

# [***ARTICLE: CONSIDERATIONS FOR ANALYZING COLORADO GROUND WATER: A TECHNICAL PERSPECTIVE***](https://advance.lexis.com/api/document?collection=analytical-materials&id=urn:contentItem:552C-91H0-00SW-500H-00000-00&context=1516831)

Fall, 2011

**Reporter**

15 U. Denv. Water L. Rev. 105 \*

**Length:** 16065 words

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**Highlight**

ABSTRACT

In ***Colorado***, ground water experts provide the basis for the development, protection and administration of ground water resources. Ground water technical experts frequently interact with water rights attorneys and legal experts in matters related to ***Colorado*** water court proceedings, well permitting, rulemaking proceedings and other regulatory processes. The purpose of this article is to present the questions that ground water experts answer as part of these proceedings and to describe the processes by which ground water experts complete their technical analyses. In ***Colorado*** water court and well permitting proceedings, the focus of technical ground water concerns is usually on water quantity issues as opposed to water quality. The focus of this article is therefore focused on water quantity considerations. Water quality contamination and drinking water quality concerns are frequently addressed through separate regulatory agencies, such as the ***Colorado*** Department of Public Health and Environment (CDPHE) or the Environmental Protection Agency (EPA). Hydrogeologic investigations that occur under the jurisdiction of the CDPHE and the EPA are not the focus of this article.

Technical issues addressed regarding ground water generally focus on the prevention of injury to senior water rights, protection of water supply wells and aquifer systems, and quantifying available ground water resources. Ground water experts rely upon available information and a variety of technical tools and methods to complete analyses of ground water flow, recharge and discharge. Ground water experts use their judgment to select the appropriate tools and methods to analyze specific ground water problems on a case-by-case basis. In this article, we explore the tools available to ground water experts and how these tools are applied to solve specific problems.

**Text**

**[\*106]**

[*I*](https://advance.lexis.com/api/document?collection=statutes-legislation&id=urn:contentItem:8T9R-T2X2-D6RV-H374-00000-00&context=1516831). INTRODUCTION TO GROUND WATER

C.R.S. [*37-90-103(19)*](https://advance.lexis.com/api/document?collection=statutes-legislation&id=urn:contentItem:68BY-DJC3-GXF6-82XJ-00000-00&context=1516831) defines ground water as any water not visible on the surface of the ground under natural conditions. [[1]](#footnote-2)1 Since ground water is invisible, people often think it occurs in underground lakes, streams and veins. [[2]](#footnote-3)2 However, most ground water is located in small void spaces within soil or rock, known as porosity. Porosity resulting from void spaces between sand and gravel particles is known as primary porosity. [[3]](#footnote-4)3 Whereas, porosity resulting from void spaces in narrow crevices such as fractures or faults is known as secondary porosity. [[4]](#footnote-5)4 Beneath the ground surface, these void spaces become saturated with water. The depth at which the earth is saturated is called the water table and more specifically can be referred to as the static water level. [[5]](#footnote-6)5 At depths below the water table, the subsurface material is generally saturated. [[6]](#footnote-7)6 If the geologic formation, group of formations, or a part of the formation is saturated and **[\*107]** sufficiently permeable to yield an economically viable water supply, it is generally called an aquifer. [[7]](#footnote-8)7

An aquifer's ability to transmit water is expressed by the parameters of hydraulic conductivity (permeability) and transmissivity (transmissibility). [[8]](#footnote-9)8 The porosity of the material and the dynamic characteristics of the water determine hydraulic conductivity. [[9]](#footnote-10)9 Hydraulic conductivity is a coefficient of proportionality describing the rate at which water can move through a permeable medium. [[10]](#footnote-11)10 Figure 1 presents a range of hydraulic conductivities for various geologic materials. [[11]](#footnote-12)11 Transmissivity is the ability of the total thickness of an aquifer to horizontally transmit water and is the product of the aquifer's hydraulic conductivity and saturated thickness. [[12]](#footnote-13)12 Transmissivity is a function of properties of the liquid, the porous media, and the thickness of the porous media. [[13]](#footnote-14)13 Storage coefficient, specific yield, specific storage and storativity are measures of the amount of water that is stored in an aquifer. **[\*108]**

 Figure 1

From GWA, supranote 10.

Figure 1 - Hydraulic conductivity values for various aquifer materials.

