3	6.3
TC1	1363.0	398.4	172.8	-12.8	5.9
WI1	648.2	374.3	76.0	-13.2	6.0
SH1	1496.3	569.7	29.7	-12.8	6.1
MY1	743.8	290.1	26.8	-12.3	6.2
BASIN INTERIOR					
YE1	5187.1	2016.9	504.6	-12.4	4.7
HD147	748.6	156.8	27.6	-12.6	6.3
PA1	6809.5	276.2	7.2	-12.7	6.8
HD3488	11744.3	258.4	12.3	-12.3	7.5
ARCHULETA CO					
MA2	**7757.1**	**68.0**	**0.6**	**-12.5**	**0.5**
GAR1	**2322.8**	**138.4**	**<0.02**	**-12.3**	**0.9**
DE	1890.0	458.5	132.1	-11.7	5.2
MA1	5300.2	469.9	4.0	-11.4	5.1
HD3433	4395.4	716.2	585.5	-11.7	4.5

APPENDIX B: FIGURES

CHAPTER 1 FIGURES

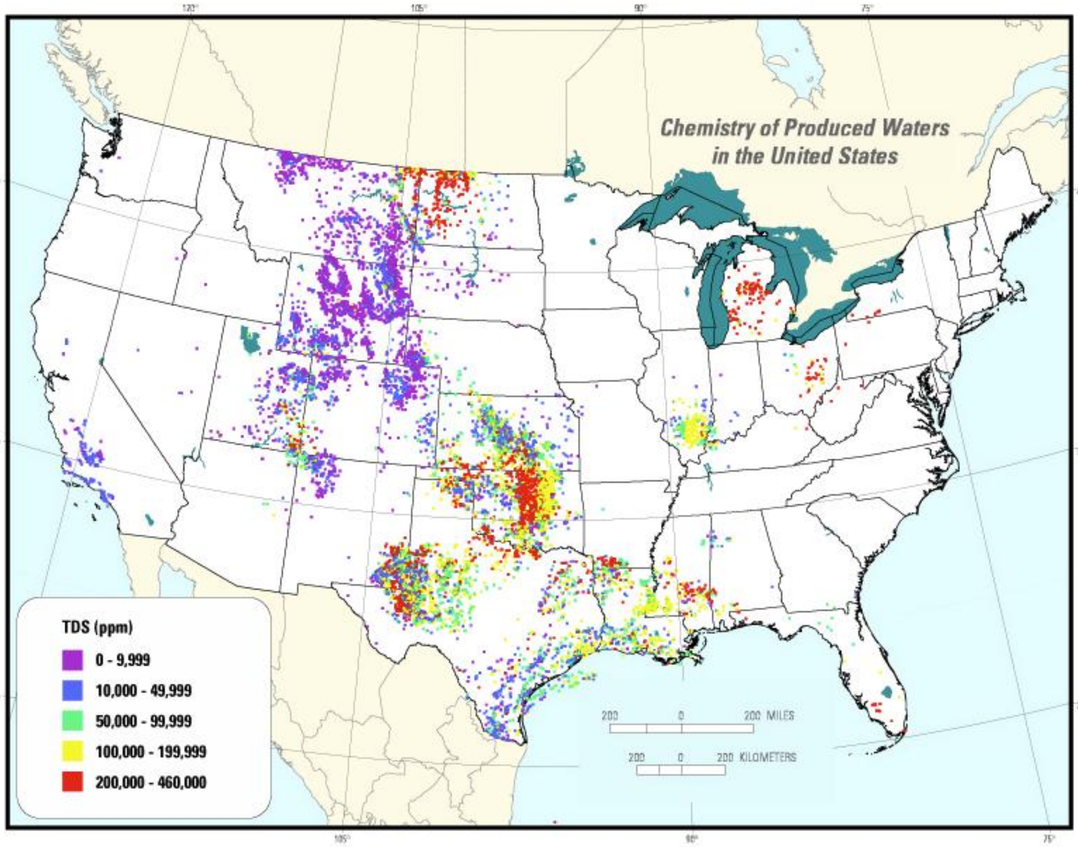


Figure 1.1 – Map of chemistry of water produced from oil and gas development in the United States, presenting Total Dissolved Solids (TDS) in parts per million. Purple dots signify produced water that contains less than 10,000 mg/l TDS, which meets the federal TDS requirement for an Underground Source of Drinking Water (EPA: http://www.epa.gov/r5water/uic/glossary.htm#usdw).

CHAPTER 2 FIGURES

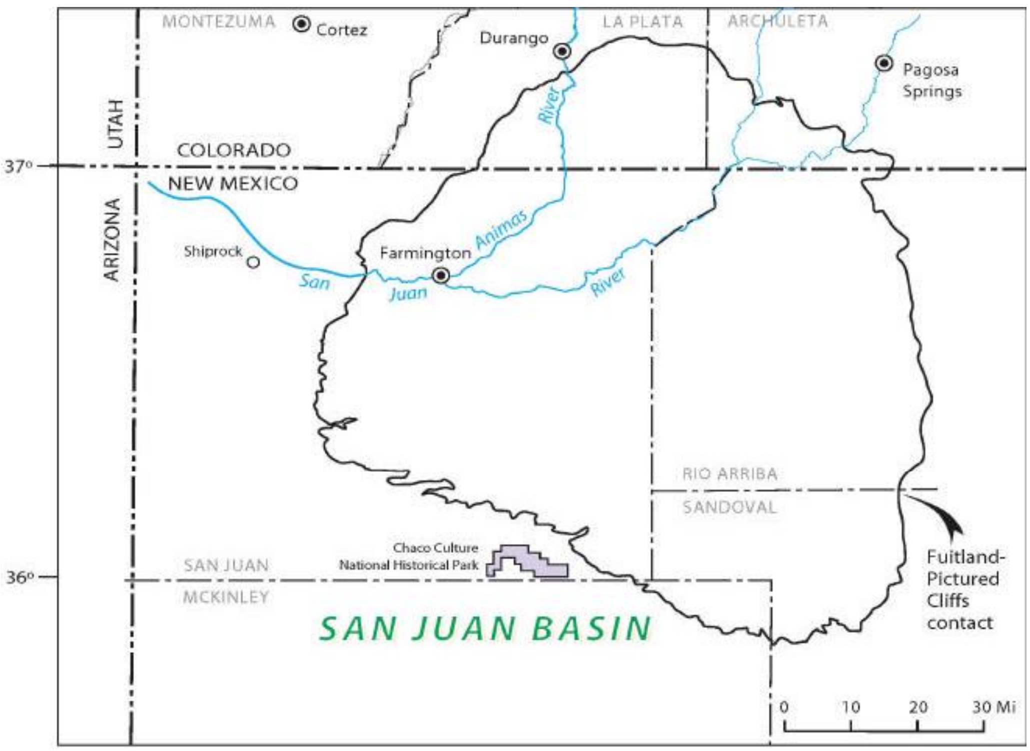


Figure 2.1 – Map of the San Juan Basin (Papdopulos, 2006). The Colorado portion, known as the Northern San Juan Basin (NSJB), is the focus of the present analysis.

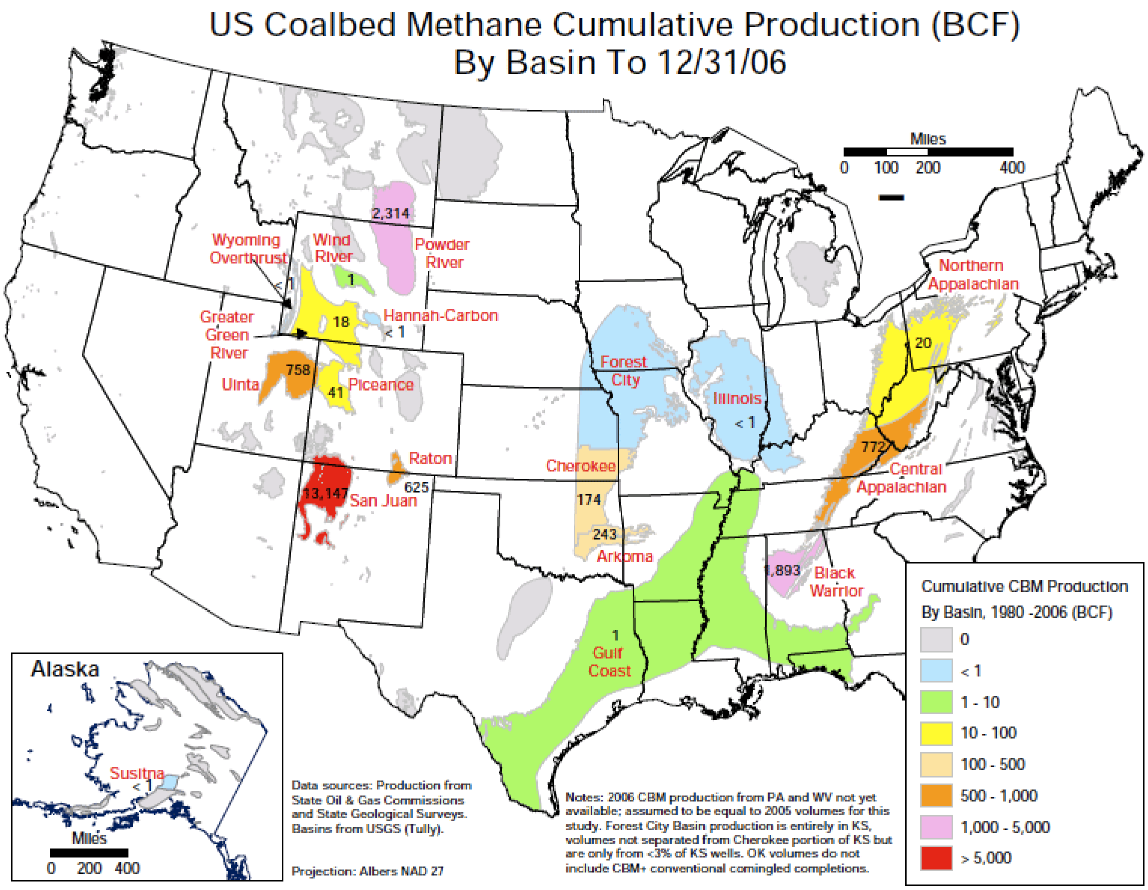


Figure 2.2 – Cumulative coalbed methane (CBM) production in the U.S. up to 2006, as compiled by the Energy Information Administration (2007). As the nation's first CBM play, the San Juan Basin is to be credited with the most cumulative production of any basin in the U.S. and therefore appears in red.

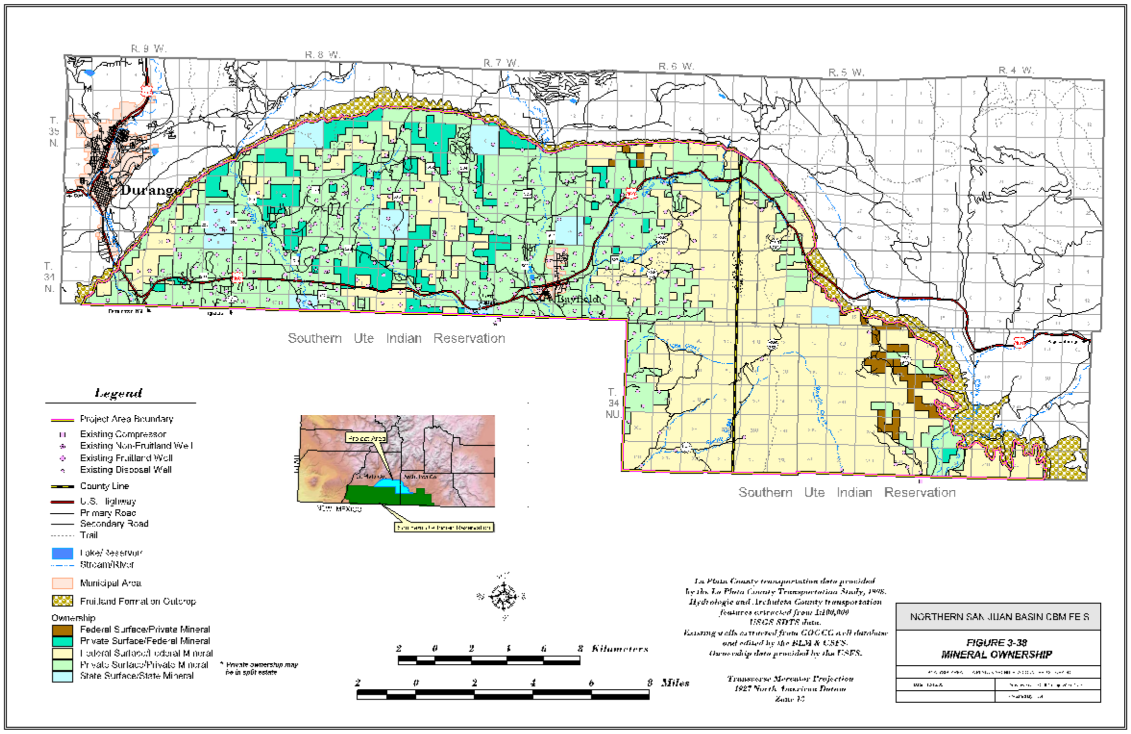


Figure 2.3 – Distribution of natural gas mineral rights in the Northern San Juan Basin, as compiled by the San Juan Public Lands Center in an Environmental Impact Statement (2006) addressing a proposal for increased CBM development on federal mineral leases in the region, shown in beige and bright green.

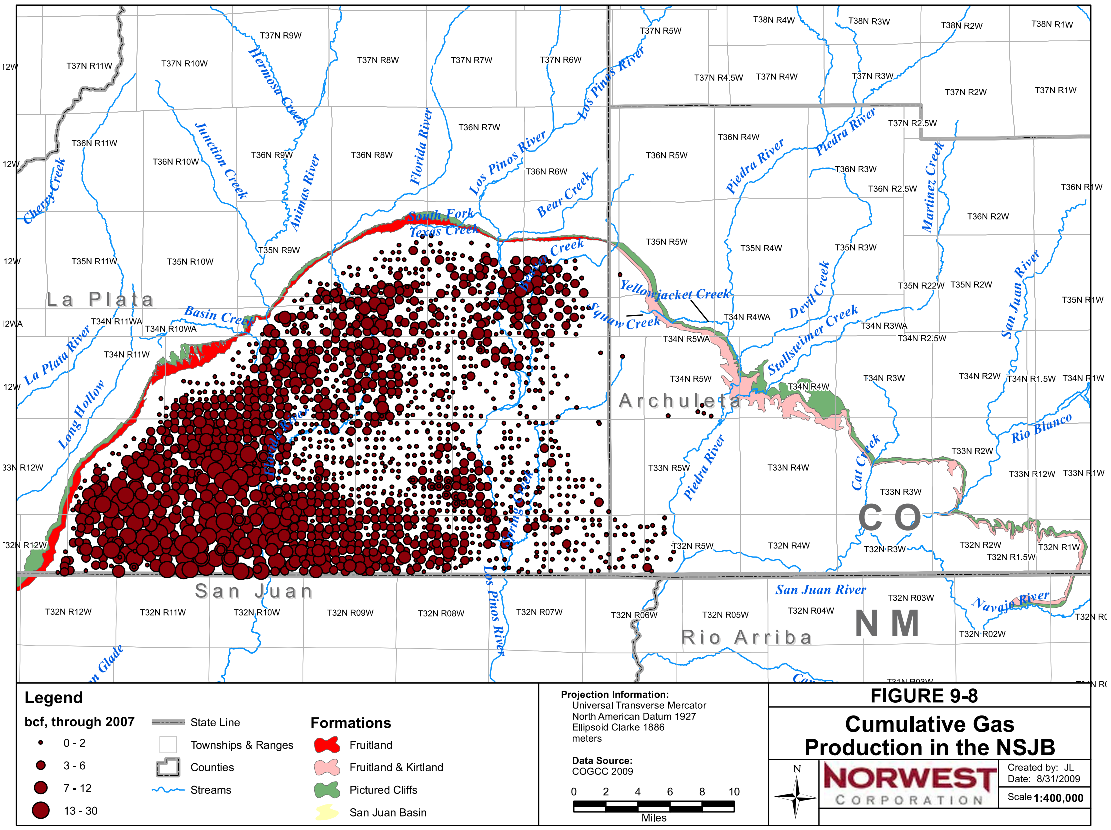


Figure 2.4 – Cumulative gas production in the Northern San Juan Basin by well up to 2009, as compiled by Norwest (2009). The high-producing region to the southwest of the basin is nicknamed “the Fairway.”

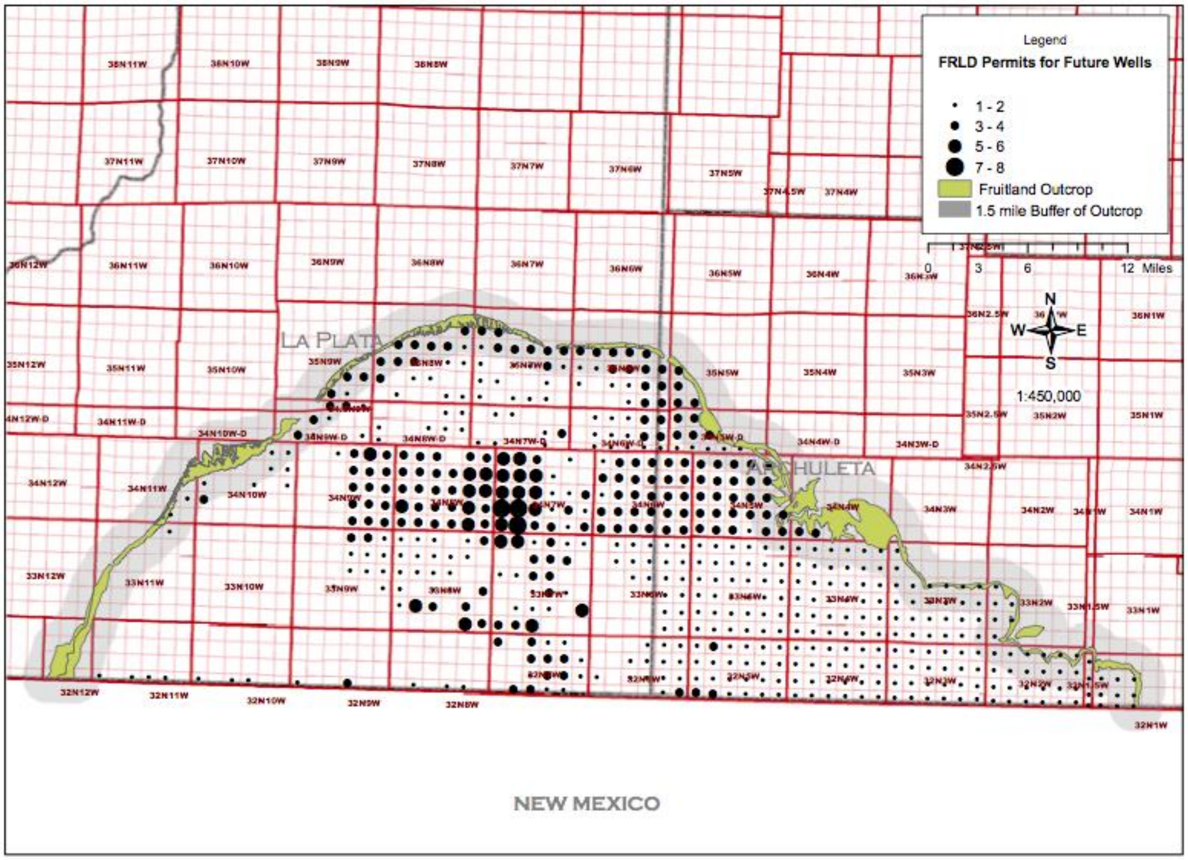


Figure 2.5 – Future CBM well projections in the Northern San Juan Basin as estimated and utilized by Papadopulos in a 2006 stream depletion study. Projects were based on COGCC well permitting orders and communication with COGCC staff as well as development scenarios presented by SJPLC in a 2006 Environmental Impact Statement addressing reduced well spacing proposals.

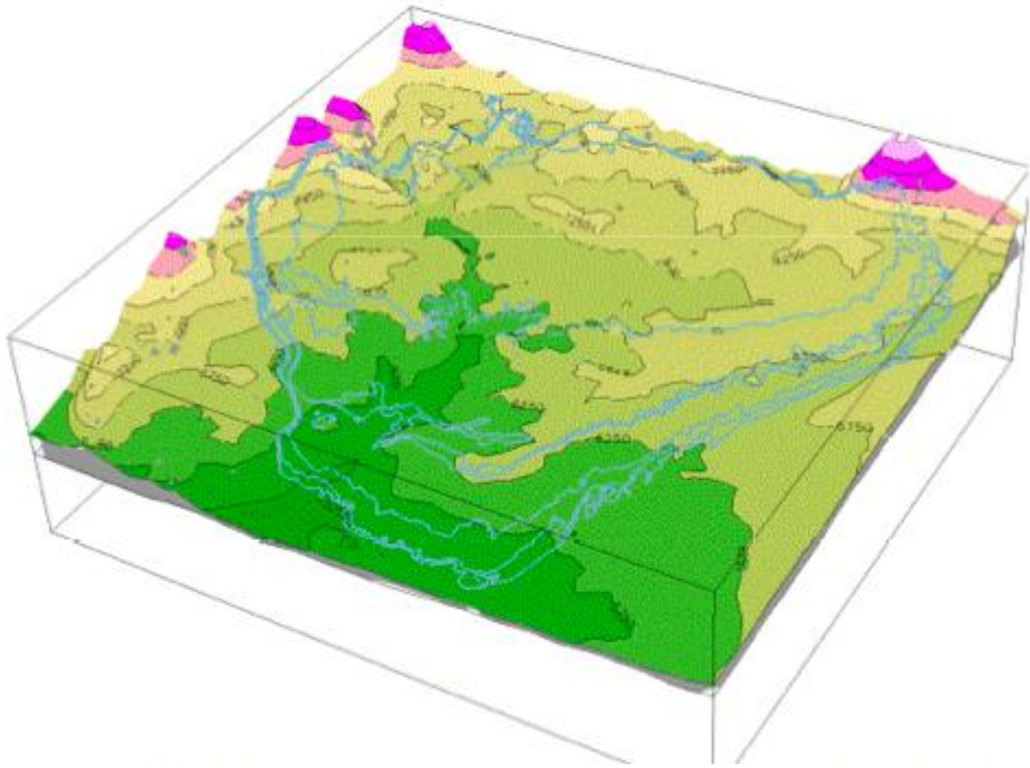
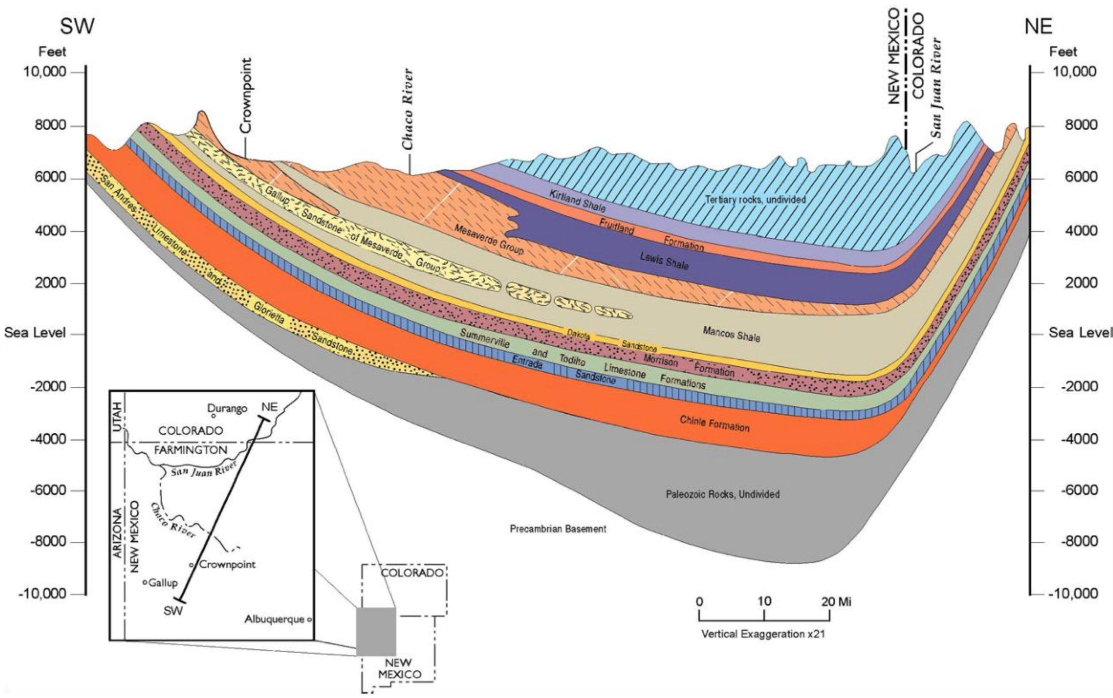


Figure 2.6 - Topography of the San Juan Basin modeled to the bottom of the Pictured Cliffs Sandstone and superimposed on vertically exaggerated 3-D surface topographic contours (AHA, 2000). The Fruitland Formation outcrops to the north at elevations around 9,000ft and drops to an elevation of around 6,000ft by the Colorado-New Mexico state line to the south.



Figuire 2.7 – Cross-section of the San Juan Basin as presented by State Engineer Dick Wolfe at a public meeting in Bayfield, CO on February 2, 2010 (original author of the cross-section unknown). The Northern San Juan Basin takes up but a fraction of the right side of the image – where the sedimentary layers dip steeply at the northeastern end of the cross-section. The Fruitland Formation is the third stratigraphic layer below ground surface (a salmon color), below the Kirtland Shale (light purple) and undivided Tertiary rocks (hashed light blue), and above the Lewis Shale (dark purple).

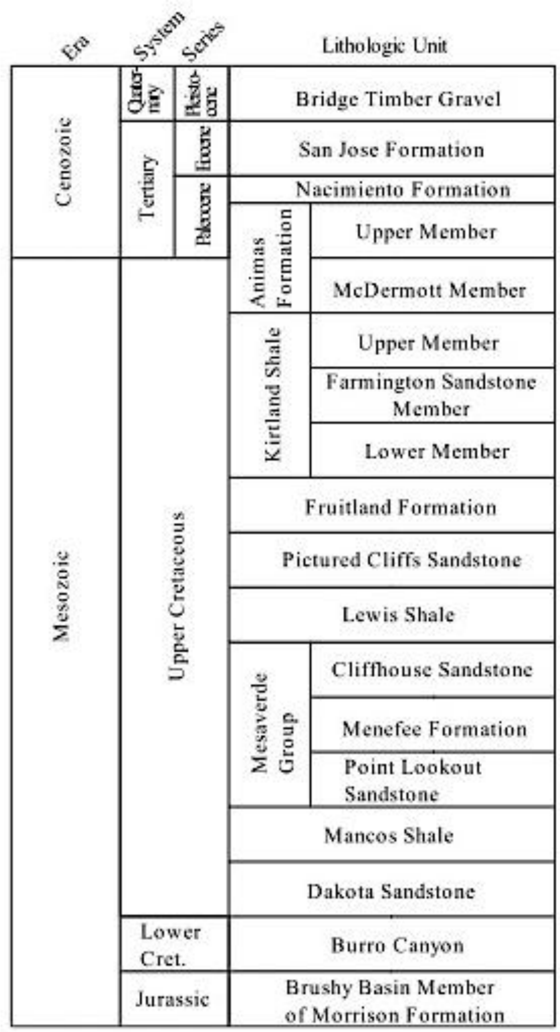


Figure 2.8 – Simplified stratigraphic column of Cretaceous-era and younger formations of the San Juan Basin. The Fruitland Formation is an Upper Cretaceous coal confined along with the Pictured Cliffs Sandstone by shale layers below (Lewis Shale) and above (Kirtland Shale) (Riese, 2005).

Figure 2.9 – Recreation of the Western Interior Seaway (Papadopulos, 2006), which deposited organic matter that would become Fruitland Formation coal as well as sediment that would become Pictured Cliffs and other sandstones as its shoreline ebbed and flowed during the Late Cretaceous.

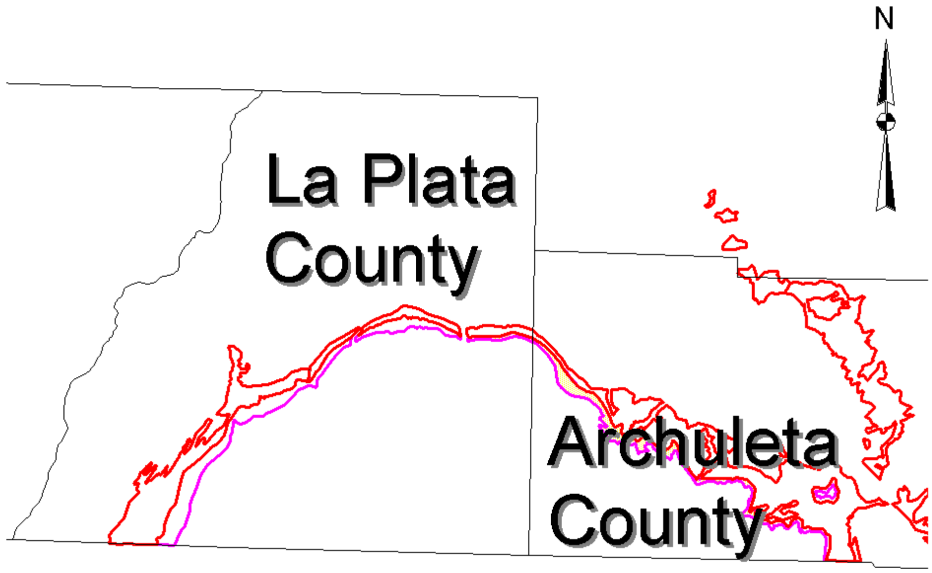


Figure 2.10 – The outcrops of the Fruitland Formation (red) and the associated Pictured Cliffs Sandstone (pink) extend in an arc nearly 85 miles long (Questa, 2001) through La Plata County and Archuleta County in southwestern Colorado. In terms of surface area, the Fruitland Outcrop spans approximately 8,900 acres in La Plata County and 9,900 acres in Archuleta County (Norwest, 2009). The Fruitland Outcrop's width is as narrow as 65 meters in La Plata County and as wide as 1.4 km in Archuleta County (Carroll et al., 2009).

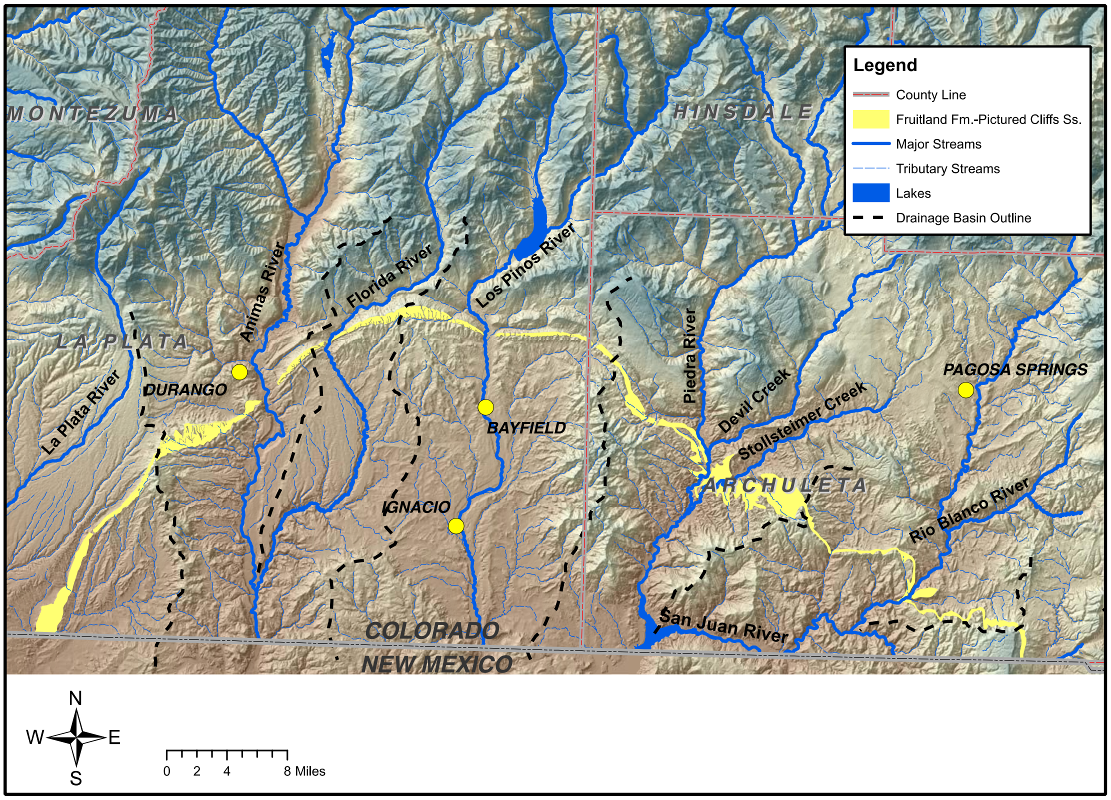


Figure 2.11 – Five major rivers cross the Fruitland Outcrop, as pictured here by Papadopulos (2006). From west to east, they are the Animas River, Florida River, Pine (or Los Pinos) River, Piedra River, and Rio Blanco River.

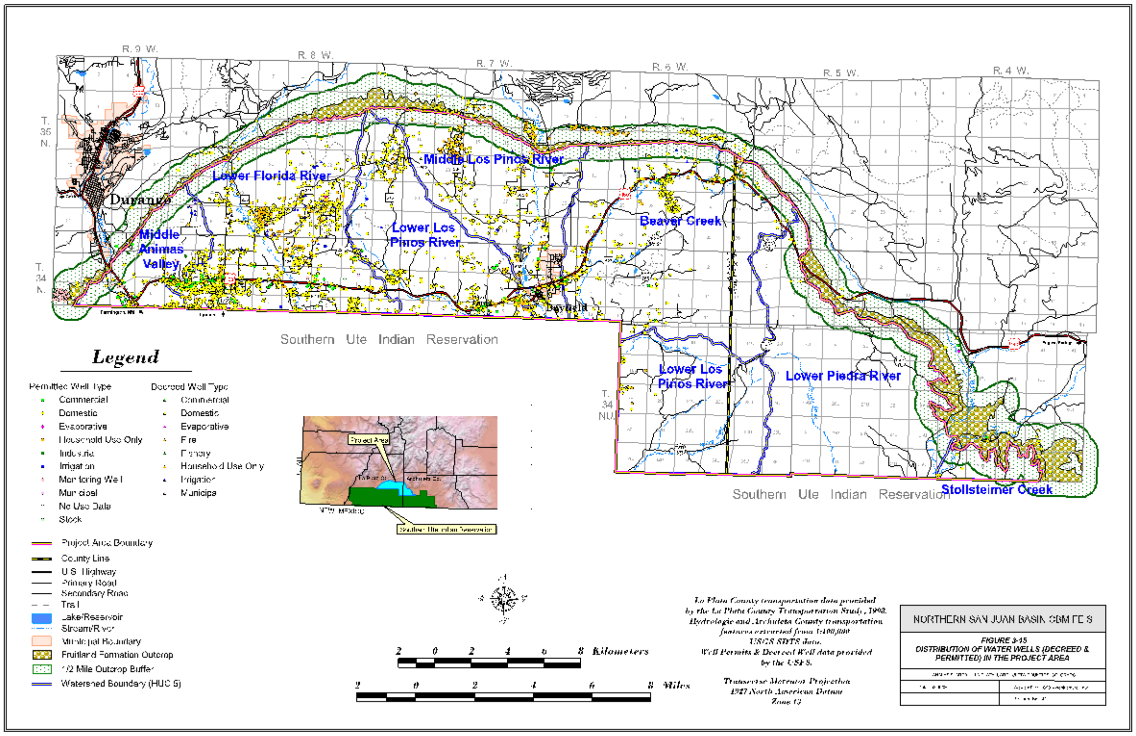


Figure 2.12 – Groundwater is a critical resource for residents of the Northern San Juan Basin. This figure shows domestic water wells across the NSJB in yellow NSJB domestic water wells (SJPLC, 2006)

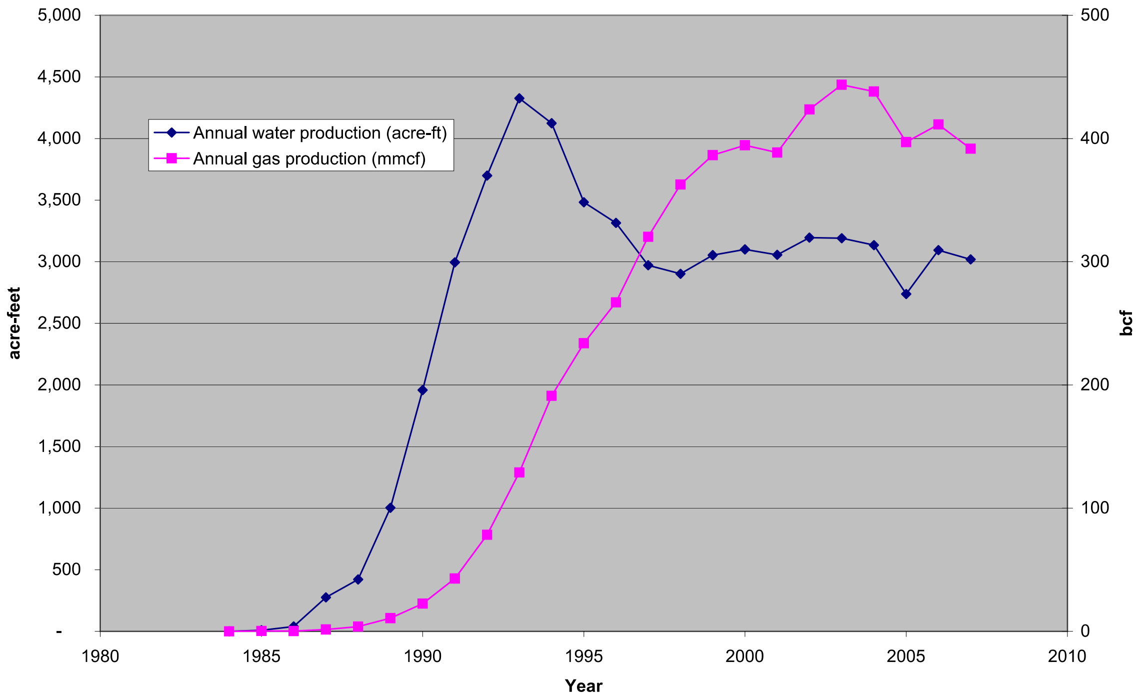


Figure 2.13 – Extraction of coalbed methane requires depressurization of water-saturated coal seams, done primarily by removing groundwater. Water production varies by CBM well, but it is typical for a CBM well to produce much more water than gas during the early part of its life. Water production in the San Juan Basin peaked in 1993 at over 4,300 af/y and has steadied at around 3,000 af/y in the years since (Norwest, 2009).

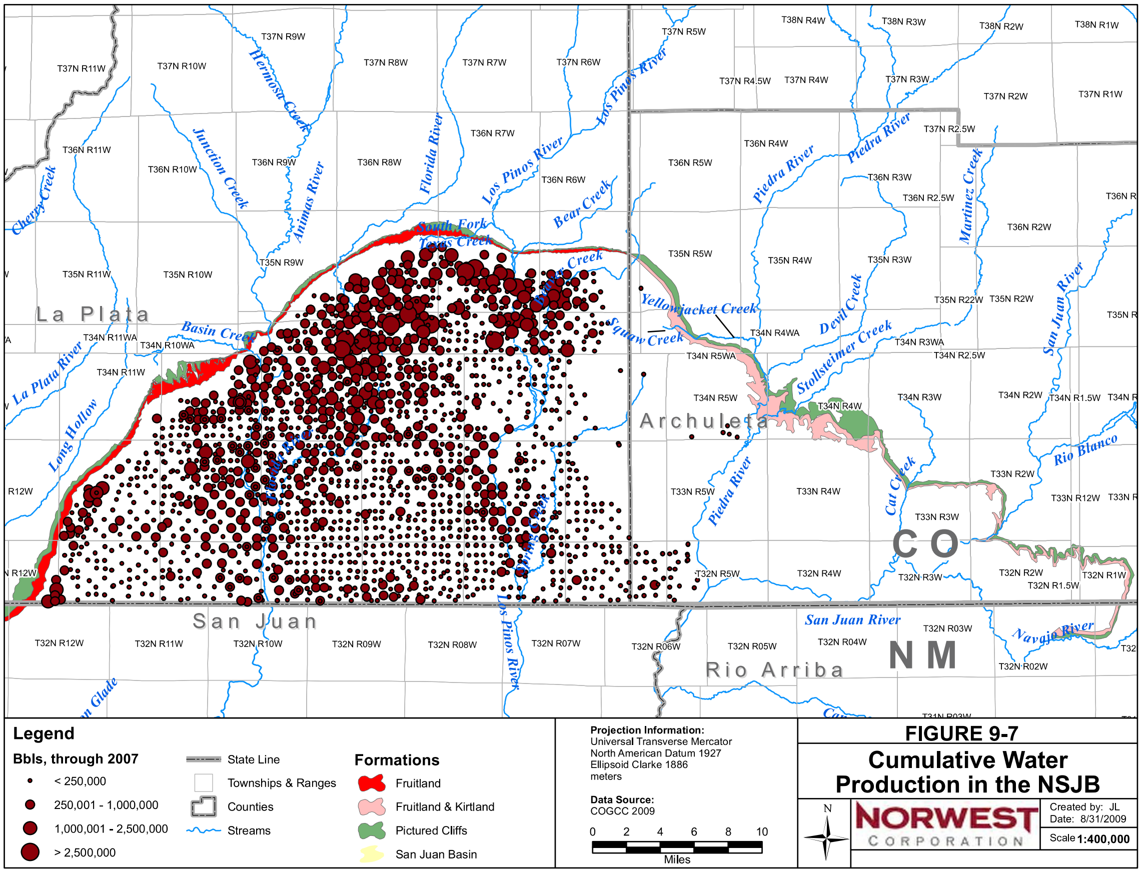


Figure 2.14 – Water production varies by well and location. As can be seen in this figure of cumulative water production , the wells producing the most groundwater tend to be closer to the Fruitland Outcrop (Norwest, 2009).

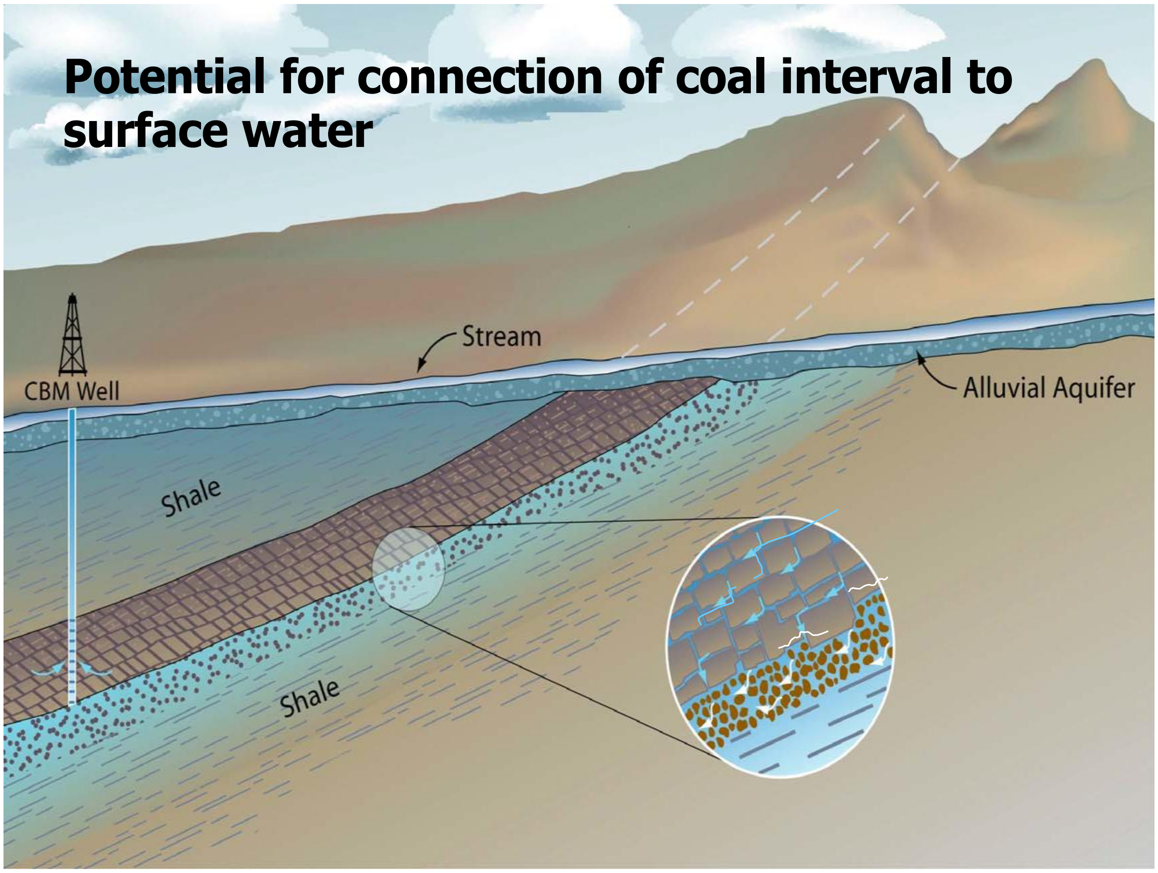


Figure 2.15 – Cross-section displaying the potential linkage between the Fruitland Formation coals/Pictured Cliffs Sandstone and alluvial aquifers/streams as they cross the Fruitland Outcrop. Image was presented by State Engineer Dick Wolfe in public meetings on the Division of Water Resources stream depletion study in 2005.

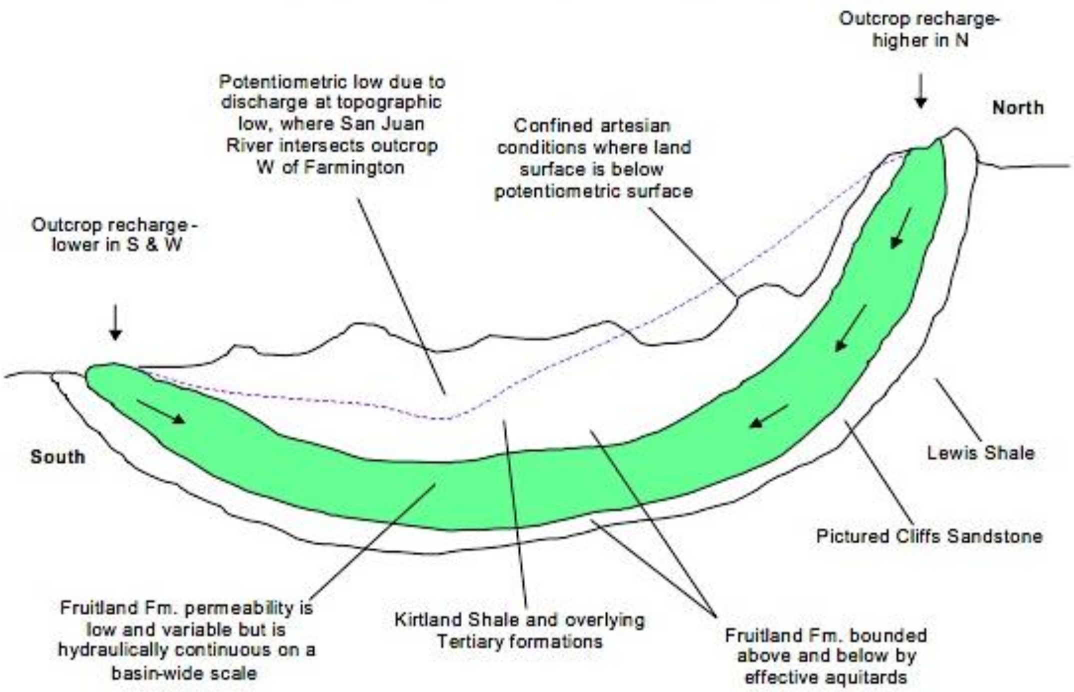


Figure 2.16 – Hydraulically Connected Basin conceptual model, as sketched by Applied Hydrology Associates (2000). Under this conceptual model recharge at the topographic high point of the Fruitland Outcrop, where the Fruitland Formation (in green) is unconfined, moves basinward via primary flowpaths to discharge at rivers and springs at lower points along the Outcrop and via secondary flowpaths into the deep basin. Deep flowpaths ultimately discharge at the San Juan River west of Farmington, New Mexico.

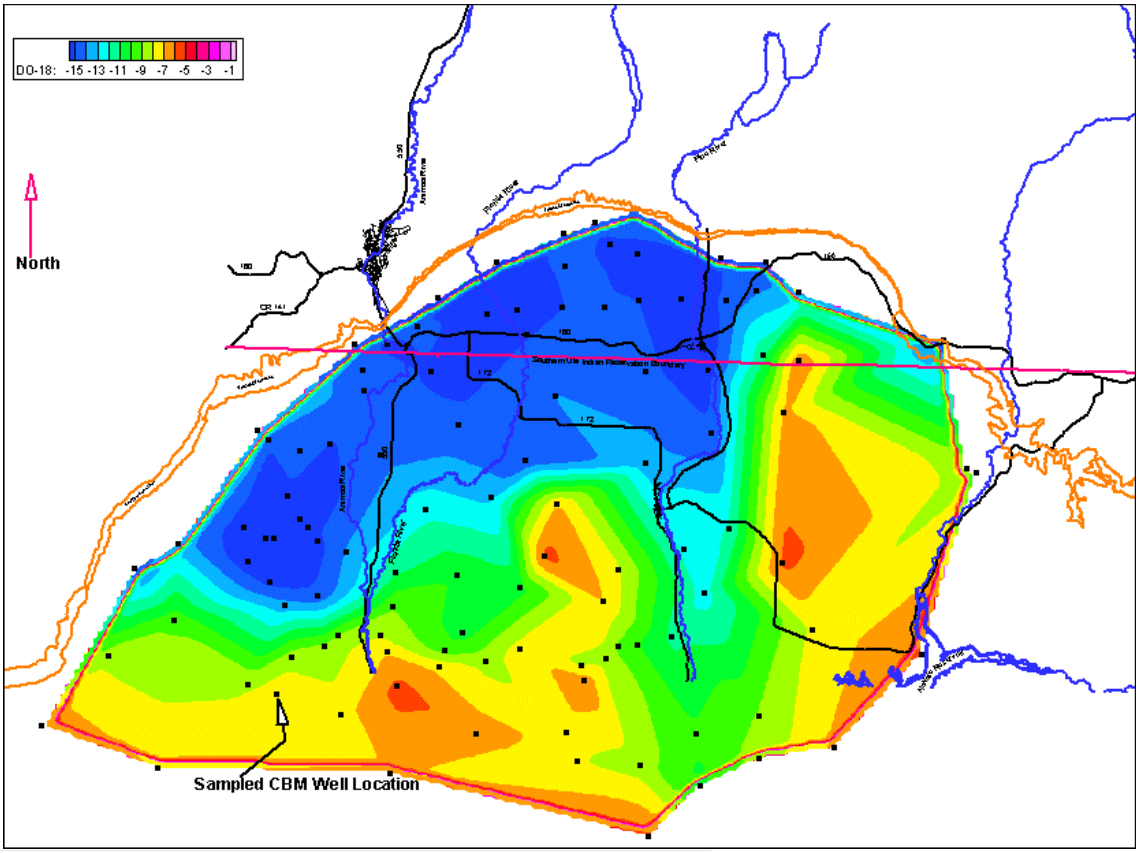


Figure 2.17 – Map of Oxygen-18 concentrations in coalbed methane produced water in the Northern San Juan Basin, as compiled by Applied Hydrology Associates (2000). The isotopic signature of produced water is lighter (more depleted in the heavy isotope of oxygen) for about 10 mi basinward from the Fruitland Outcrop ($\delta^{18}O$ of -15‰ to -13‰), suggesting meteoric recharge.

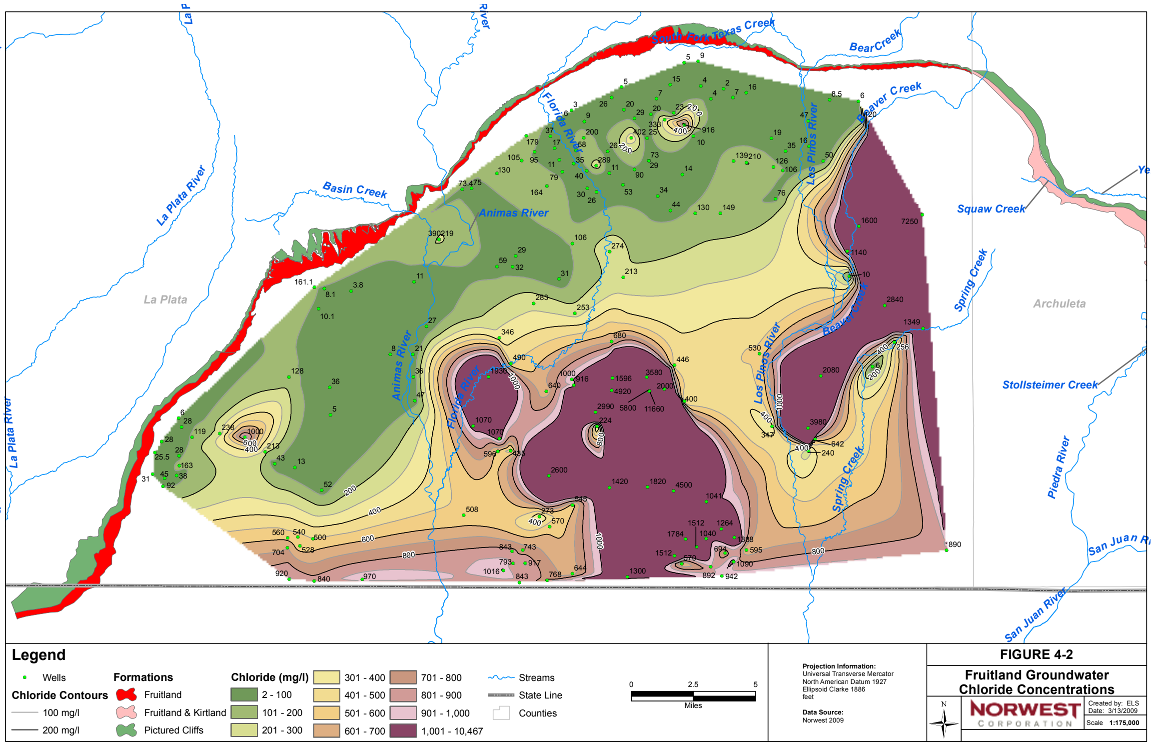


Figure 2.18 – Map of chloride concentrations developed by Norwest (2009) using 3M Project data updated since 1999 with 180 new data points. Chloride concentrations are lowest near the Fruitland Outcrop (green) and increase basinward, suggesting that the Outcrop is a recharge point and groundwater moves into the deep basin via preferential flowpaths shown by relatively lighter chloride concentrations (beige).

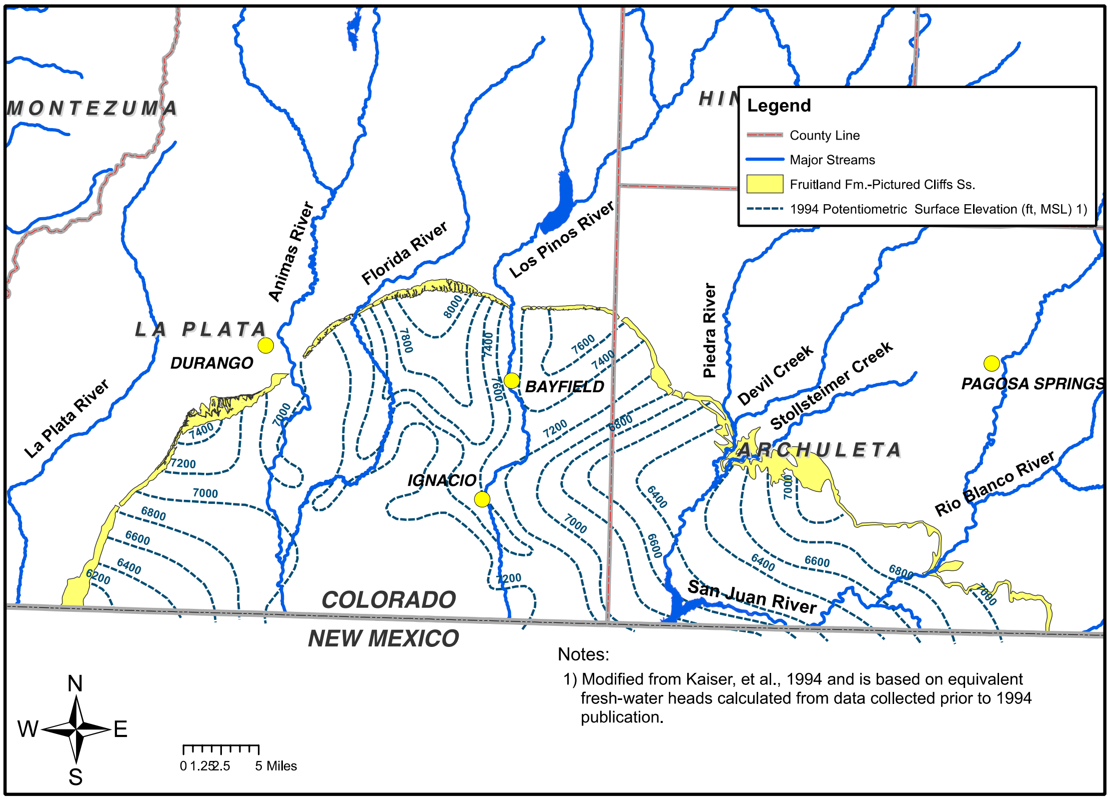


Figure 2.19 – Map of the potentiometric surface in the Northern San Juan Basin in 1994, as mapped by Kaiser et al. (1994) and reproduced by Papadopulos (2006). The smoothly changing pressure gradient with high points at the Fruitland Outcrop (~8,000 ft) and low points at the state line (~6,000ft) led Kaiser et al. to conclude that the Fruitland Formation is a "single hydrologic unit" at the regional scale.

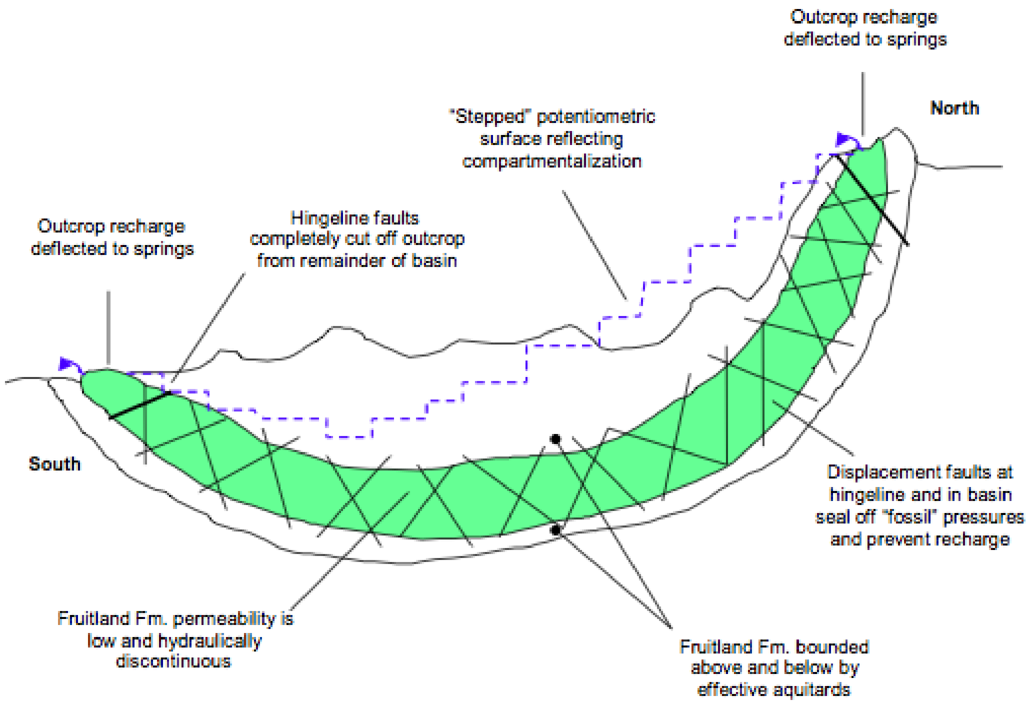


Figure 2.20 – Compartmentalized Basin conceptual model, as sketched by Applied Hydrology Associates (2000). Under this model, hingeline faults and shingled coal stratigraphy serve as no-flow boundaries that prevent recharge at the Outcrop from flowing into the deep basin. Recharge is deflected to springs; it does not discharge to rivers. Groundwater in the Fruitland Formation is connate water trapped during the uplift of the basin and exists under pressures – "fossil" heads – from that time period, sealed in place by flow barriers and low permeability shale layers. The model is characterized by discontinuity and lack of regional groundwater flow.

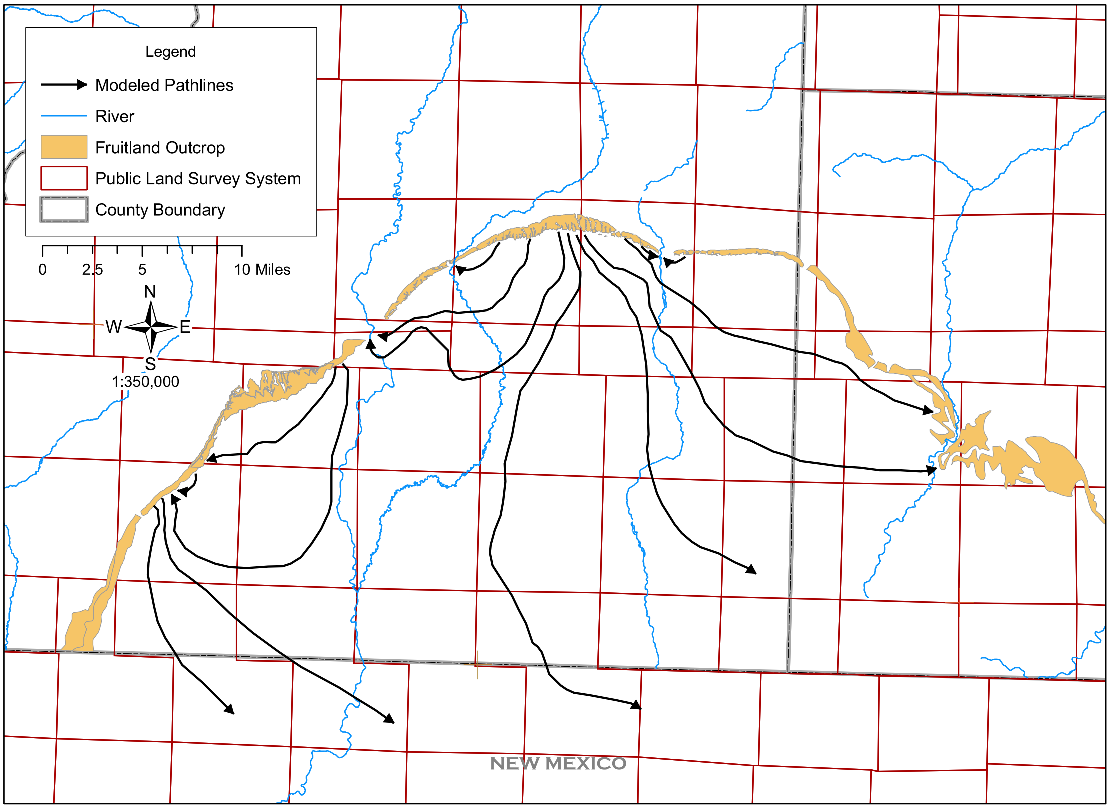


Figure 5.3. Modeled 100,000 year Flow Pathlines (modified from AHA, 2000)

Figure 2.21 – Northern San Juan Basin groundwater flowpaths modeled by Applied Hydrology Associates (2000). Recharge at the Outcrop flows via primary flowpaths that discharge to streams and secondary flowpaths into the deep basin. Flowpaths were modeled following the Hydraulically Connected Basin conceptual model, after the Compartmentalized Basin conceptual model failed to calibrate to field observations.

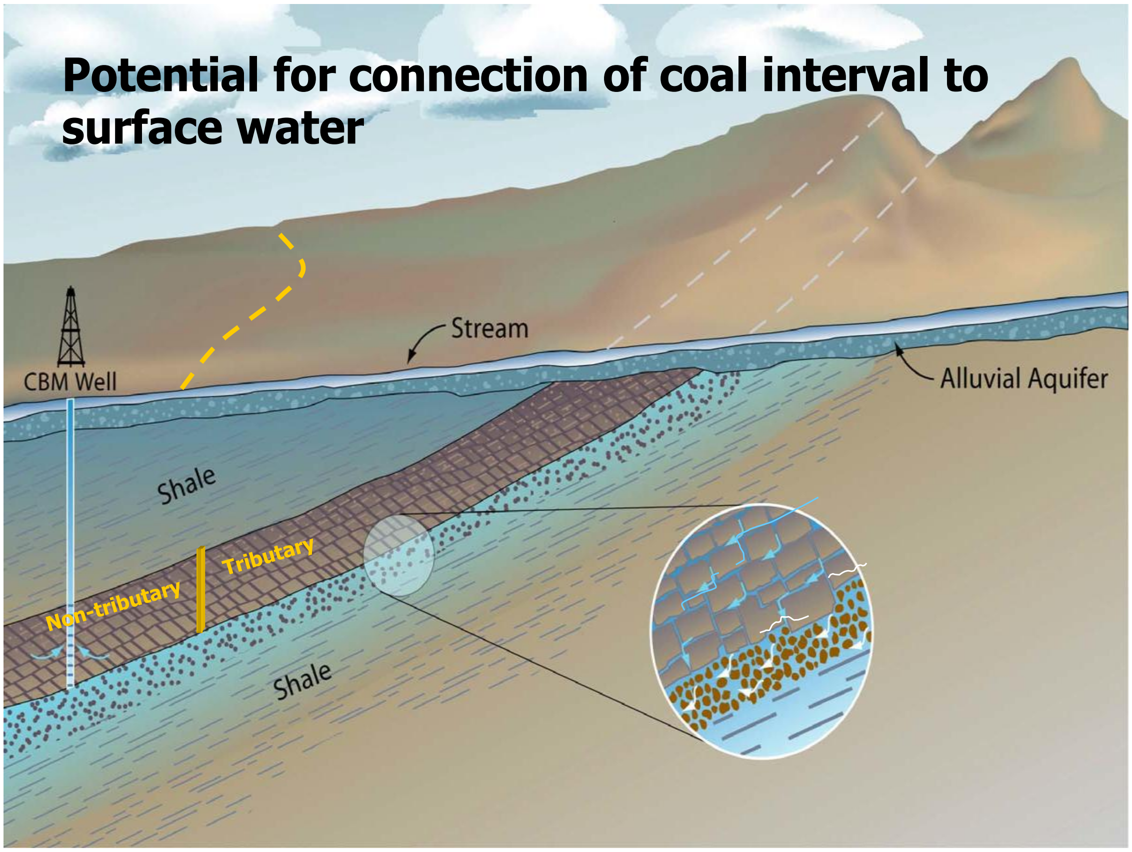


Figure 2.22 – Schematic of the tributary/non-tributary groundwater boundary (yellow) in the Fruitland Formation as presented by the State Engineer Dick Wolfe in an Oct. 24, 2005 public meeting on the Division of Water Resource's stream depletion study. Generally speaking, under this conceptual model of regional groundwater flow, groundwater on the non-tributary side of the line would not impact surface water features if removed, whereas groundwater on the tributary side of the line would be expected to deplete rivers if removed.

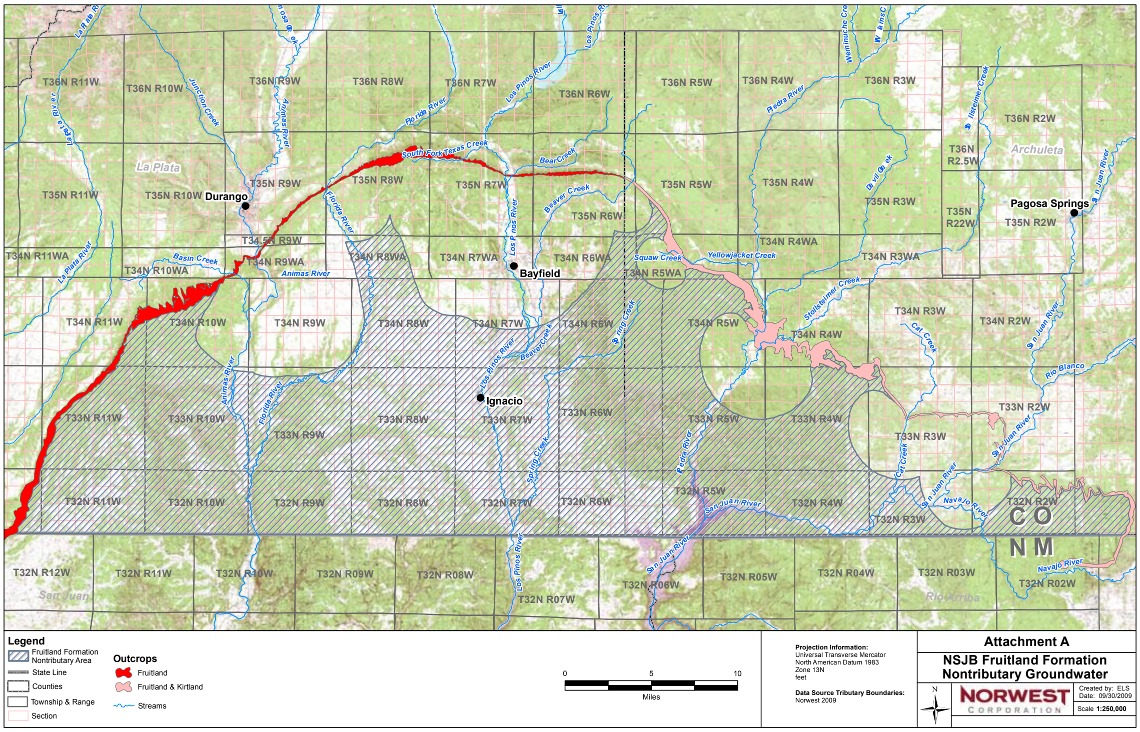


Figure 2.23 – Map of tributary/non-tributary groundwater zones of the Fruitland Formation as produced by the Norwest 2009 modeling effort on behalf of the Southern Ute Indian Tribe, BP American Production Corp., Chevron U.S. A. Inc., ConocoPhillips Co., XTO Energy Inc., and others. Fruitland Formation non-tributary groundwater zones, as modeled by Norwest, are shaded in blue. Tributary groundwater zones appear near the Fruitland Outcrop and along the major river drainages crossing the Outcrop.

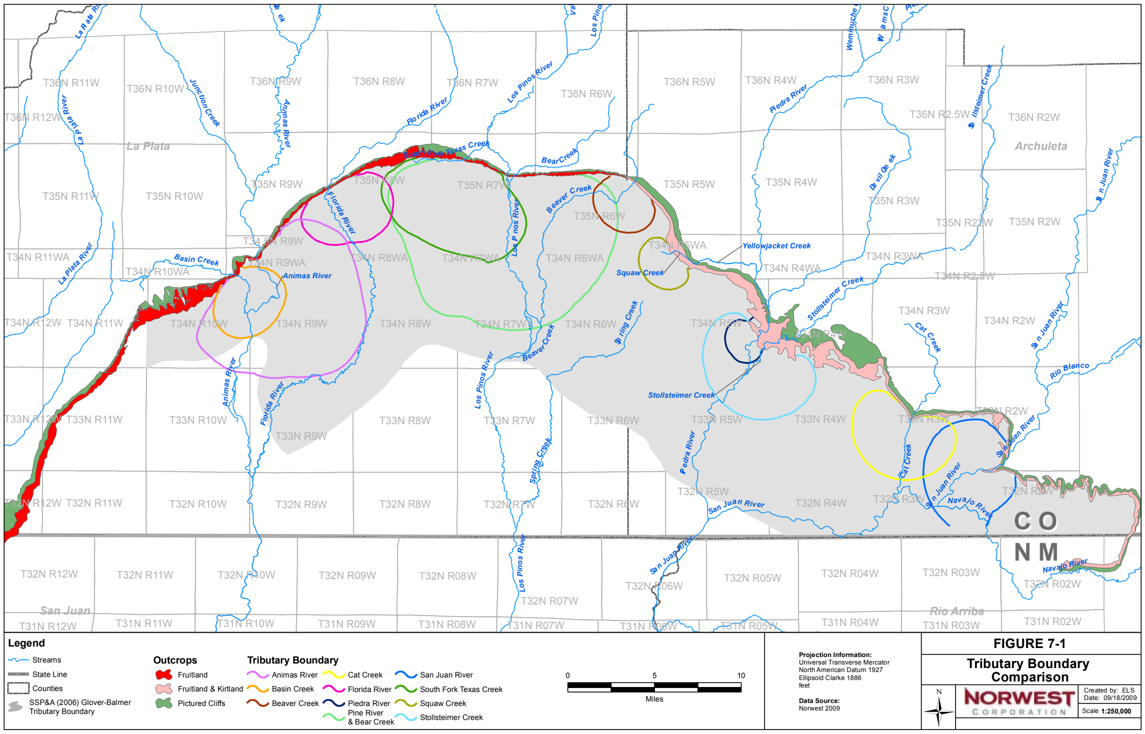


Figure 2.24 – Norwest's tributary/non-tributary boundaries derived from their regional groundwater modeling project (2009) superimposed on the tributary/non-tributary boundaries derived from the Papadopulos stream depletion assessment (2006) using the Glover Balmer analytical method. The Papadopulos tributary/non-tributary boundary (in grey) is 10.5 mi from the Fruitland Outcrop, whereas the Norwest boundary extends about 8 mi from the Outcrop along the Animas and Pine rivers, 4 mi from the Outcrop at the Florida, Piedra, and San Juan rivers, and 0 mi from the Outcrop elsewhere.

CHAPTER 3 FIGURES

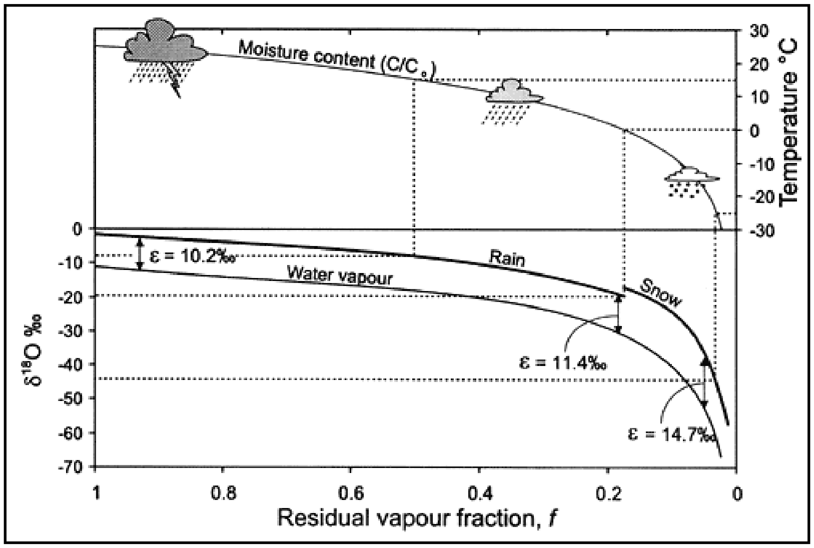


Figure 3.1 – Change in the δ^{18}O content of precipitation as a function of temperature and residual vapor fraction (fraction of original moisture remaining in cloud) (Clark & Fritz, 1997).

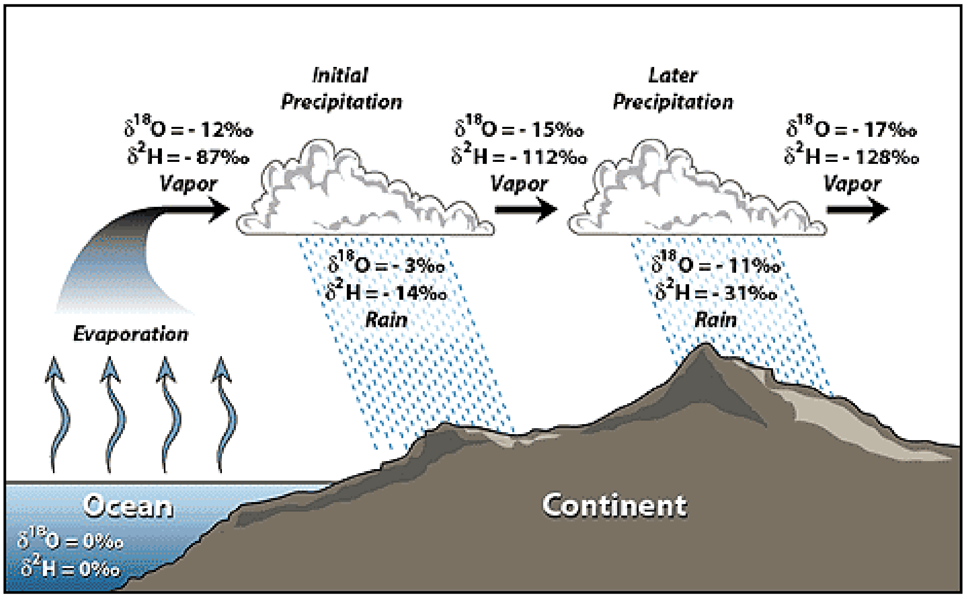


Figure 3.2 – Rainout effect on $\delta^{18}O$ and $\delta^{2}H$ values based on Hoefs (1997) and Coplen & Kendall (2000).

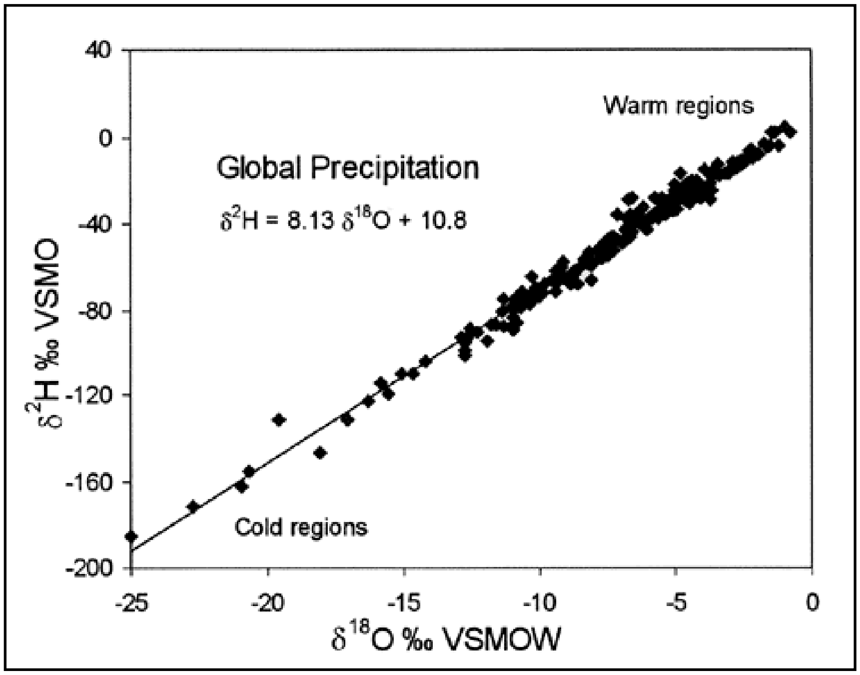


Figure 3.3 – Compilation of average annual values of $\delta^{18}O$ and δ^2H isotopes ($\delta^2H/\delta^{18}O$) as plotted against the GMWL for precipitation monitored at stations throughout the IAEA global network (Clark & Fritz, 1997, as compiled by Rozanski et al., 1993).

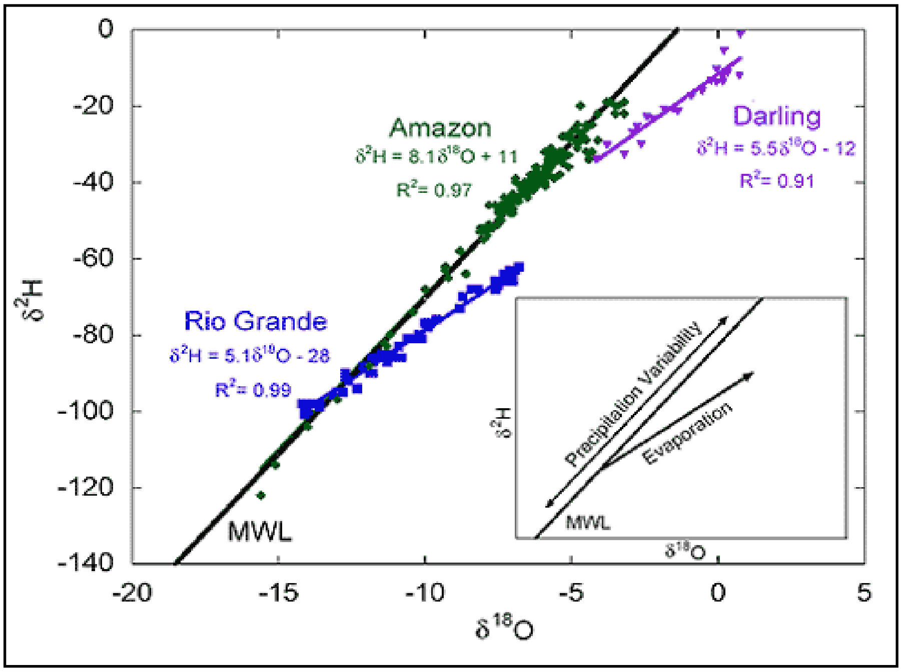


Figure 3.4 – Deviations from the Global Meteoric Water Line ($\delta^2H/\delta^{18}O$) due to evaporative effects. At very low relative humidities (< 25 percent) the slope of the evaporation line will be close to 4; for moderate relative humidities (25—75 percent) the slope will be between 4 and 5; only for relative humidities above 95 percent does the slope approach 8, the slope of the meteoric water line (Clark & Fritz, 1997).

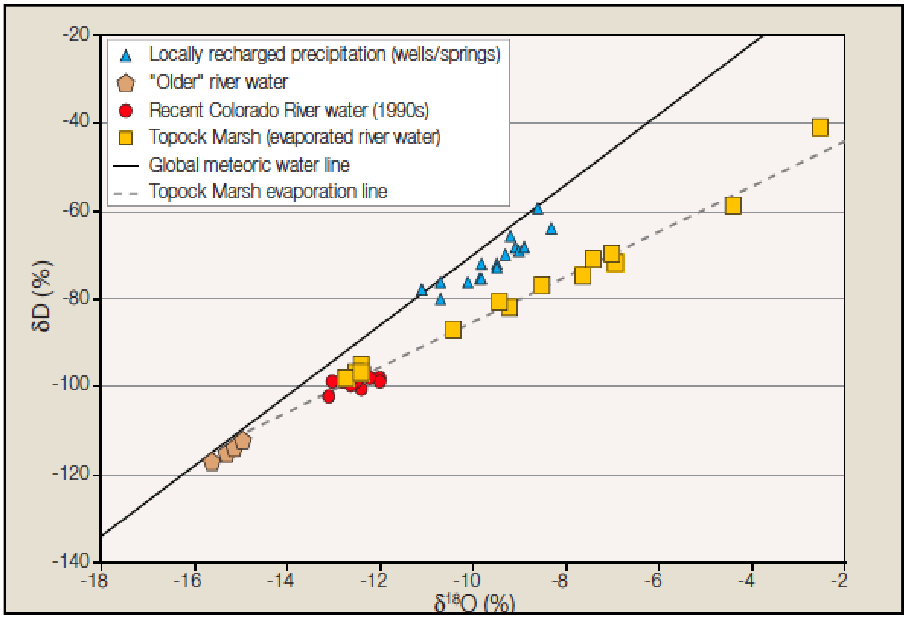


Figure 3.5 – Representative $\delta^2H/\delta^{18}O$ relationships from groundwater and surface water types collected in the 1990s in Mohave Valley, CA. Locally recharged samples came from wells and springs above river elevation and a few deeper wells on alluvial terraces. Local recharge is generally derived from winter rain, with δ^2H measuring about -71‰ (Friedman et al., 1992). Older Colorado River water has values similar to Upper Colorado River Basin river water, derived primarily from snowmelt (Wyman, 1997). Recent Colorado River samples were collected in Laughlin Nevada and near Needles California. The lower slopes of the recent Colorado River water and Toprock Marsh water are consistent with evaporated river water (Guay et al., 2008).

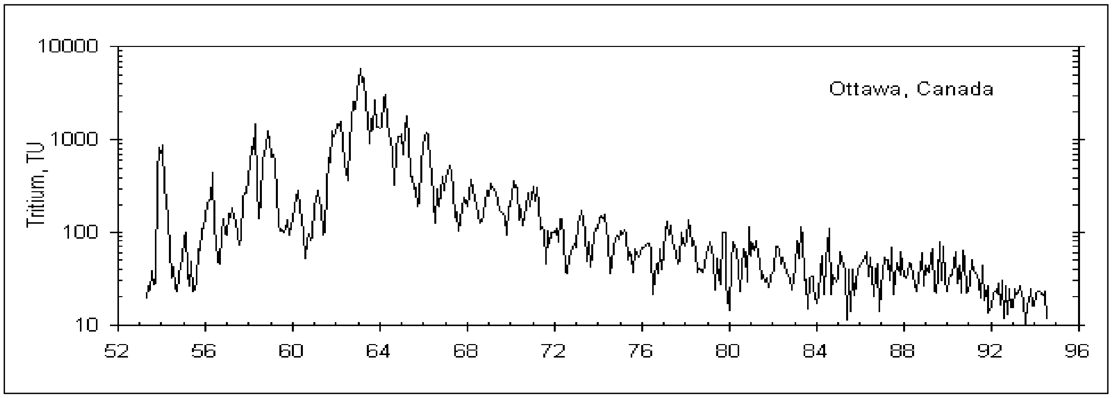


Figure 3.6 – Tritium concentrations in groundwater, with "bomb spike" effect apparent in the 1950s and 1960s. (Cordy et al., 2000).

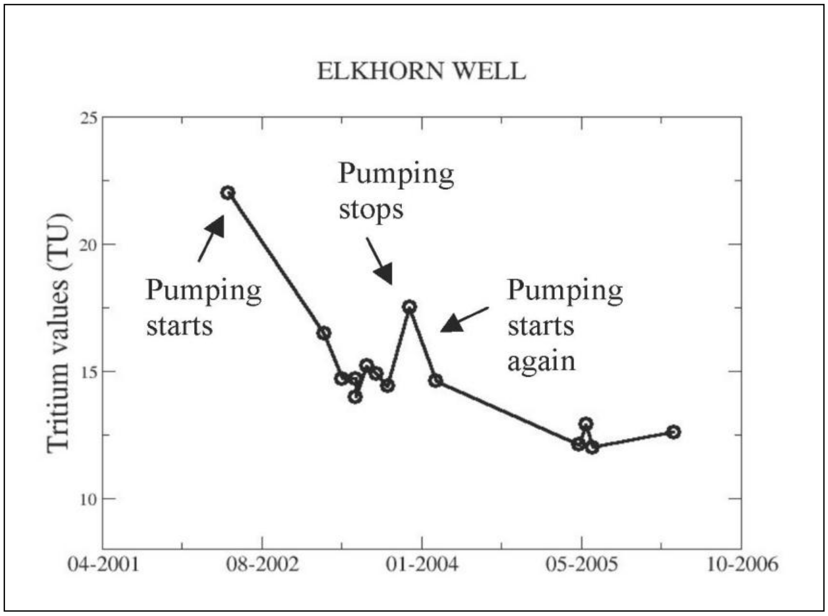


Figure 3.7 – A time series of tritium concentrations in the Elkhorn Well near Leadville Colorado, from Wireman et al. (2006). Initial values were about 23 TU, indicating a large contribution of bomb spike water to groundwater recharge. Once pumping began, tritium declined toward the concentration found in modern precipitation.

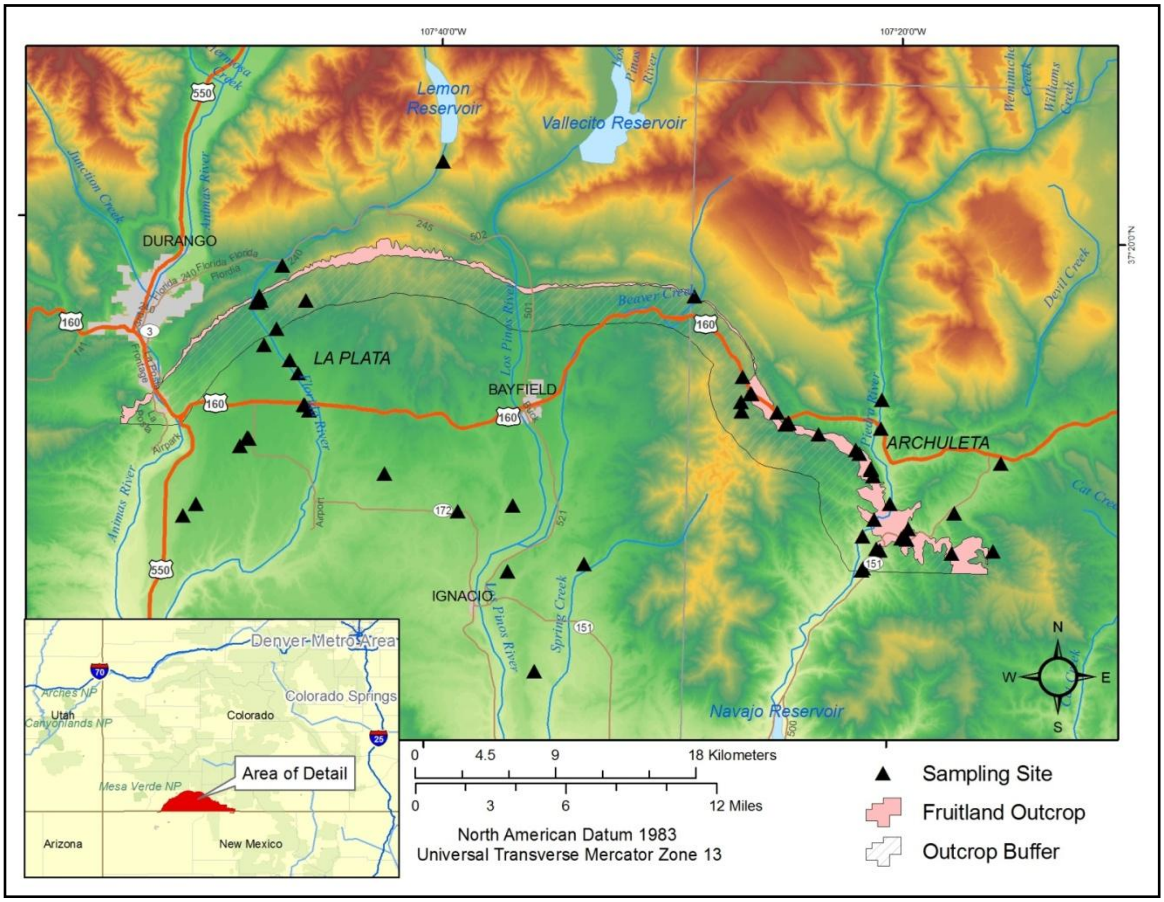


Figure 3.8 – The study area encompassed 1,750 km^2 in La Plata and Archuleta counties, where a total of 67 sites were sampled between fall of 2008 and spring of 2009.

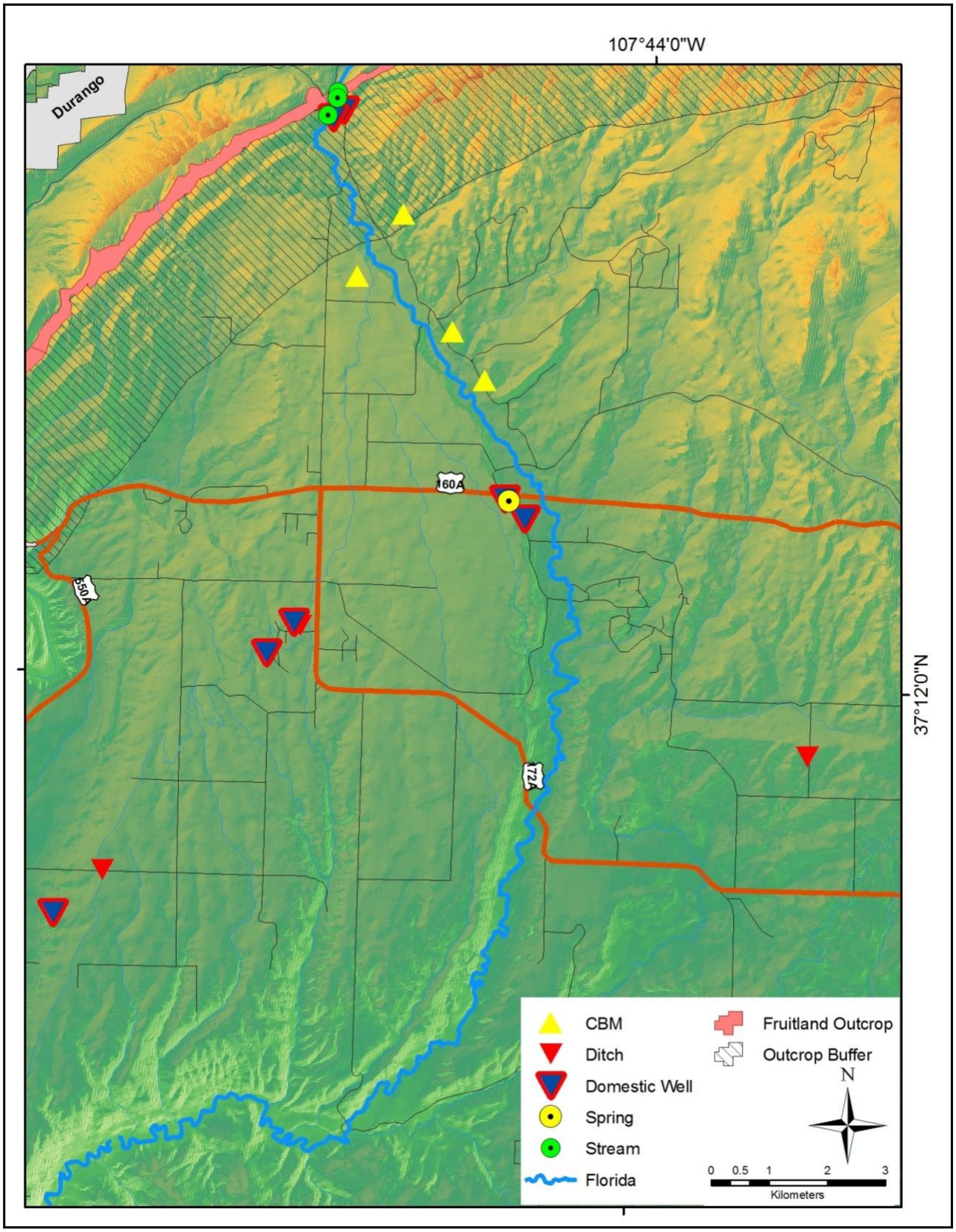


Figure 3.9 – Florida drainage sample sites and Fruitland Outcrop, with the Florida River at center. Please note that this map does not show the surface water sites near the Lemon Reservoir because of scale considerations; the sampling sites near the Lemon Reservoir are shown in Figure 3.8.

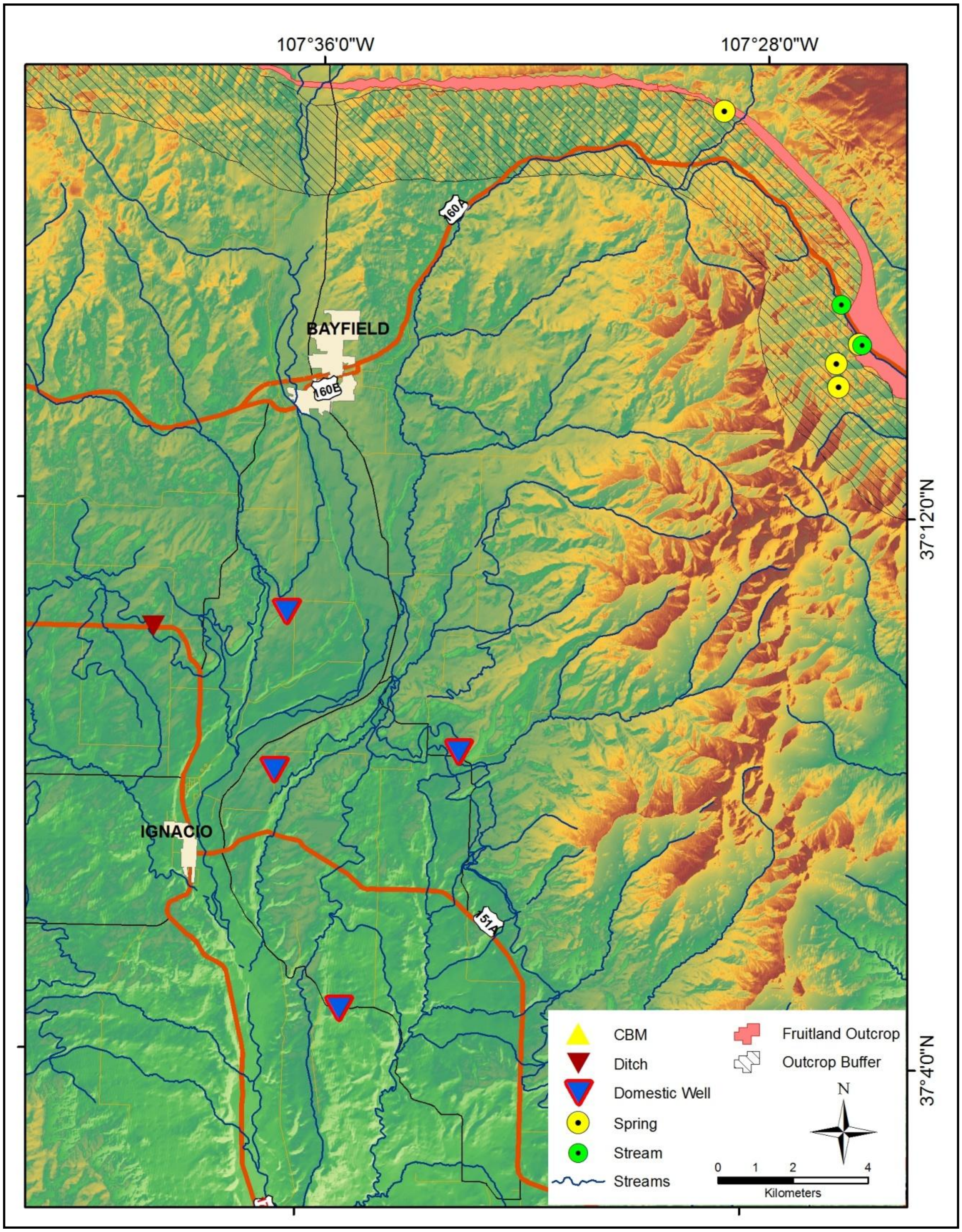


Figure 3.10 – Basin Interior region of the study area.

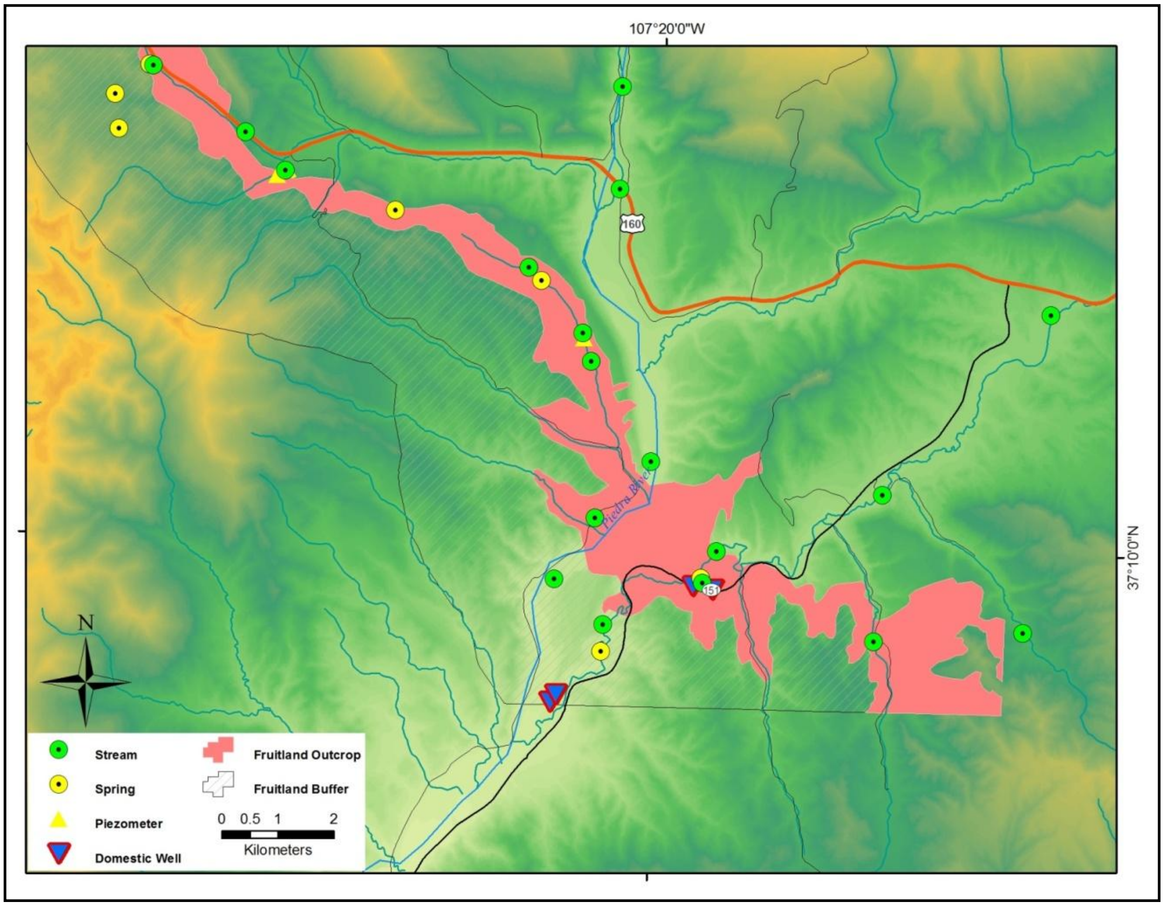


Figure 3.11 – Piedra drainage and Fruitland Outcrop, with Piedra River and tributaries at center (Stollsteimer, Archuleta, Cabezon Squaw, Little Squaw creeks; Fossett and Peterson gulches).

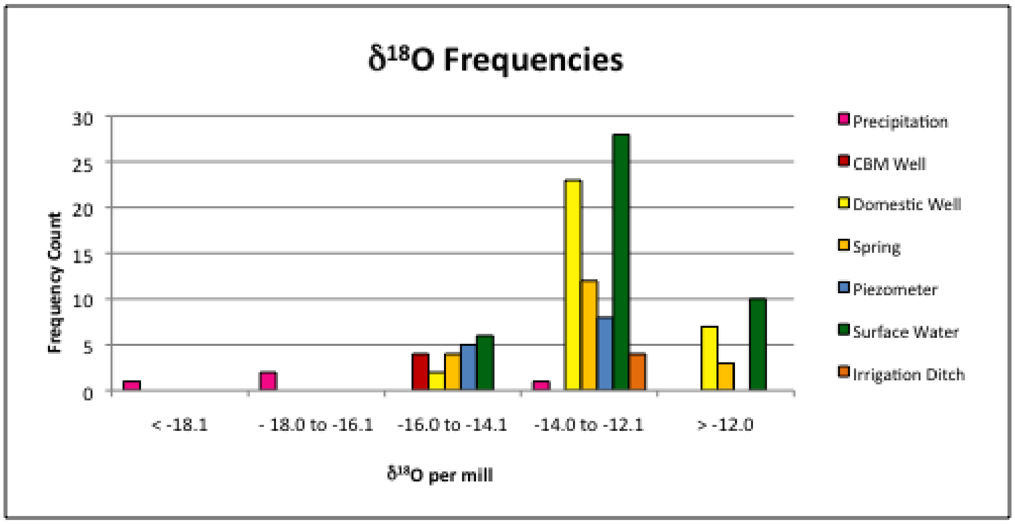


Figure 3.12 – Frequency analysis of $\delta^{18}O$ concentrations for all samples (n = 120), divided by water body.

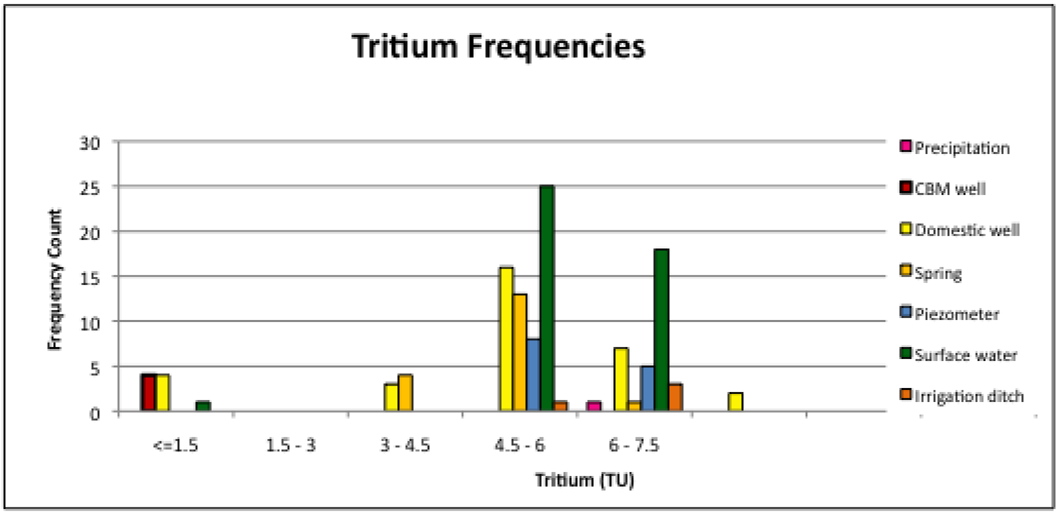


Figure 3.13 – Frequency analysis of tritium concentrations for all samples (n = 118), divided by water body.

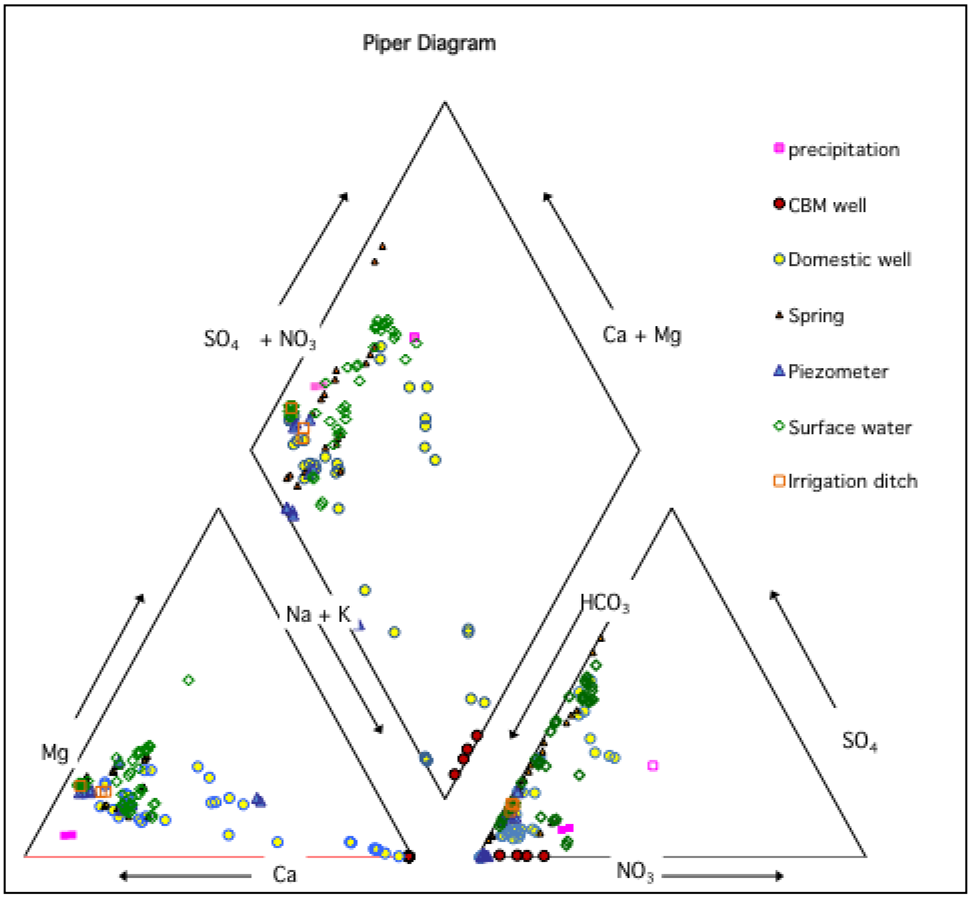


Figure 3.14 – Piper diagram of major cations and anion concentrations for all samples (n = 120), divided by water body.

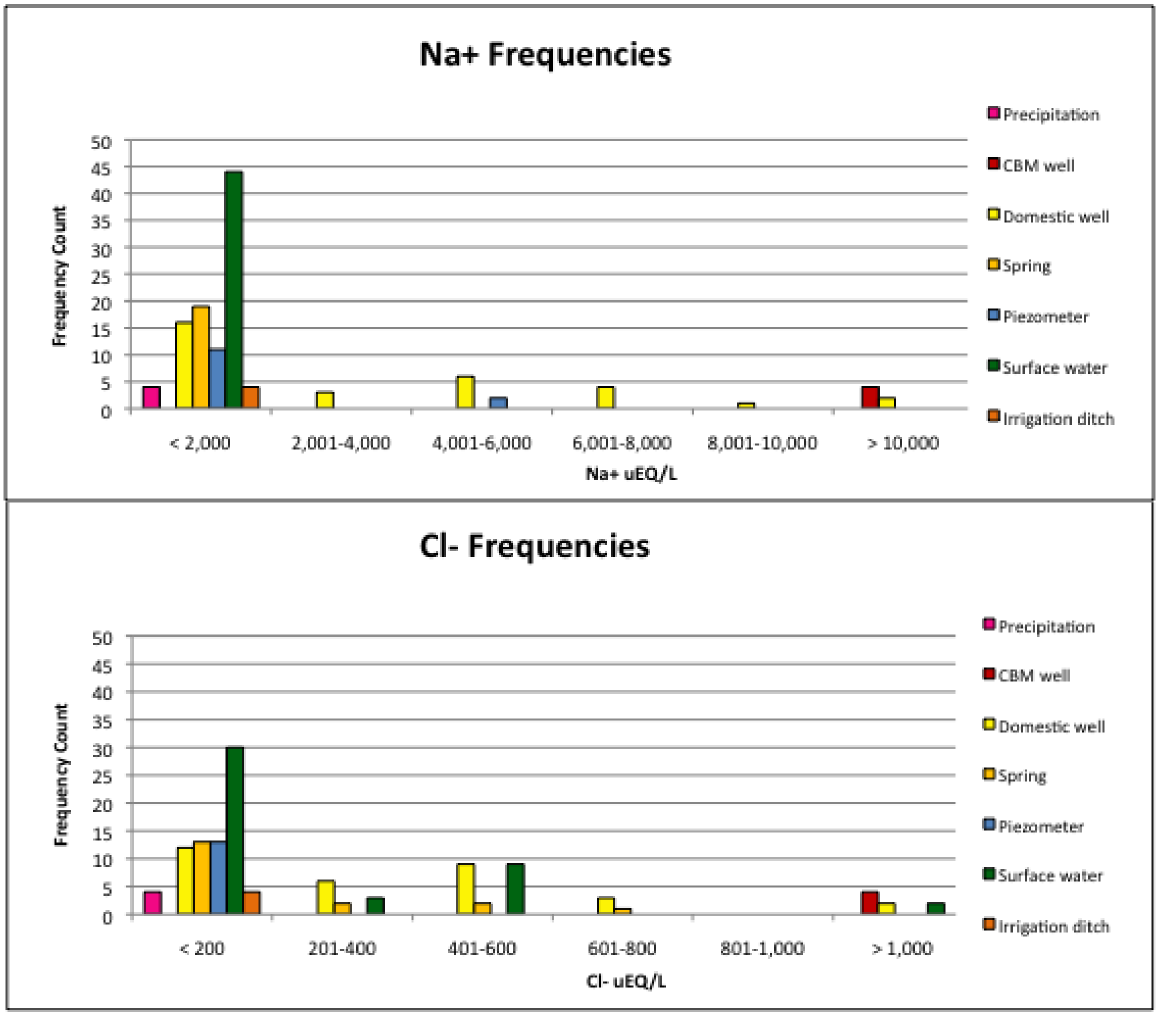


Figure 3.15 – Frequency analysis of sodium and chloride concentrations for all samples (n = 120), divided by water body. Note that horizontal axes differ by one order of magnitude, with sodium concentrations higher than chloride.

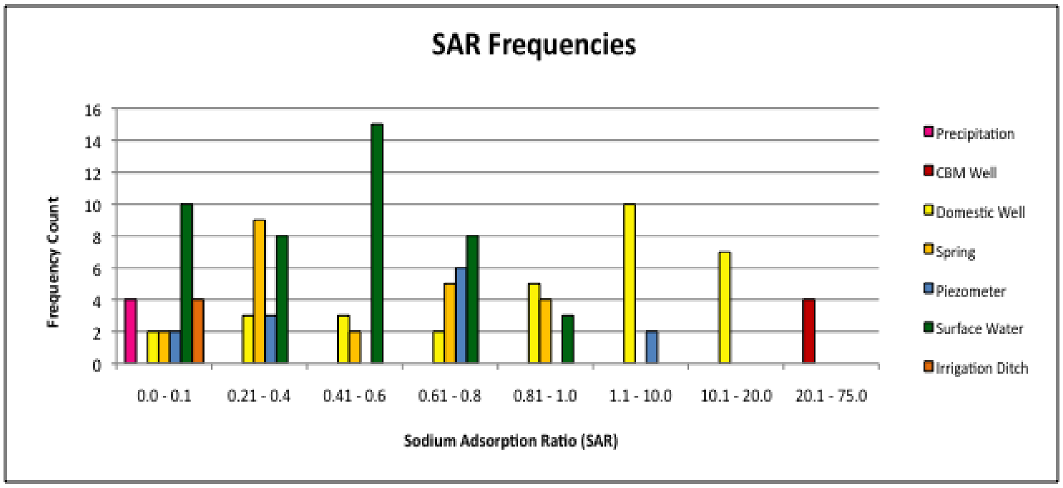


Figure 3.16 – Sodium adsorption ratios (SAR) for all samples (n = 120), divided by water body.

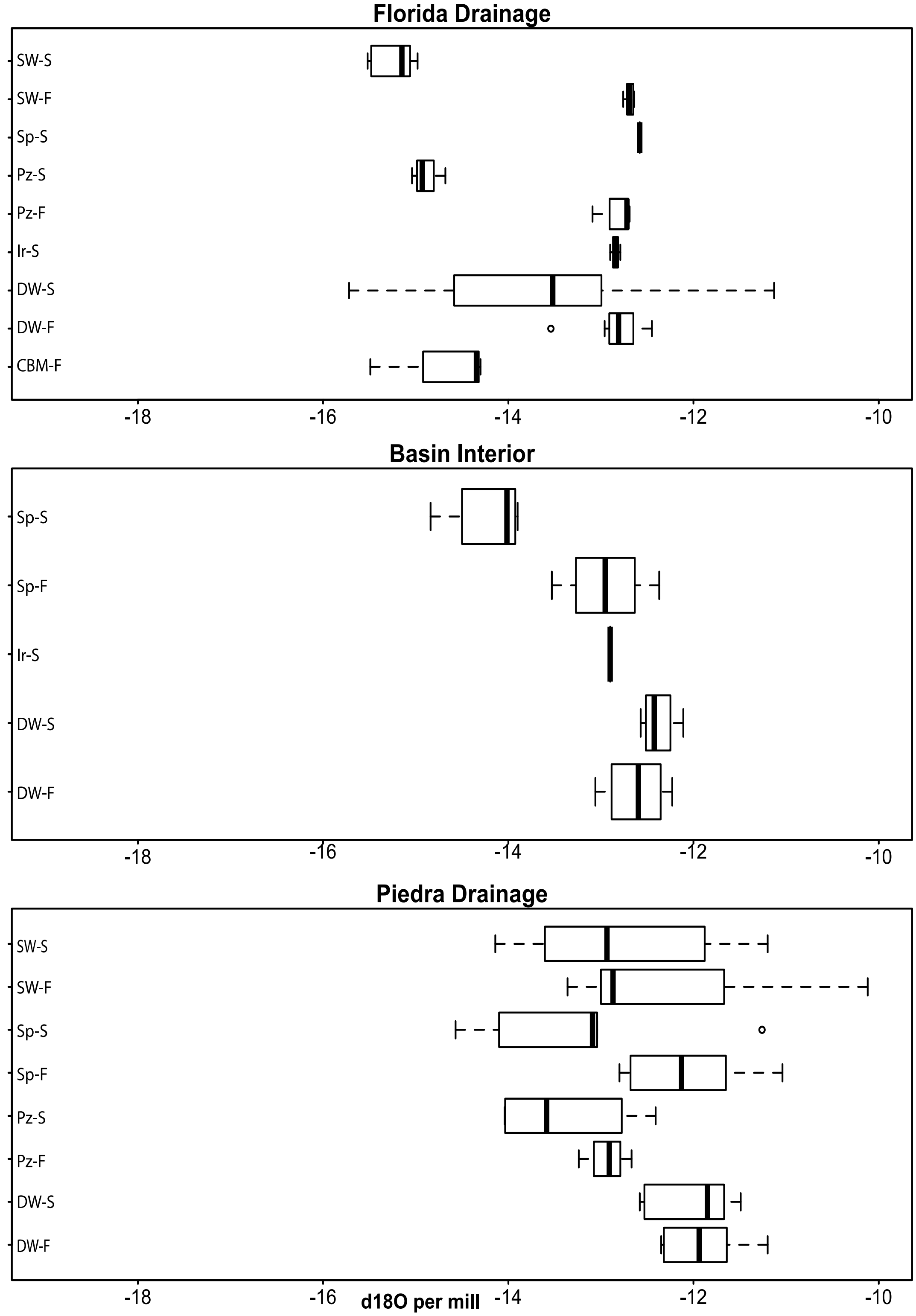


Figure 3.17 – Oxygen-18 concentrations across water sources in each major sampling region, divided by season: F=Fall, S=Spring; DW=Domestic Wells, Pz=Piezometers, Sp=Springs, SW=Surface Water, Pr=Precip, CBM=Coalbed Methane Wells.

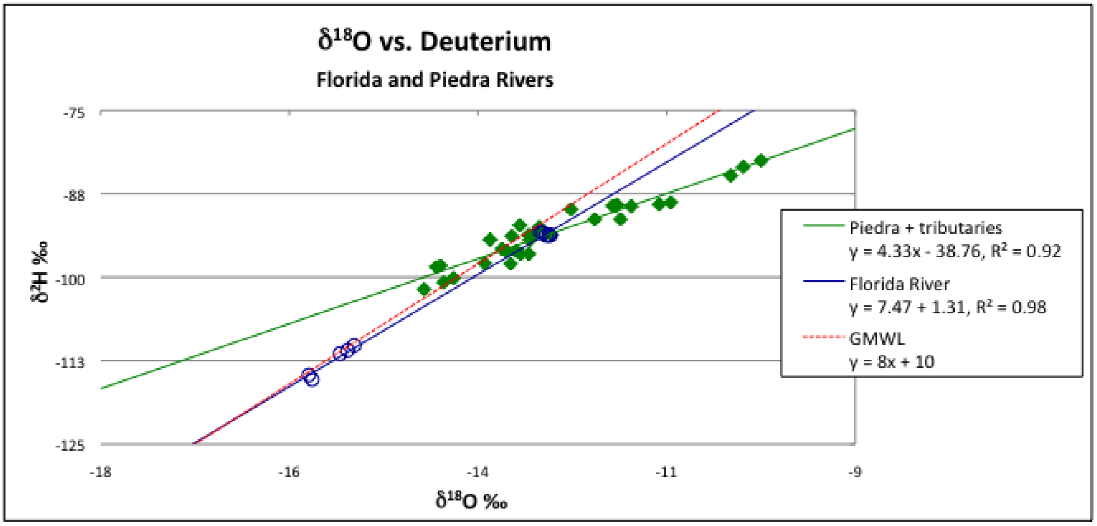


Figure 3.18 – $\delta^2H/\delta^{18}O$ plot for the Florida River and Piedra River plus tributaries (Stollsteimer, Archuleta, Cabezon Squaw, Little Squaw creeks; Fossett and Peterson gulches). Global Meteoric Water Line is presented in red for comparison.

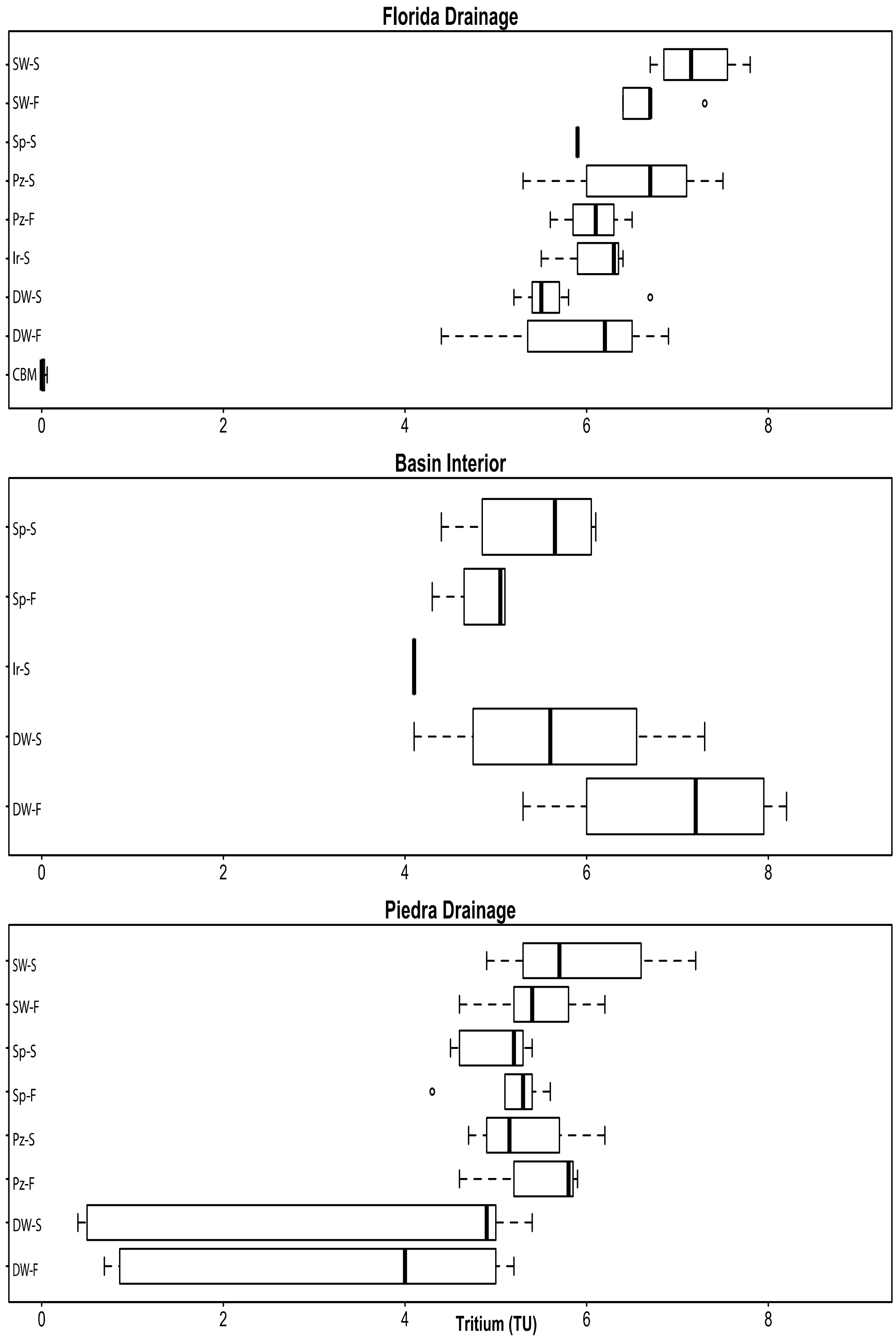


Figure 3.19 – Tritium concentrations across water sources in each major sampling region, divided by season: F=Fall, S=Spring, DW=Domestic Wells, Pz=Piezometers, Sp=Springs, SW=Surface Water, Pr=Precip, CBM=Coalbed Methane Wells.

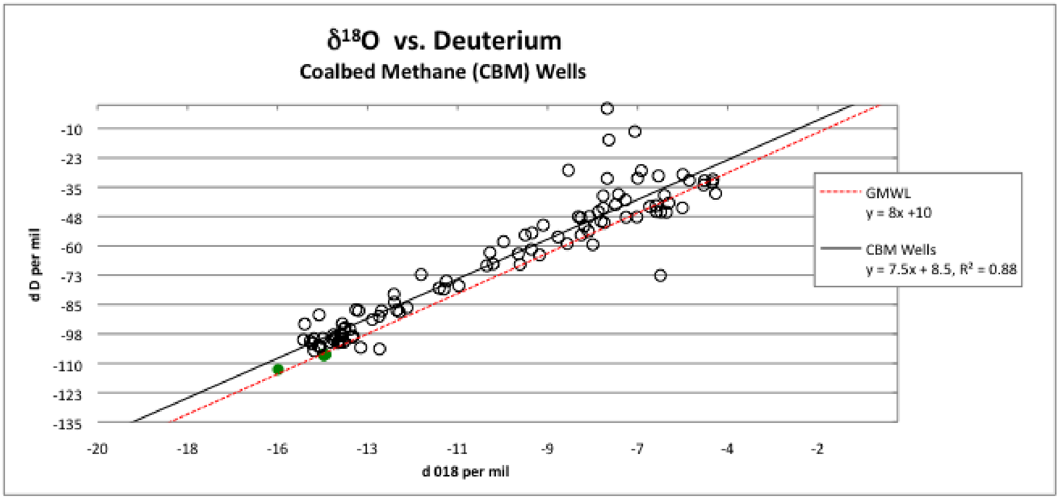


Figure 3.20 – $\delta^2H/\delta^{18}O$ plot for waters from coalbed methane wells. Green points are the CBM wells sampled by this study (n=4). Black points are CBM wells from the 3M Project (n=109). Global Meteoric Water Line is presented in red for comparison. The slope for CBM wells is similar to that of the GMWL.

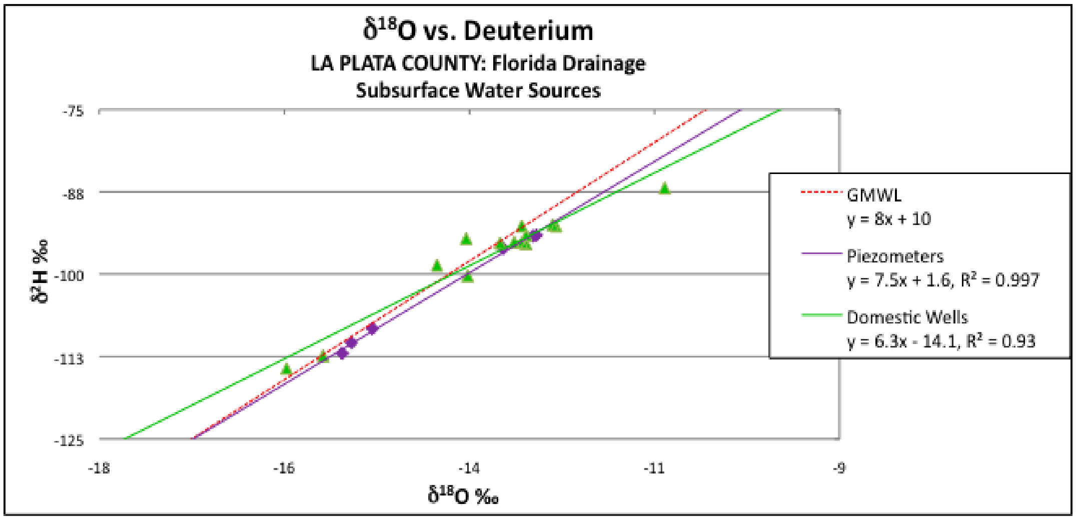


Figure 3.21 – $\delta^2H/\delta^{18}O$ plot for subsurface water sources sampled in the Florida drainage. Global Meteoric Water Line is presented in red for comparison.

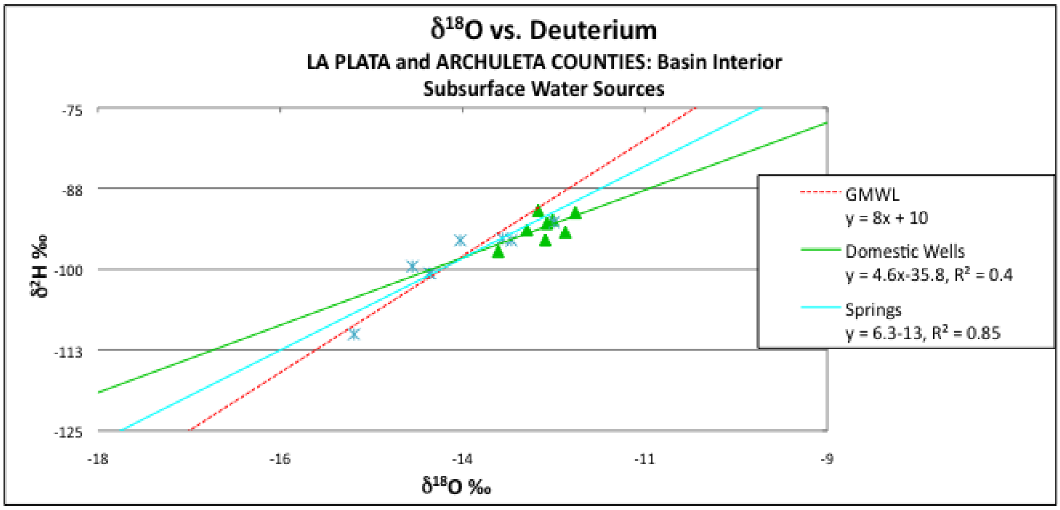


Figure 3.22 – $\delta^2H/\delta^{18}O$ plot for subsurface water sources sampled in the Basin Interior, which straddles the La Plata and Archuleta county line. Global Meteoric Water Line is presented in red for comparison.

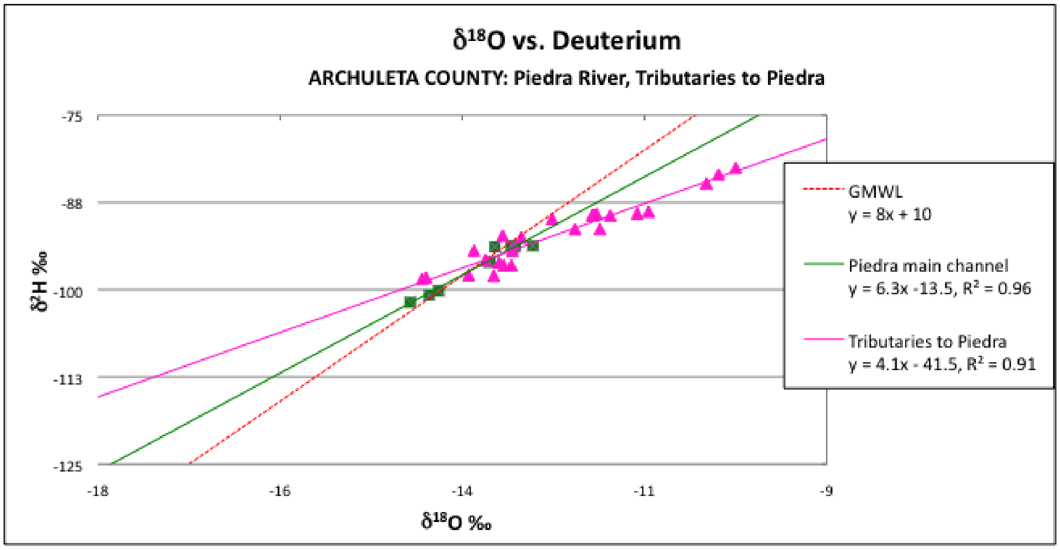


Figure 3.23 – $\delta^2H/\delta^{18}O$ plot for the Piedra River divided between main channel samples and samples from tributaries (Stollsteimer Creek, Archuleta Creek, Squaw Creek, Little Squaw Creek, Fosset Gulch, and Peterson Gulch). Tributaries show a much lower slope. Global Meteoric Water Line is presented in red for comparison.

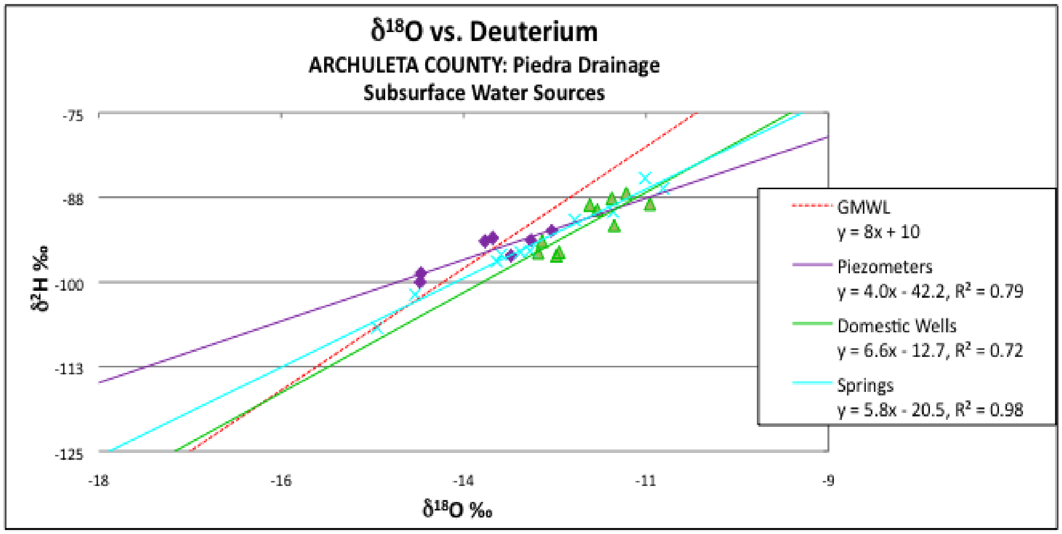


Figure 3.24 – $\delta^2H/\delta^{18}O$ plot for subsurface water sources sampled in the Piedra drainage (piezometers, domestic wells and springs). Global Meteoric Water Line is presented in red for comparison. All sources plot with a lower slope than the GMWL.

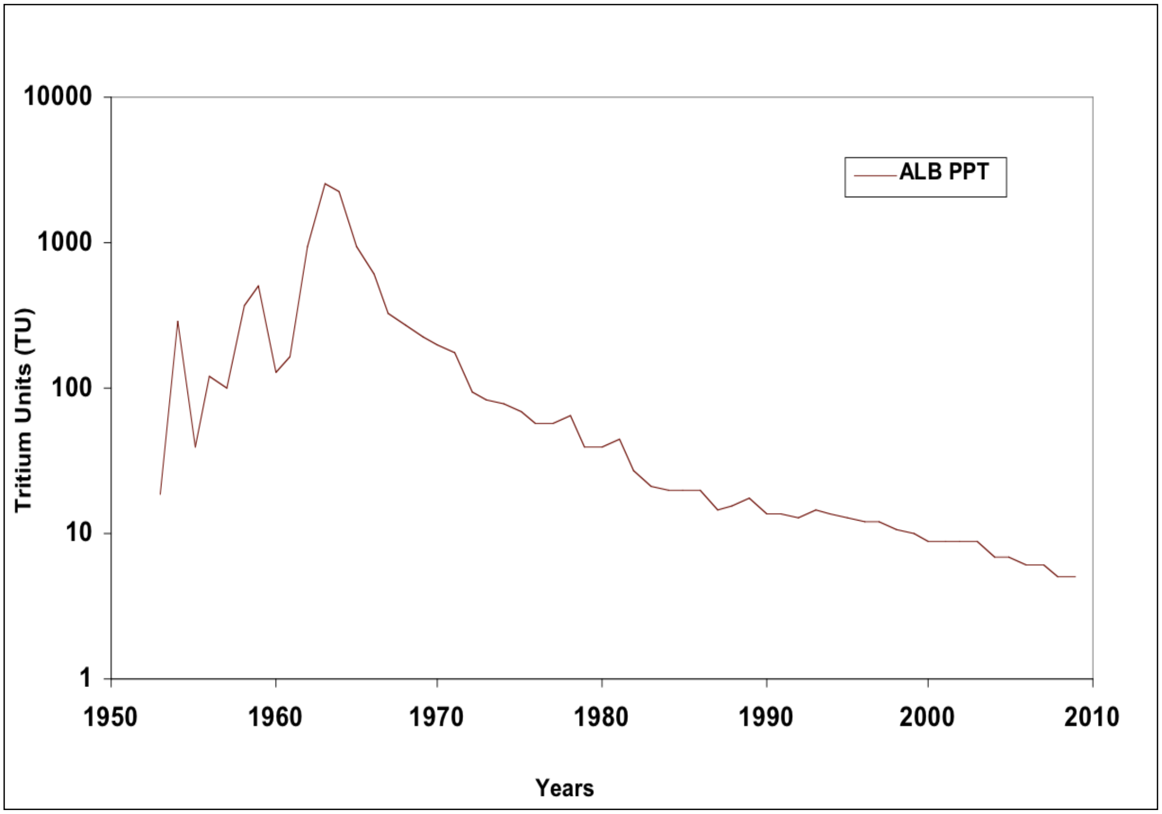


Figure 3.25 – Measured tritium values from a precipitation station at Albuquerque, NM and values estimated from correlation with tritium measurements in precipitation in Vienna Austria, were used to develop a precipitation input function for tritium for our study area. Note the transient peak in tritium values in the 1960's from extensive aboveground testing of thermonuculear weapons. Current values of tritium in precipitation at Albuquerque NM are about 5 TU.

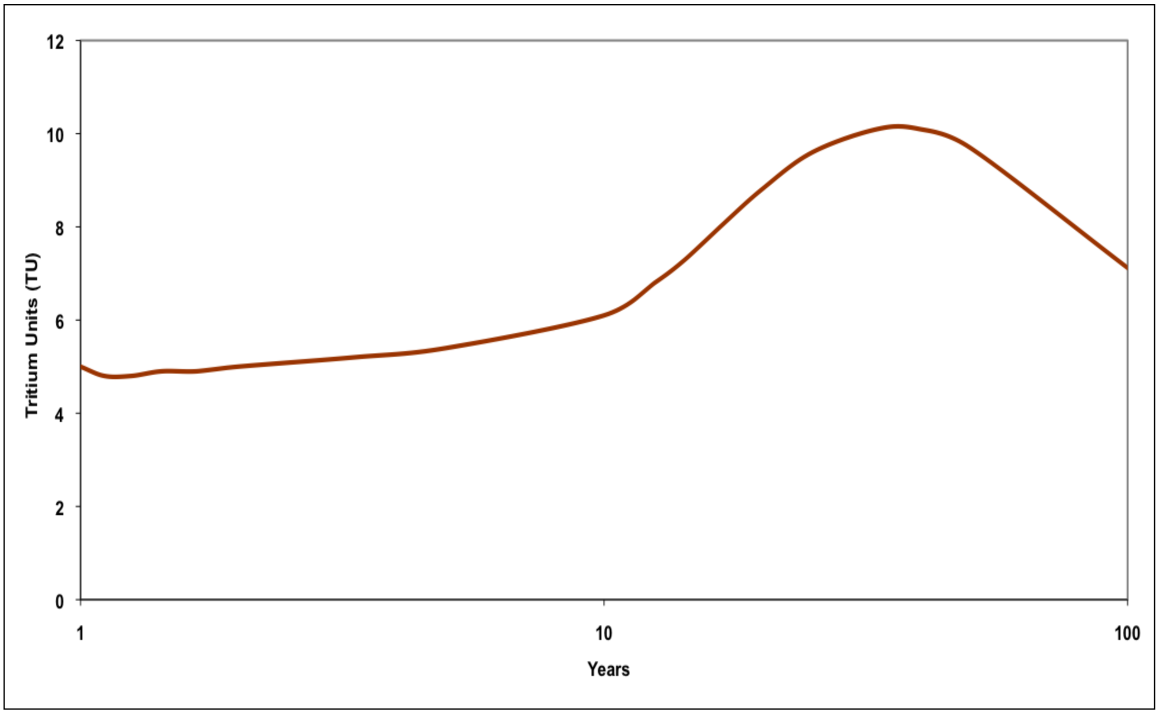


Figure 3.26 – Estimates of mean ages of water from tritium values for our study area, using the Albuquerque precipitation input function and an exponential subsurface mixing model (Revelle and Suess, 1957; Michel, 2004).

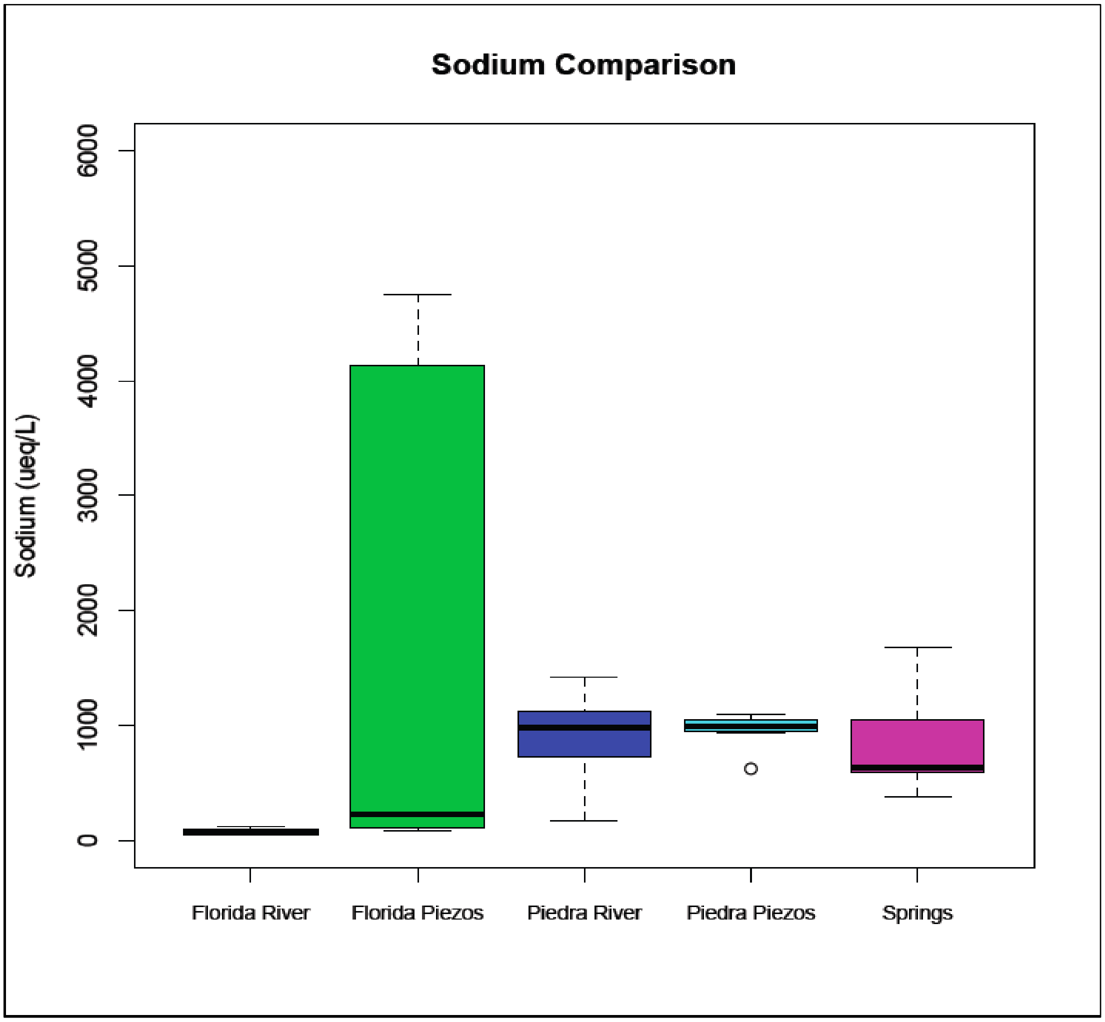


Figure 3.27 – Comparison of Florida River and Piedra River sodium concentrations, with springs plotted as a reference. Aside from an outlier piezometer in the Florida River, FR2, which had a sodium concentration of 4,500 μeq L^{-1}, the piezometers in the Florida produced low-sodium water similar to that found in the river above. In the Piedra River, sodium concentrations were much higher. Piedra sodium concentrations were also similar between the river and the piezometers, and closely matched spring sodium data.

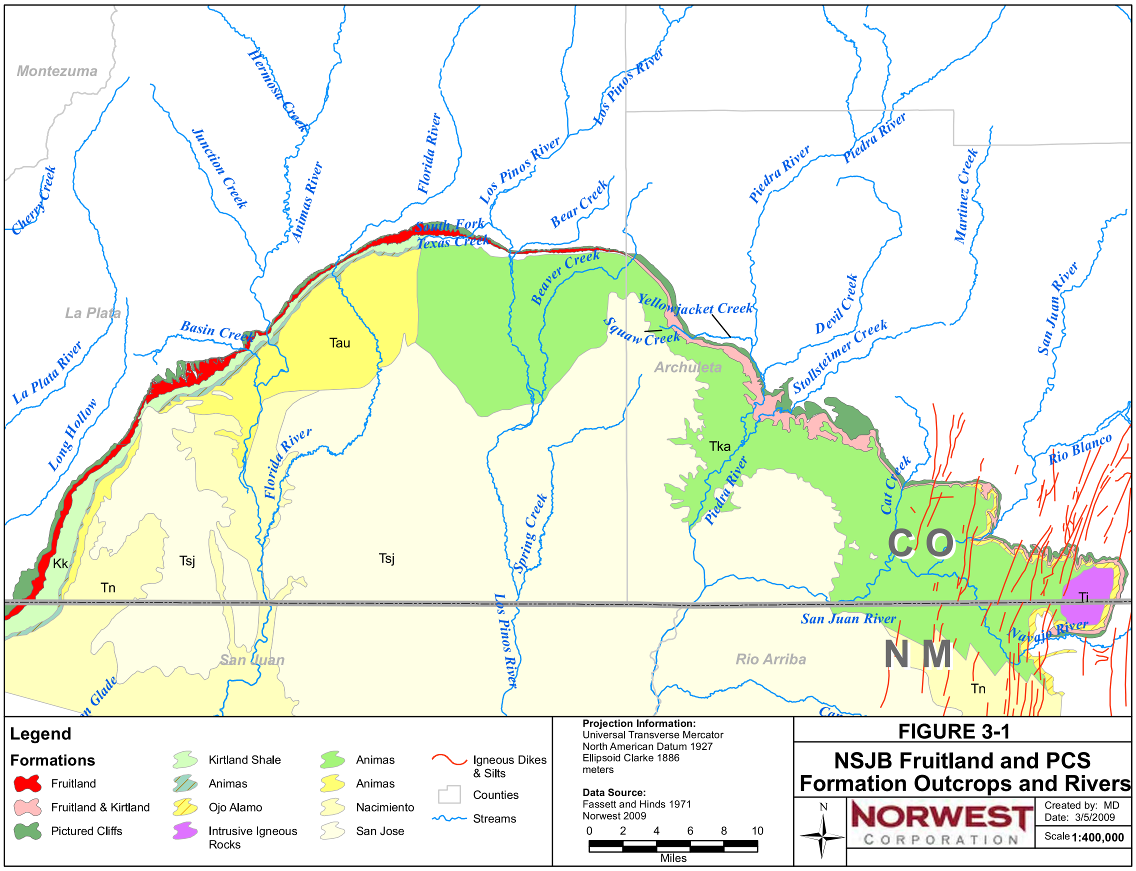


Figure 3.28 – Outcrops of the Fruitland Formation and Pictured Cliffs Sandstone, as well as other sedimentary formations in the Northern San Juan Basin, which emerge basin-ward from the northern Fruitland/PCS boundary.

265

Era	System	Stratigraphic Unit	Unit Thickness (feet)	Physical Characteristics	Hydrogeologic Units	Hydrologic Characteristics
Cenozoic	Quaternary	Alluvium	120	Clay, silt, sand, gravel, and boulders; generally poorly sorted and confined to present-day stream valleys	Alluvial aquifer	Reported well yields average 15 gpm; water quality is variable; total dissolved solids (TDS) concentration ranges from 137 to 360 mg/L in the Durango area
		Terrace deposits	60	Clay, silt, sand, gravel, and boulders; remnants of alluvial fans and higher level stream valleys		Saturated only in the lower part; transmits water to underlying aquifers
	Tertiary	Animas Fm: Unnamed Member	2,700	Varicolored shale, with interbedded breccia, conglomerate, and tuffaceous sandstone; the sandstones vary from light to rusty brown and contain abundant silicified wood and clay spheres	Animas aquifer	Well yields of 1–10 gpm are common; important source of water in areas southeast of Durango; TDS concentration ranges from 312 to 1,350 mg/L; hydraulic conductivity of fractured shale range from 0.2 to 0.3 ft/day
Mesozoic	Cretaceous	Animas Fm: McDerrmott Member		Predominantly coarse-grained, tuffaceous sandstone and thick beds of massive, fine- to coarse-grained tuff, with interbedded shale, breccia, and volcanic conglomerate		Little data available to differentiate from the Unnamed member; probable aquifer near its outcrop
		Kirtland Shale	1,500	Interbedded sandstone, shale, and siltstone; the shales are olive to medium gray; the Famington Sandstone Member is thick to massive, with crossbedding being characteristic.		Yields up to 10 gpm reported; water can be calcium carbonate type; usable yields probably limited to Farmington Sandstone Member
		Fruitland Formation	500	Varying proportions of interbedded sandstone, shale, and coal; the fine- to medium-grained sandstone beds are gray, brown, and olive in color		Little data available to differentiate from Kirtland Shale; target formation for coal mining and coalbed methane development; typically poor quality water due to coals
		Pictured Cliffs Sandstone	400	Sandstone, light-olive-gray, to grayish-orange and orange, well-sorted, fine- to medium-grained, medium- to thick-bedded, and cliff-forming		Local aquifer in outcrop areas; yields of less than 10 gpm along southern perimeter of basin
		Lewis Shale	1,800	Interbedded shale, light- to dark-gray and black; marine origin	Confining layer	Is a confining unit that separates the Pictured Cliffs and Cliff House Sandstones
		Mesaverde Group: Cliff House Sandstone	350	Gray calcareous marine sandstone, shaly sandstone, and silty shale; crossbedded and massive in places	Mesaverde aquifer	Well yields average 8.5 gpm; can be an important source of water west of Durango; water quality varies from a sodium bicarbonate type to a calcium sulfate type; TDS concentrations ranges from 180 to 2,500 mg/L
		Mesaverde Group: Menefee Formation	1,000	Light-gray sandstone, siltstone, and shale with several interbedded coal seams; thickness decreases to the north where it pinches out		Well yields average 10 gpm; presence of coal beds often determines water quality; TDS concentrations range from 210 to 3,350 mg/L; widely used regional aquifer where water quality is acceptable
		Mesaverde Group: Point Lookout Sandstone	350	Light-gray to brown marine sandstone, massive and cliff-forming; contains interbedded siltstone and shale in the lower part		Water is a sodium bicarbonate type; TDS concentration ranges from 560 to 15,344 mg/L; not a good aquifer
		Mancos Shale	1,900	Dark-gray, silty and sandy marine shale; contains some interbedded sandstones and limestones	Confining layer	Wells yield as much as 10 gpm; highest well yields are developed in landslides and slump blocks; water is predominantly a sodium bicarbonate type; TDS concentration ranges from 207 to 4,820 mg/L; water may contain excessive chloride, iron and sulfate
		Dakota Sandstone	300	Sandstone, light-gray to yellowish-brown, with interbedded siltstone and black carbonaceous shale	Dakota aquifer	Well yields are typically less than 10 gpm; wells may be flowing where sandstone is overlain by the Mancos; water is predominantly a calcium bicarbonate type; TDS concentration ranges from 273–440 mg/L
		Burro Canyon Fm	100	Interbedded conglomerate and grayish-green shale, with light-brown sandstone lenses		No information
		Morrison Formation	800	Varying amounts of sandstone and shale with some limestone; the sandstones are thin bedded, fine- to medium-grained and white to grayish orange in color	Morrison aquifer	Yields are as much as 25 gpm; water is a calcium bicarbonate type; TDS concentration ranges from 211 to 296 mg/L; water may contain excessive iron; a primary aquifer in New Mexico

Figure 3.29 – Hydrostratigraphic units of the Northern San Juan Basin (Topper et al., 2003).

CHAPTER 4 FIGURES

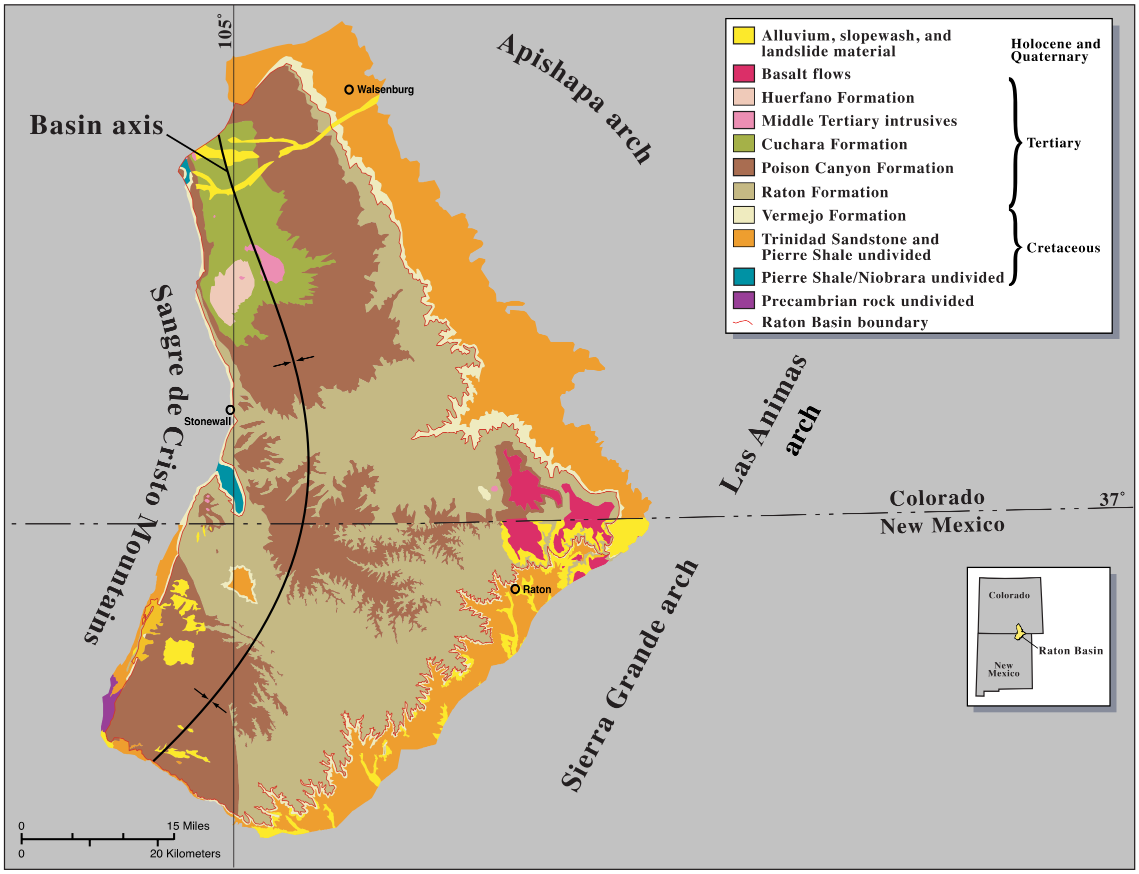


Figure 1. Generalized geologic map of the Raton Basin, Colorado and New Mexico. From Flores and Bader (1999).

Figure 4.1 – Generalized geologic map of the Raton Basin, Colorado and New Mexico. Modified from Flores and Bader (1989) and reprinted by Johnson & Finn (2001).

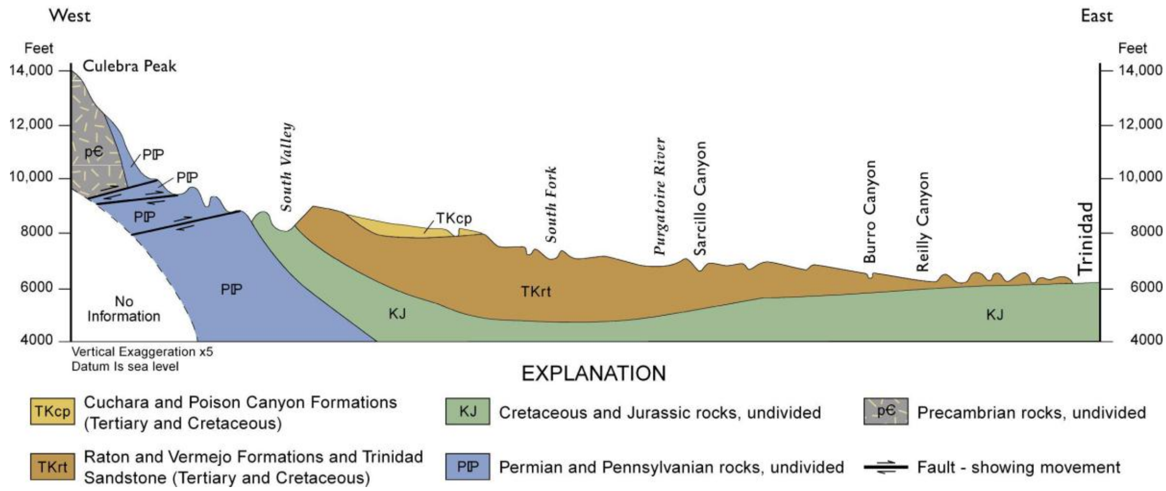


Figure 4.2 – Geologic cross-section of the Raton Basin, Colorado (Topper et al., 2003).

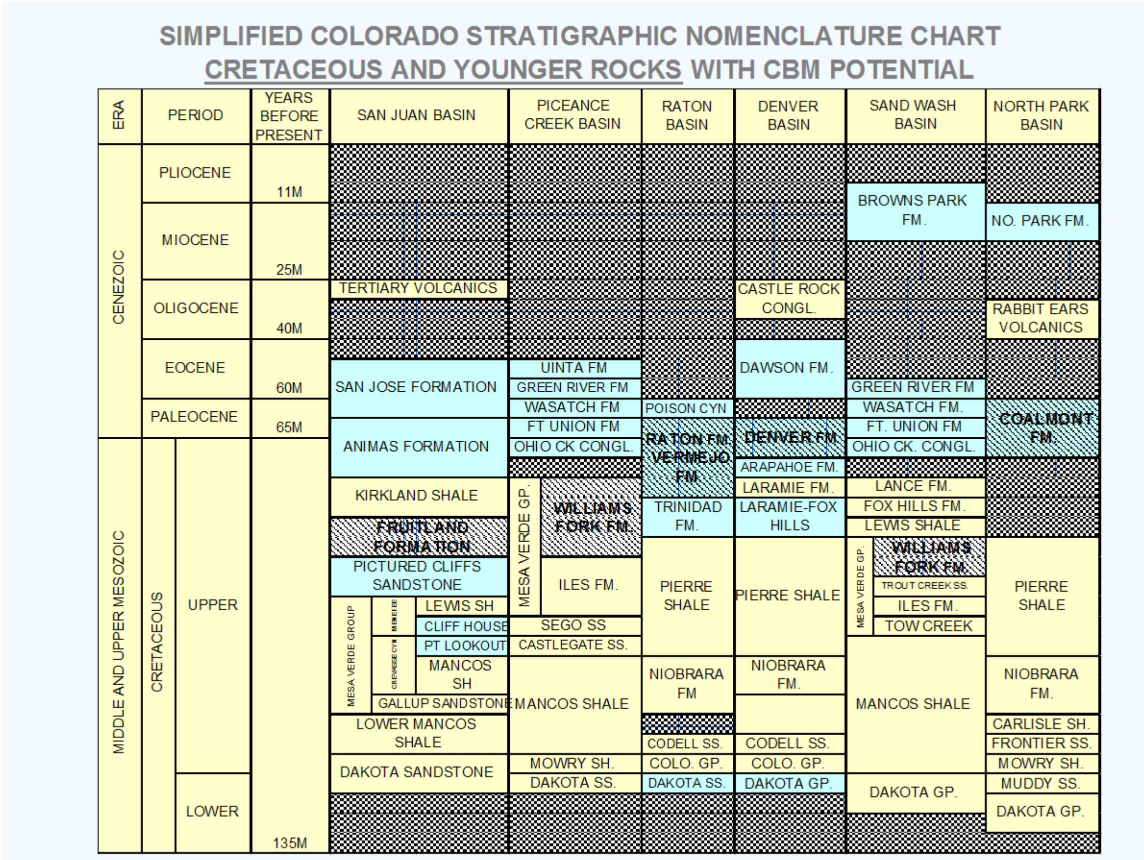


Figure 4.3 – Cretaceous and younger strata of coalbed methane basins in Colorado, as presented by State Engineer Dick Wolfe in an Oct. 24, 2005 public presentation on the Division of Water Resource’s stream depletion study (Wolfe, 2005).

Era	System	Series	Stratigraphic Unit	Unit Thickness (feet)	Physical Characteristics	Hydrogeologic Unit	Hydrologic Characteristics
Cenozoic	Quaternary	Holocene	Alluvium		Silt, sand, and gravels	Alluvial aquifer	Water-table aquifer of limited extent
		Pleistocene					
	Tertiary	Oligocene	Devil's Hole Formation				
			Farisita Conglomerate				
			Intrusive igneous rocks		Granitic to gabbroic stocks, dikes, and sills		
		Eocene	Huerfano Formation	2,000	Variegated shale and limestone		
			Cuchara Formation	5,000	Pink and white sandstone with shale	Cuchara-Poison Canyon aquifer	Transmissivities of 0.20–575 ft^2/day; yields 0.07–33 gpm
		Paleocene	Poison Canyon Formation	2,500	Tan, gray and olive sandstone, conglomerate and shale		
			Raton Formation	1,000–1,600	Gray, green, and black shale, siltstone with sandstone, coal	Raton-Vermejo-Trinidad aquifer	Target formation for coalbed methane; transmissivities of 0.02–79 ft^2/day; yields 0.04–16 gpm
Mesozoic	Cretaceous	Upper Cretaceous	Vermejo Formation	80–550	Gray, green, and black shale, siltstone with sandstone, coal		
			Trinidad Sandstone	45–310	Tan and gray sandstone with shale partings		
			Pierre Shale	1,600–2,300	Shale, with interbedded sandstone in the upper 100–300 feet	Confining layer	Sandstone layers might yield limited water
			Niobrara Formation	450–570	Chalky and sandy shale with limestone in lower 50–70 feet	Ft. Hayes Limestone Member	Ft. Hayes Limestone Member supplies wells in adjacent areas
			Carlile Shale	225–290	Sandstone in upper 5–30 feet, shale below	Codell Sandstone Member	Codell Sandstone Member supplies wells in adjacent areas
			Greenhorn Limestone	25–35	Thin gray limestone interbedded with shale		Yields small quantities of water to wells in adjacent areas
			Graneros Shale	185–235	Shale and limestone	Confining layer	Not an aquifer in Raton Basin
		Lower Cretaceous	Dakota Sandstone	50–200	White and tan sandstone	Dakota aquifer	Average porosity range 10–20%; average hydraulic conductivity 0.2 ft/day

Figure 4.4 – Primary hydrostratigraphic units of the Raton Basin, Colorado (Topper et al., 2003).

271

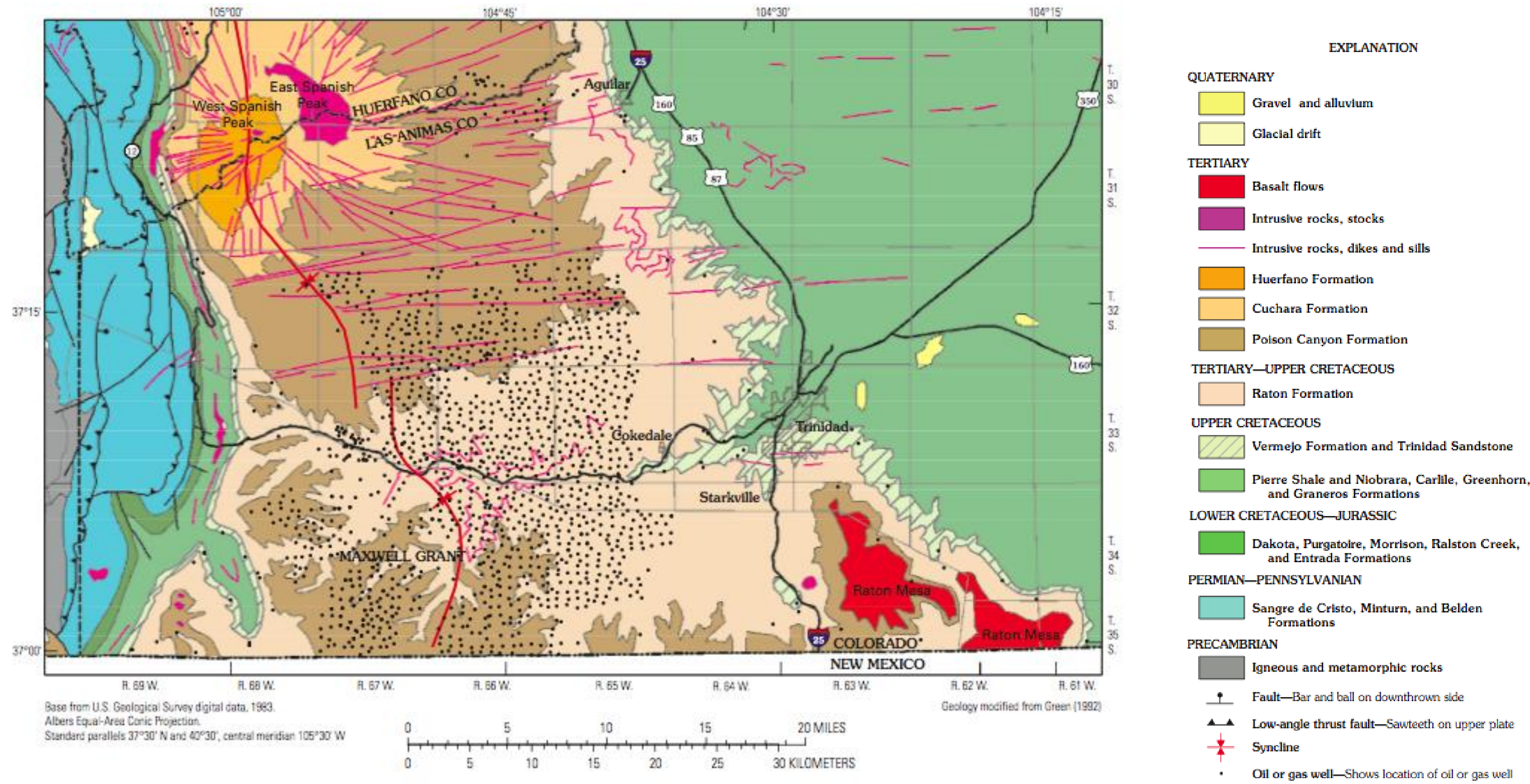


Figure 4.5 – Geologic map of Raton Basin, Colorado, including igneous dikes and sills (in pink) (Watts, 2007).

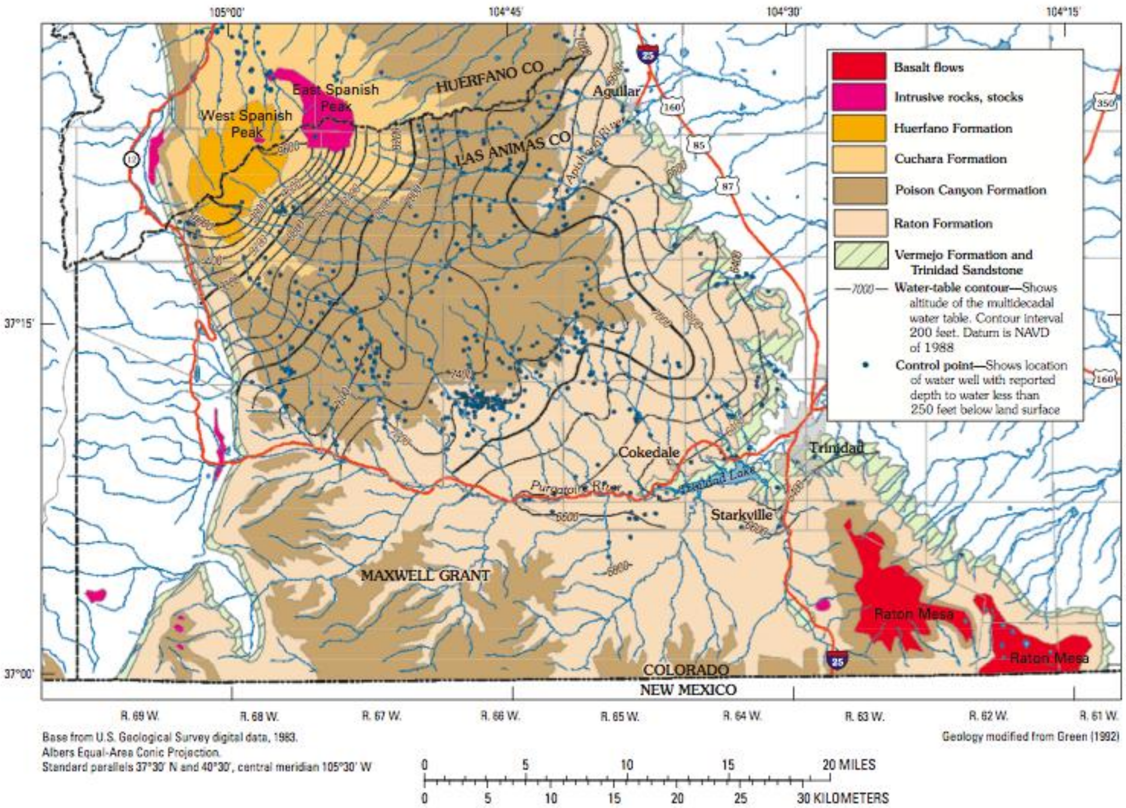


Figure 4.6 – Generalized configuration of the long-term water table in the northern region of the Raton Basin, Colorado (Watts, 2006).

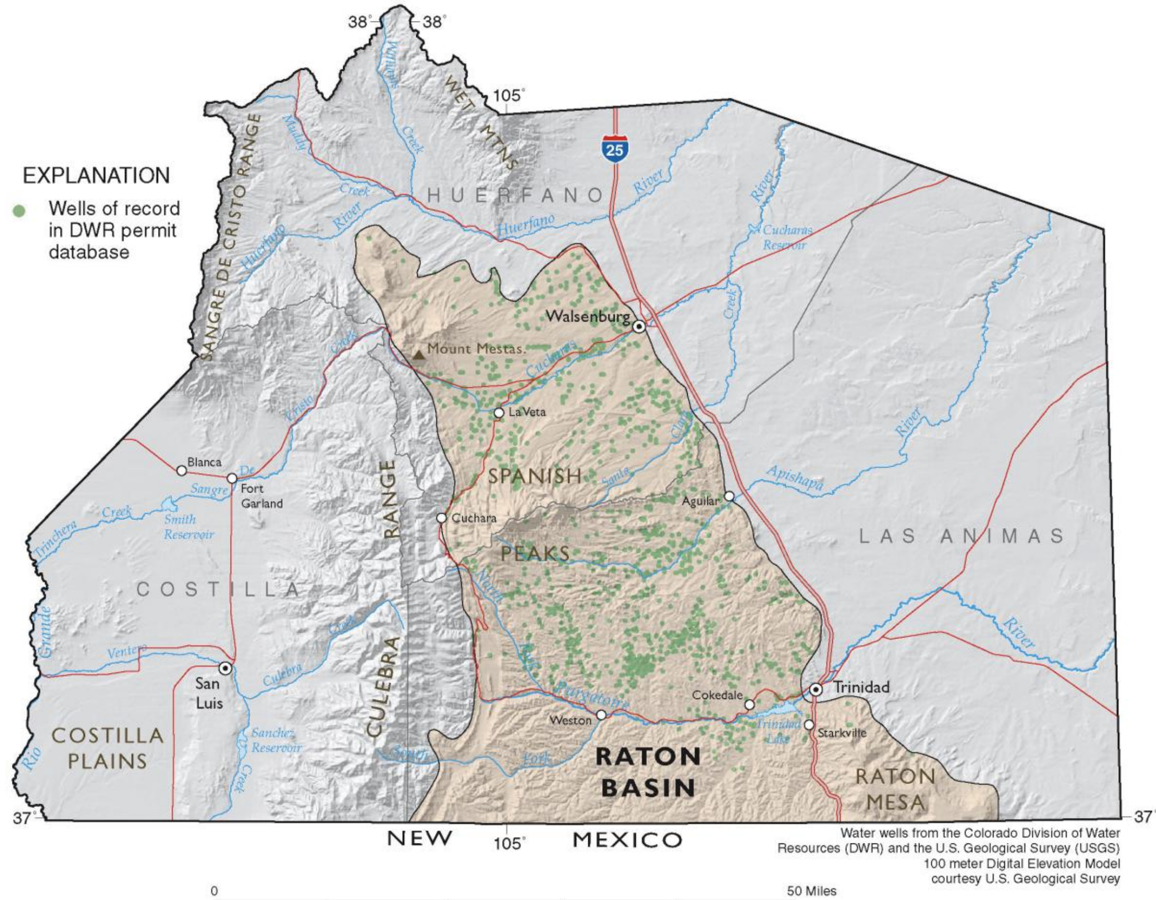


Figure 4.7 – There are an estimated 1,500 permitted water wells in the Raton Basin, Colorado (Topper et al., 2003).

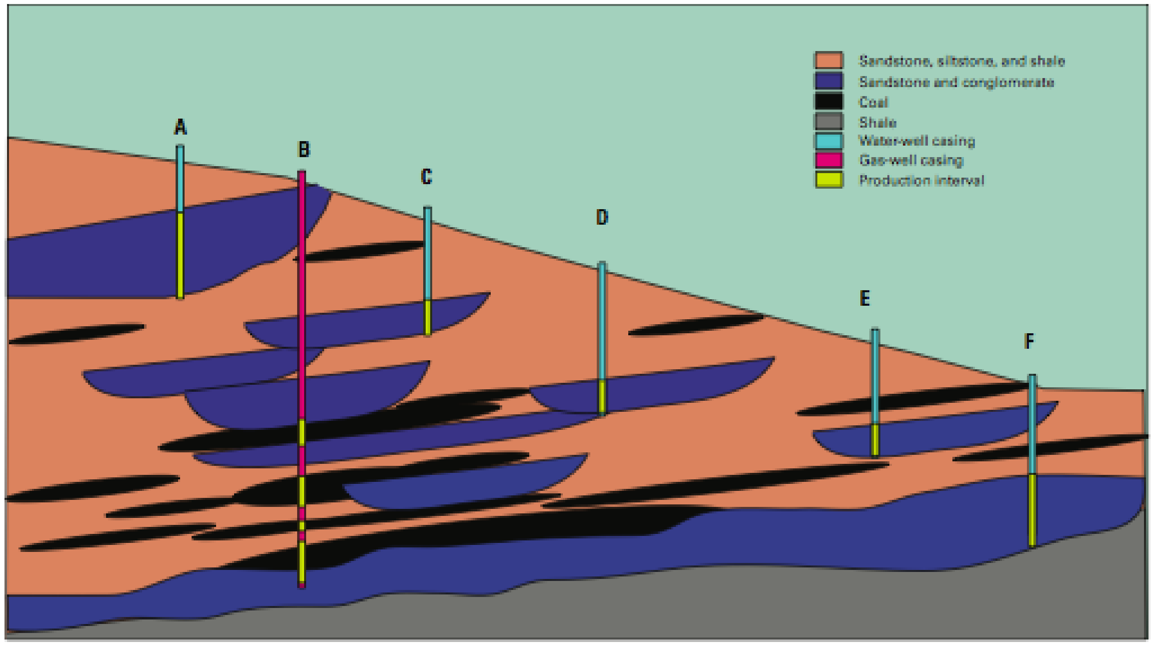


Figure 4.8 – Hypothetical hydraulic connections between production zones of a coalbed methane well and nearby domestic water wells (Watts, 2006).

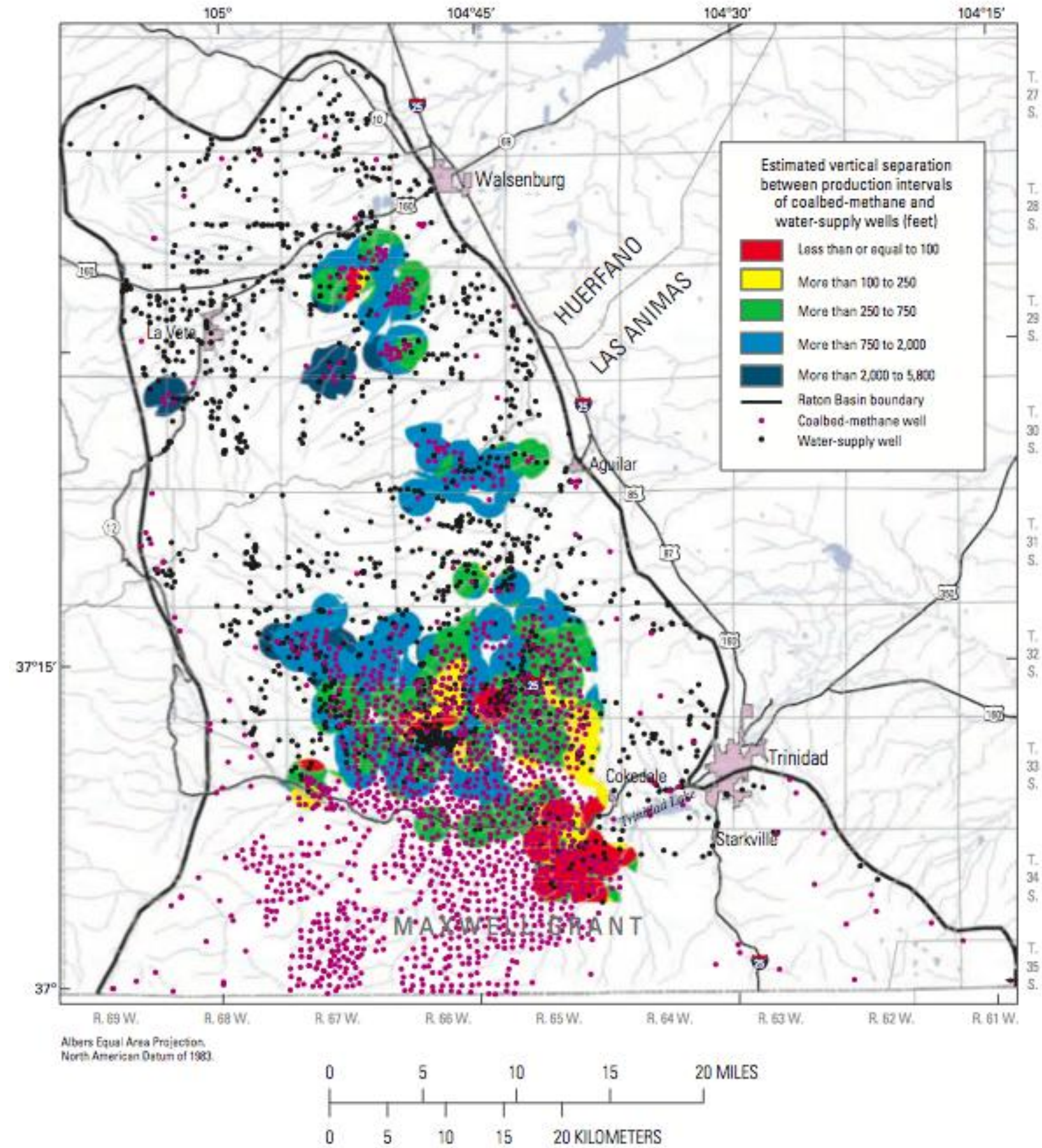


Figure 4.9 – Map of vertical separation between domestic water wells and coalbed methane wells in the Raton Basin, Colorado (Watts, 2006).

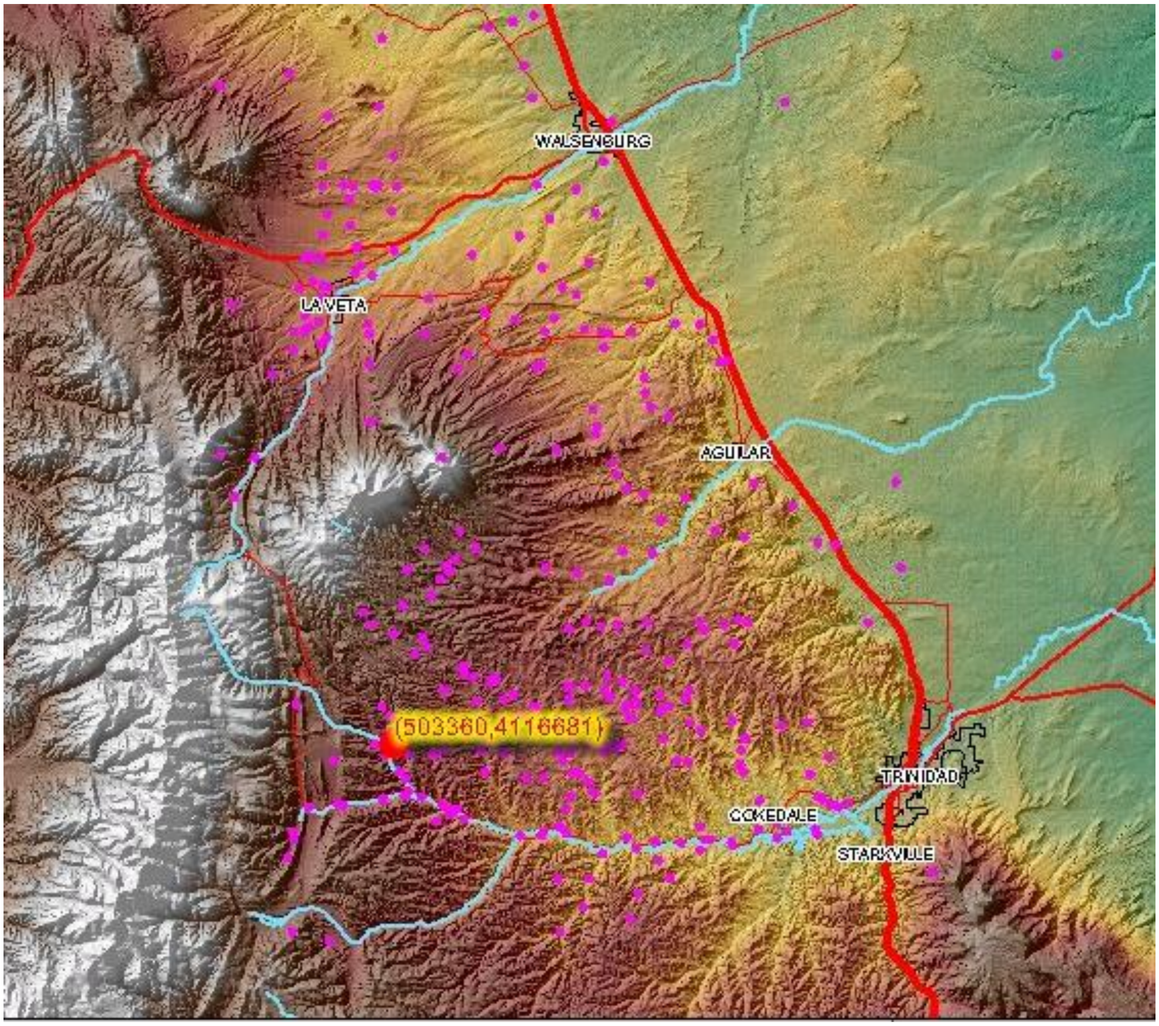


Figure 4.10 – Dahl well on western side of Raton Basin (503360 easting, 4116681 northing) as pictured by Colorado Decision Support System map viewer, partnership of Colorado Division of Water Resources (within Department of Natural Resources) and Colorado Water Conservation Board. Other permitted domestic wells in the area pictured with pink dots.

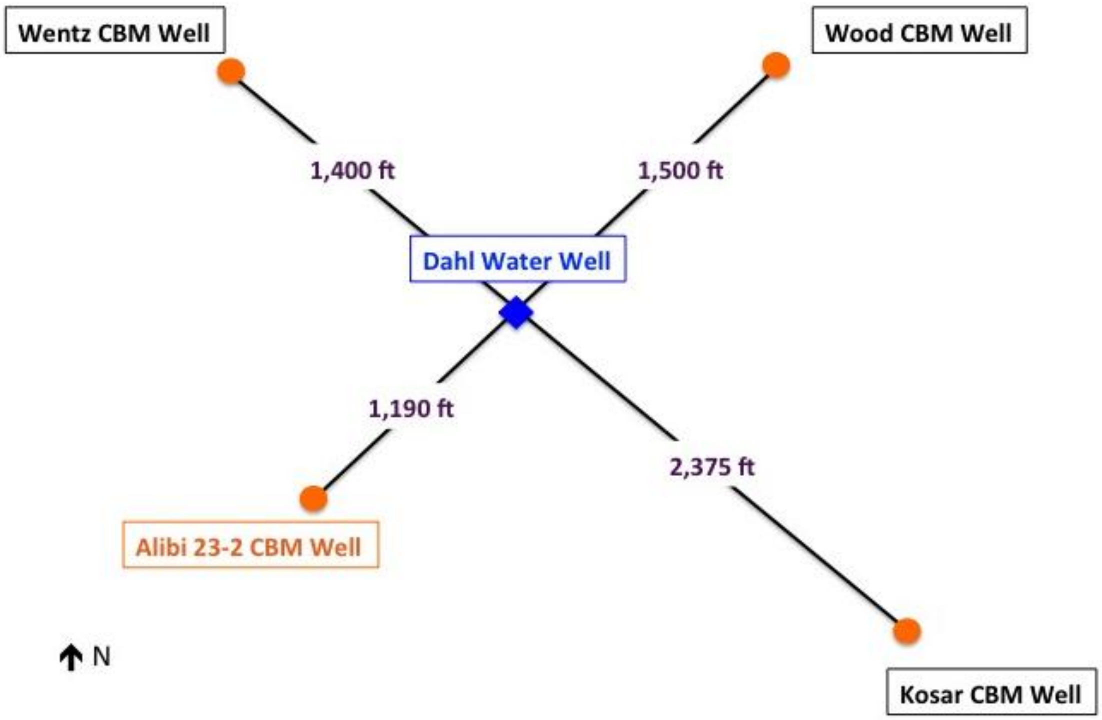


Figure 4.11 – View of the horizontal plane and separation between Alibi 23-2 CBM well and Dahl domestic water well, derived from testimony and drilling records in the COGCC case docket. *Not to scale.*

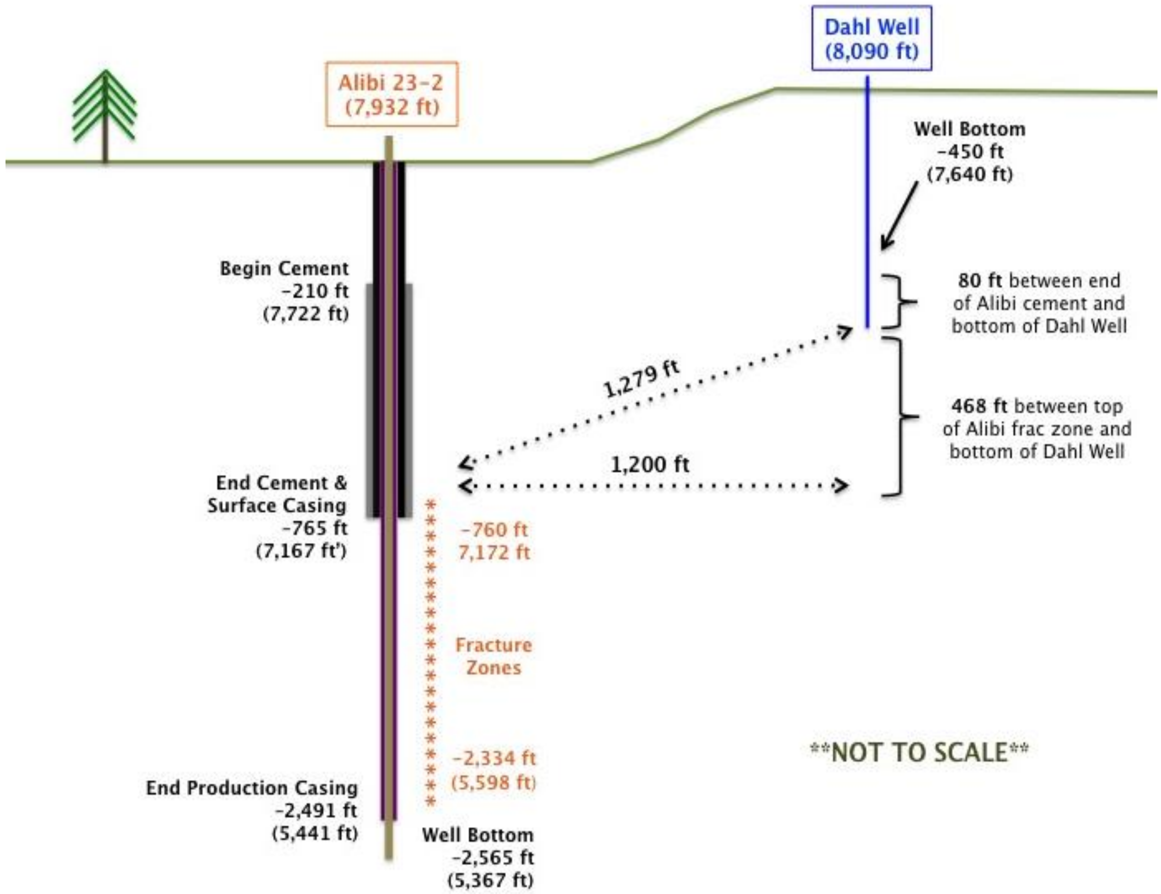


Figure 4.12 – Vertical separation between Alibi 23-2 and Dahl well water well, derived from testimony and drilling records in the COGCC case docket. *Not to scale.*

Figure 4.13 – Dahl well water from spigot (top) and in cistern (bottom) as photographed by Tracy Dahl on June 30, 2010 and included in testimony before the COGCC.

Figure 4.14 – Norwest staff sample Alibi 23-2 frac tank (top) and flowback pit (bottom) on July 1, 2010, as presented in COGCC investigator final report on Dahl well investigation (COGCC, 2010).

July 1

July 8

Figure 4.15 – Dahl well water as pumped directly from well into buckets on July 1(top). Well and cistern water on July 8 at bottom. (As presented in COGCC investigator final report on Dahl well investigation (COGCC, 2011).)

Parameter	Water Well Sample												
	Sample Date	Sample Date	Sample Date	Sample Date	Sample Date	Sample Date	Sample Date	Sample Date	Sample Date	Sample Date	Sample Date	Sample Date	
	15-Oct-04	15-Aug-06	28-Sep-06	06-Feb-08	10-Jun-08	02-Apr-09	17-Nov-09	12-Jan-10	17-Feb-10	01-Jul-10	01-Jul-10	08-Jul-10	
	Result	Result	Result	Result	Result	Result	Result	Result	Result	Result	Result	Result	Unit
										Cistern(COGCC)	WW(Norwest)		
Aluminum	0.04 (total)	0.03	NA	NA	NA	NA	ND(<0.05)	NA	ND(<0.05)	ND(<0.05)	0.16	ND(<0.05)	mg/l
Antimony	0.0002	ND(<0.002)	NA	0.0011	ND(<0.002)	0.0003	ND(<0.005)	ND(<0.0003)	ND(<0.005)	0.001	ND(0.005)	0.0011	mg/l
Boron	0.01	0.01	ND	ND (<0.1)	ND(<0.1)	ND(<0.1)	ND(<0.1)	ND(<0.1)	ND(<0.1)	ND(<0.1)	ND(<0.1)	ND(<0.1)	mg/l
Copper	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	mg/l
Arsenic	0.0014	0.003	NA	0.0031	ND(<0.005)	ND(<0.002)	0.0069	ND(<0.002)	ND(<0.0025)	0.0039	0.0068	0.0034	mg/l
Barium	0.044	0.05	NA	ND (<0.1)	0.046	ND(<0.1)	ND(<0.1)	ND(<0.1)	ND(<0.1)	ND(<0.1)	ND(<0.1)	ND(<0.1)	mg/l
Berylium	ND	ND	NA	ND	ND	ND	ND	ND	ND	ND	ND	ND	mg/l
Cadmium	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	mg/l
Calcium	2.6	2.5	2.8	2.5	2.3	2.3	3.16	2.4	2.3	3.5	3.1	3.3	mg/l
Chromium	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	mg/l
Iron	0.03	ND(<0.05)	ND	ND (<0.1)	ND(<0.1)	ND(<0.1)	ND(<0.1)	ND(<0.1)	ND(<0.1)	ND(<0.1)	ND(<0.1)	ND(<0.1)	mg/l
Lead	0.0004	0.0013	NA	0.0007	ND(<0.001)	ND(<0.0005)	MD(<0.0015)	0.0014	ND(<0.0015)	ND(<0.0005)	ND(<0.0015)	ND(<0.0005)	mg/l
Lithium	NA	NA	NA	ND	ND	ND	NA	ND	NA	ND	NA	ND	mg/l
Magnesium	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	mg/l
Manganese	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	mg/l
Molybdenum	ND (<0.05)	ND(<0.05)	NA	0.0015	ND(<0.002)	0.0014	0.0027	0.0012	ND(<0.001)	0.0031	0.0036	0.0022	mg/l
Nickel	ND	ND	NA	ND	ND	ND	ND	ND	ND	ND	ND	ND	mg/l
Potassium	0.6	0.7	ND(<3)	ND(<1)	ND(<3)	ND(<1)	ND(<1)	ND(<1)	ND(<1)	ND(<1)	ND(<1)	ND(<1)	mg/l
Selenium	ND	0.0003	NA	ND(<0.001)	ND(<0.005)	ND(<0.001)	ND(<0.0025)	ND(<0.001)	ND(<0.0025)	ND(<0.001)	ND(<0.0025)	ND(<0.001)	mg/l
Silver	ND	NA	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	mg/l
Sodium	114	131	119	110	120	100	126	100	140	92	130	98	mg/l
Strontium	NA	NA	NA	0.076	0.07	0.068	0.0825	0.073	0.073	0.081	0.086	0.079	mg/l
Thallium	ND	NA	NA	ND	ND	ND	ND	ND	ND	ND	ND	ND	mg/l
Uranium	0.00016	0.0002	NA	0.0002	ND(<0.001)	ND(<0.0001)	NA	0.00016	NA	0.00036	NA	0.00026	mg/l
Zinc	ND(<0.05)	0.02	0.021	ND(<0.02)	ND(<0.02)	ND(<0.02)	ND(<0.02)	0.023	ND(<0.02)	ND(<0.02)	ND(<0.02)	ND(<0.02)	mg/l

Figure 4.16 – Baseline water quality data for Dahl well, compiled by COGCC from Dahl sampling, operator sampling under Rule 608, and July 2010 investigation sampling, as presented in COGCC investigator final report on Dahl well investigation (COGCC, 2010). (Table continued on next page).

Parameter	15-Oct-04	15-Aug-06	28-Sep-06	06-Feb-08	10-Jun-08	02-Apr-09	17-Nov-09	12-Jan-10	17-Feb-10	01-Jul-10	01-Jul-10	08-Jul-10	
										Cistern	WW		Unit
Chloride	5	4	4.4	5.1	5.1	4.5	5.7	4.3	4.6	17	22	3.6	mg/l
Nitrite	ND	ND	NA	ND	ND	ND	ND	ND	ND	ND	ND	ND	mg/l
Nitrate	0.19	0.19	0.13	ND (<0.2)	ND(<0.5)	0.24	ND(<0.1)	0.24	0.2	ND(<0.2)	ND(<0.1)	ND(<0.2)	mg/l
Total Nitrite/Nitrate	0.19	0.19	NA	ND (<0.2)	ND(<0.5)	0.24	ND(<0.1)	0.24	0.2	ND(<0.2)	ND(<0.1)	ND(<0.2)	mg/l
Fluoride	0.5	NA	0.44	0.48	0.65	0.58	0.55	0.54	0.56	0.55	0.7	0.33	mg/l
Total Dissolved Solids	320	310	324	310	320	320	306	310	310	320	350	310	mg/l
pH	8.1	8.8	8.7	8.61	8.7	8.67	8.8	8.75	8.84	8.76	8.76	8.77	No units
Sulfate	60	50	53.5	54	55	49	48.2	49	48	49	45	55	mg/l
Bromide	NA	NA	ND	ND	ND	ND	ND	ND	ND	ND	2.1	ND	mg/l
Total Alkalinity	206	214	205	200	200	210	201	210	210	210	210	210	mg/l
Bicarbonate	191	193	192	190	200	200	178	190	190	200	200	200	mg/l
Carbonate	15	21	12.9	ND(<20)	ND(<5)	ND(<20)	22.8	18	17	ND(<20)	12	ND(<20)	mg/l
Conductivity	499	565	NA	503	520	502	506	517	520	551	540	494	umhos/cm
methane	NA	ND(<0.002)	ND(<5)	0.0025	ND(<0.005)	ND(<0.001)	ND(<0.005)	ND(<0.001)	ND(<0.005)	0.0048 ~~(WW)~~	0.0054	NA	mg/l
Total Organic Carbon	NA	NA	NA	ND(<1)	ND(<1)	ND(<1)	NA	ND(<1)	NA	1.4 (WW)	NA	NA	mg/l
chloroform	NA	NA	NA	0.0028	0.0021	0.00077	NA	0.0043	NA	0.018 (WW)	NA	NA	mg/l

Figure 4.16 – Continued from previous page.

283

Parameter	Water Sample					CDPHE Standards		
	Sample Date	Sample Date	Sample Date	Sample Date				
	01-Jul-10	01-Jul-10	01-Jul-10	08-Jul-10				
	Result	Result	Result	Result	Unit	Domestic	Agriculture	Unit
	Cistern-Norwest	Cistern-COGCC	Water Well-Norwest	Water Well - COGCC				
Aluminum	0.25	ND(<0.05)	0.16	ND(<0.05)	mg/l	NS	5	mg/l
Antimony	ND(<0.005)	0.001	ND(<0.005)	0.0011	mg/l	0.006	NS	mg/l
Arsenic	0.0038	0.0039	0.0068	0.0034	mg/l	0.01	0.1	mg/l
Barium	ND	ND	ND	ND	mg/l	2.0	NS	mg/l
Berylium	ND	ND	ND	ND	mg/l	0.004	0.1	mg/l
Boron	ND	ND	ND	ND	mg/l	NS	0.75	mg/l
Cadmium	ND	ND	ND	ND	mg/l	0.005	0.01	mg/l
Calcium	3.3	3.3	3.1	2.5	mg/l	NS	NS	
Chromium	ND	ND	ND	ND	mg/l	0.1	0.1	mg/l
Cobalt	ND	ND	ND	ND	mg/l	NS	0.05	mg/l
Copper	ND	ND	ND	ND	mg/l	1	0.2	mg/l
Iron	ND	ND	ND	ND	mg/l	0.3	5	mg/l
Lead	ND	ND	ND	ND	mg/l	0.05	0.1	mg/l
Lithium	NA	ND	NA	ND	mg/l	NS	NS	
Magnesium	ND	ND	ND	ND	mg/l	NS	NS	
Manganese	ND	ND	ND	ND	mg/l	0.05	0.2	mg/l
Molybdenum	0.0025	0.0031	0.0036	0.0022	mg/l	0.035	NS	mg/l
Nickel	ND	ND	ND	ND	mg/l	0.1	0.2	mg/l
Potassium	ND	ND	ND	ND	mg/l	NS	NS	
Selenium	ND	ND	ND	ND	mg/l	0.05	0.02	mg/l
Silver	ND	ND	ND	ND	mg/l	0.05	NS	mg/l
Sodium	120	98	130	93	mg/l	NS	NS	
Strontium	0.086	0.079	0.086	0.073	mg/l	NS	NS	
Thallium	ND	ND	ND	ND	mg/l	0.002	NS	mg/l
Uranium	NA	0.00036	NA	0.00026	mg/l	0.03	NS	mg/l
Zinc	ND	ND	ND	ND	mg/l	5	2	mg/l
Chloride	16	17	22	3.6	mg/l	250	NS	mg/l
Nitrite	ND	ND	ND	ND	mg/l	1.0	10	mg/l
Nitrate	ND	ND	ND	ND	mg/l	10.0	100	mg/l
Total Nitrite/Nitrate	ND	ND	ND	ND	mg/l	10.0	100	mg/l
Fluoride	0.49	0.55	0.7	0.33	mg/l	4.0	NS	mg/l
Total Dissolved Solids	320	320	350	310	mg/l	400	*1500	mg/l
pH	8.82	8.76	8.76	8.77	No units	6.5 - 8.5	6.5 - 8.5	No units
Sulfate	45	49	45	55	mg/l	250	NS	mg/l
Bromide	ND(<0.2)	ND(<0.2)	2.1	ND(<0.2)	mg/l	NS	NS	
Total Alkalinity	210	210	210	210	mg/l	NS	NS	
Bicarbonate Alk.	190	200	200	200	mg/l	NS	NS	
Carbonate Alk.	15	ND(<20)	12	ND(<20)	mg/l	NS	NS	
Conductivity	530	551	540	494	umhos/cm	NS	NS	
methane	NA	0.0048(WW)	0.0054	NA	mg/l	NS	NS	
Tot. Suspended Solids	ND(<4)	NA	8.8	ND(<20)	mg/l	NS	NS	

Notes

CDPHE	Colorado Department of Public Health and the Environment.
Domestic	Water Quality Control Commission 5 CCR 1002-41, Regulation No. 41 - The Basic Standards For Groundwater (eff. 11/2009)
Agriculture	* Standards for agriculture complied from CDPHE and other sources.
mg/l	milligrams per liter (ppm or parts per million).
mhos/cm	micromhos per centimeter
NA	Not Analyzed.
ND	Not Detected.
NS	No Standard.
**	Health Advisory.
	Table 1. Human health standard. (5 CCR 1002-41)
	Tables 2 and 4. (5 CCR 1002-41)

Figure 4.17 – COGCC table summarizing analytical data collected on July 1 and July 8, 2010 by COGCC and Norwest Corp, as presented in COGCC investigator final report on Dahl well investigation (COGCC, 2010).

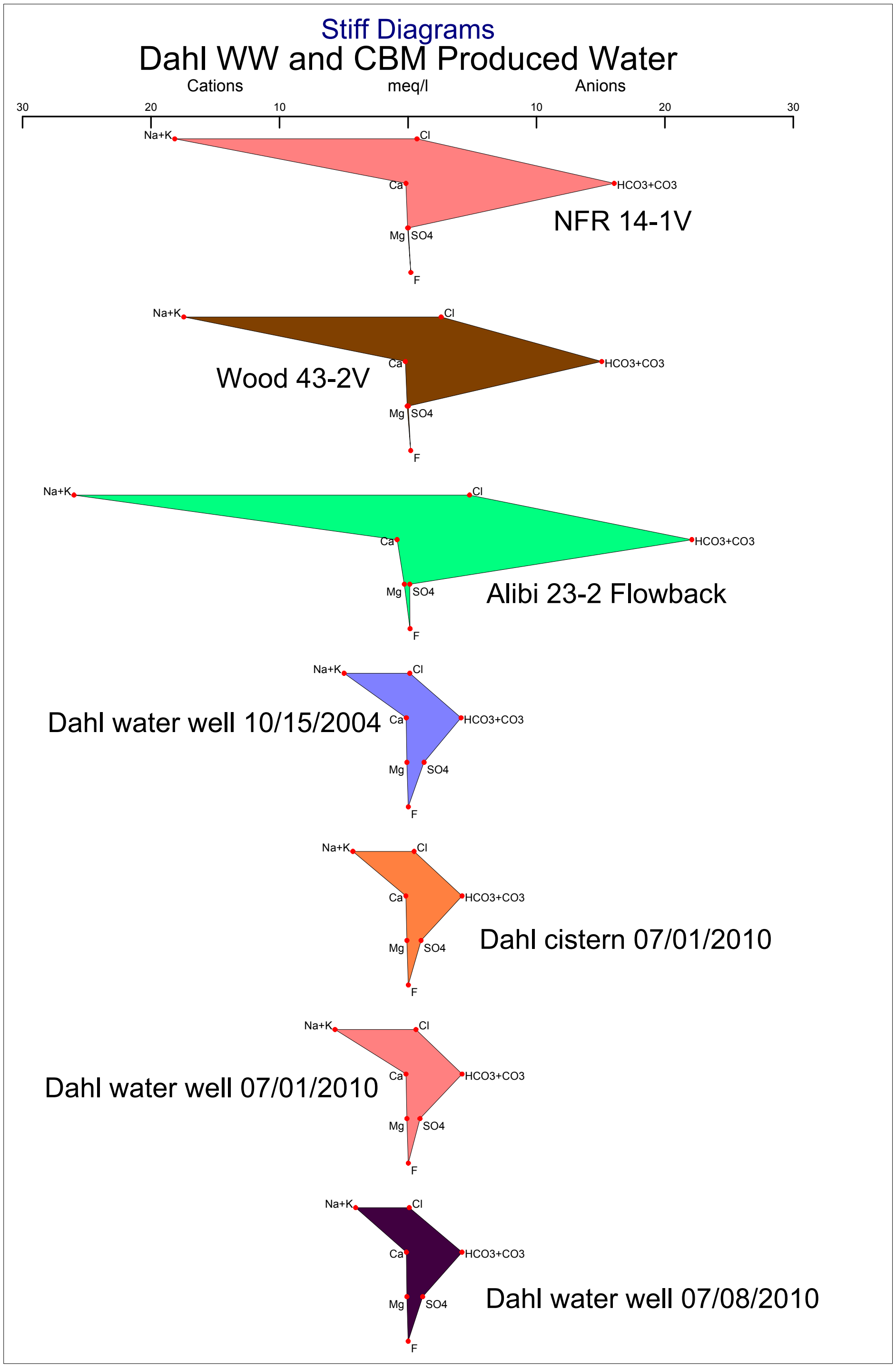


Figure 4.18 – Stiff diagrams comparing major ion chemistry between Alibi 23-2 and two other nearby CBM wells with Dahl water well between 2004 and 2010, as presented in COGCC investigator final report on Dahl well investigation (COGCC, 2010).

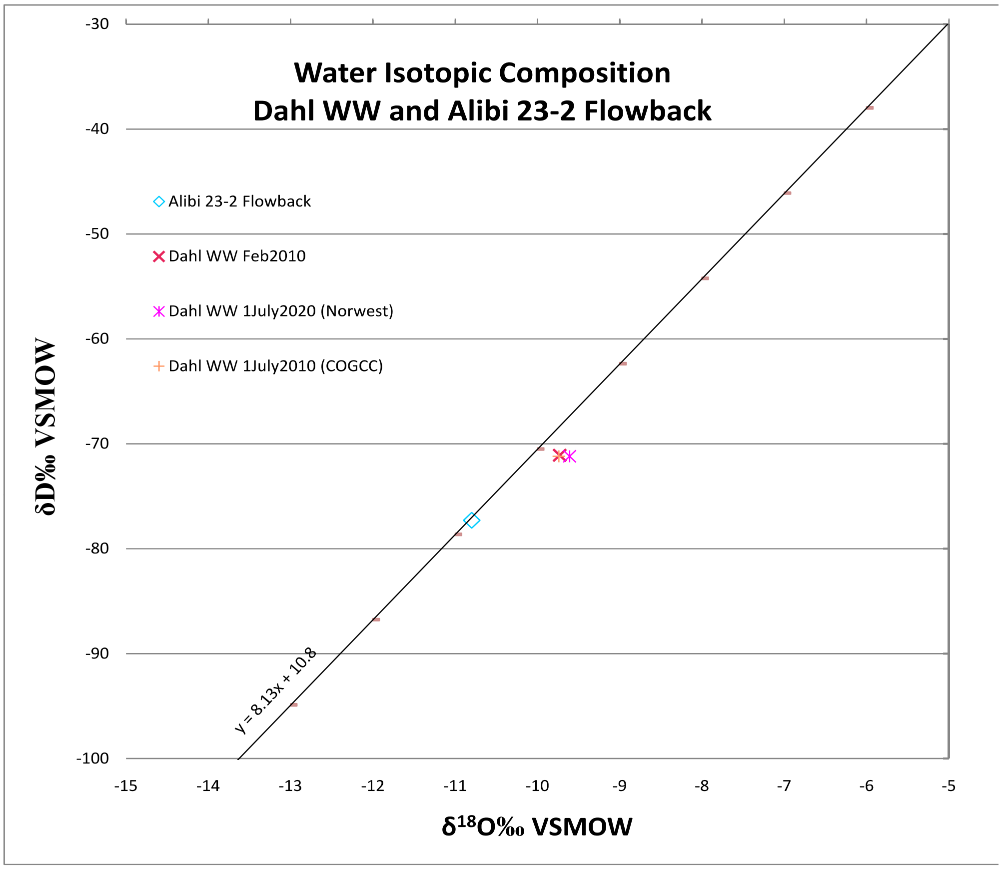


Figure 4.19 – $\delta^2H/\delta^{18}O$ plot for Dahl well water before impact (in February 2010) and after impact (July 1, 2010), and for Alibi 23-2 flowback water (on July 1, 2010), as compared to the Global Meteoric Water Line. Presented in COGCC investigator final report on Dahl well investigation (COGCC, 2010).

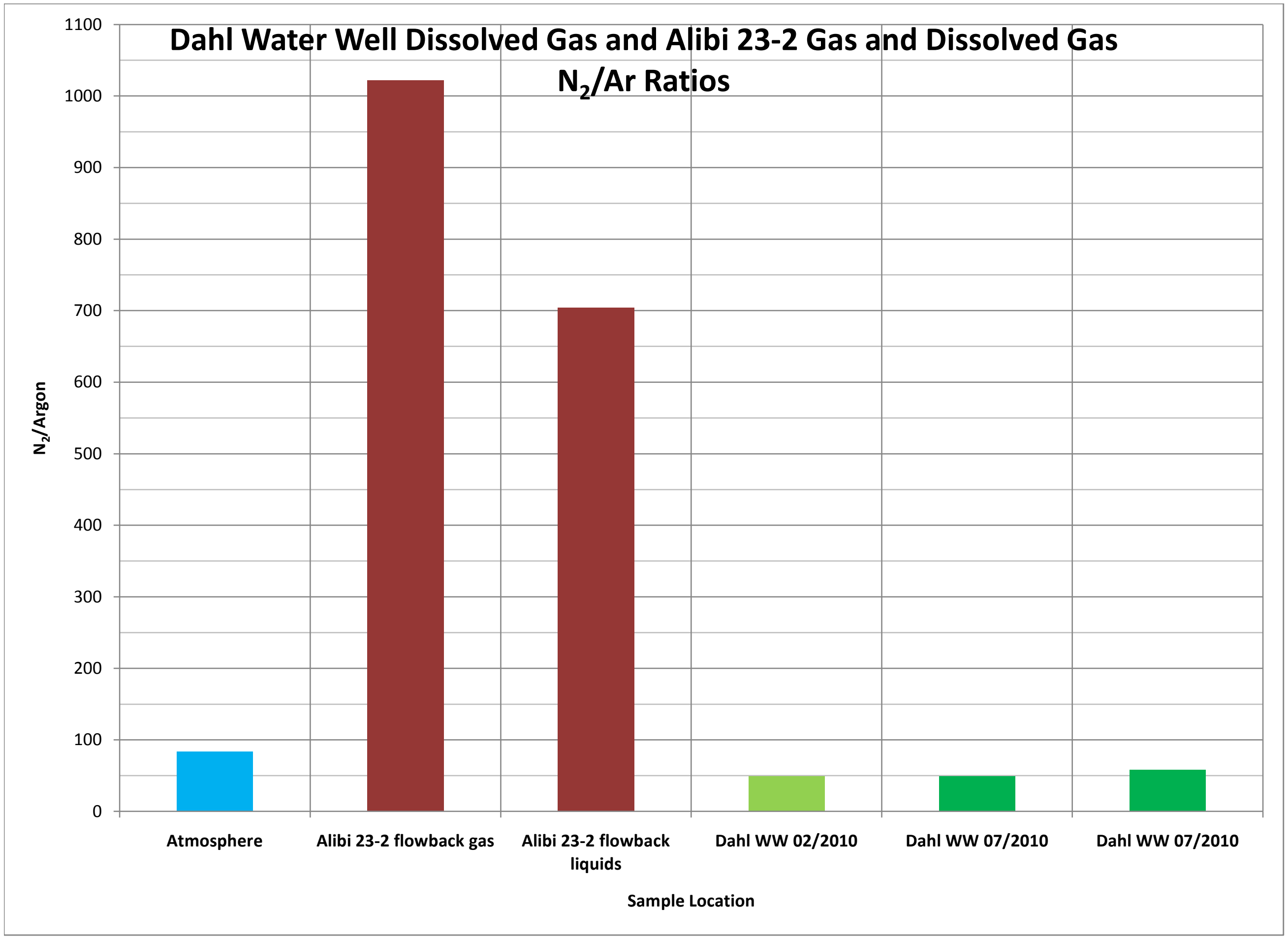


Figure 4.20 – Nitrogen to argon ratios for Dahl well water before and after impact, and for Alibi 23-2 flowback fluid and flowback gas emerging from flowback pipe, as presented in COGCC investigator final report on Dahl well investigation (COGCC, 2010).

APPENDIX C: MONITORING GUIDE

Colorado Water & Energy
RESEARCH CENTER

GROUNDWATER MONITORING GUIDE

Author's note, December 2011:

Not to be released in draft form.
Please refer to the CWERC Website for the peer-reviewed copy,
available in early 2012.