Water supply wells are typically used to extract ground water from an aquifer. Ground water professionals typically design production wells to be open to the saturated, and most permeable, portion(s) of the aquifer through perforations in the well casing or manufactured well screen intervals. [[14]](#footnote-15)14 When a well pumps ground water the water level in the well is lowered, the change in water level is referred to as drawdown. The lowered water level during pumping is referred to as the pumping water level. Pumping water level is defined as the level at which water stands in a well when pumping is in progress. [[15]](#footnote-16)15 The rate of flow that a well can yield is a function of the aquifer transmissivity, the amount of available drawdown above the well pump, the capacity of the pump and the efficiency of the well structure. [[16]](#footnote-17)16

If the water bearing geologic formation is not completely saturated with water, it is called an unconfined aquifer. [[17]](#footnote-18)17 An unconfined aquifer is **[\*109]** defined as an aquifer having a water table, whose surface is at atmospheric pressure. [[18]](#footnote-19)18 The water level in the a well constructed in an unconfined aquifer is equal to the water table in the aquifer. When a well pumps water from an unconfined aquifer, water drains from the aquifer pore space and/or fractures to the well, temporarily dewatering a portion of that aquifer. [[19]](#footnote-20)19 Typical types of unconfined aquifers include alluvial and hard rock bedrock aquifers, which are discussed in more detail later. The amount of water that drains from the aquifer as a result of gravity is referred to as the specific yield. [[20]](#footnote-21)20 For example, if a ten-gallon container is filled with sand and gravel material with a porosity of twenty-five percent and a specific yield of twenty percent, up to two and a half gallons of water could be added to the container without overtopping. However, if holes were drilled at the bottom of the container allowing the water to drain by gravity, two gallons of water would eventually drain out the container. The remaining half-gallon of water would remain affixed to the sand and gravel under surface tension.

Some geologic formations greatly impede the movement of ground water. These formations are generally referred to as confining units or aquitards. [[21]](#footnote-22)21 Confining units are typically made up of low permeability clay and shale. [[22]](#footnote-23)22 If an aquifer is completely saturated, overlain by a confining unit and under pressure, the aquifer is considered a confined aquifer. [[23]](#footnote-24)23 As a result of the pressure, the water level in a well drilled into a confined aquifer will rise above the top of the aquifer. [[24]](#footnote-25)24 This water level is the potentiometric surface. [[25]](#footnote-26)25 If the water level rises above the ground surface resulting in water flowing out of the well, this is commonly referred to as an artesian flowing well. [[26]](#footnote-27)26 When a well pumps water from a confined aquifer, the aquifer yields water through compression of the aquifer material, expansion of the water, and drainage of adjacent unconfined areas. [[27]](#footnote-28)27 Ground water professionals define the amount of water per unit volume of a confined aquifer stored or expelled from the storage by the compression **[\*110]** of the aquifer material and expansion of water as specific storage, which is typically several orders of magnitude lower than specific yield. [[28]](#footnote-29)28

Ground water moves as a result of a pressure differential, and flows from areas of higher pressure to areas of lower pressure. The total amount of pressure within a column of ground water, frequently referred to as head, is generally expressed in feet or meters of water above a datum. [[29]](#footnote-30)29 One of the factors that controls the rate of ground water movement is the hydraulic gradient, which is defined as the difference in total head over a specific distance. [[30]](#footnote-31)30 When a well pumps ground water, the pumping lowers the water level in the well creating a hydraulic gradient between the well and surrounding aquifer, known as drawdown. [[31]](#footnote-32)31 This drawdown drives the flow of water into a well and creates a cone of depression in the aquifer. [[32]](#footnote-33)32 In an unconfined aquifer, the cone of depression dewaters a portion of the aquifer and reduces saturated thickness; whereas in a confined aquifer, the saturated thickness remains constant but the pressure head is reduced. [[33]](#footnote-34)33

Aquifer systems are hydraulically connected with surface water systems, including streams, ***rivers***, lakes and springs. [[34]](#footnote-35)34 As a result, changes in aquifer inflow, outflow, or water level (stresses) will generally result in changes in flow of a surface water system. [[35]](#footnote-36)35 Aquifer stresses include but are not limited to: the pumping of a well, a change in ground water return flows if an irrigation practice is altered, the dewatering of a gravel pit, and the recharge of water to an aquifer system. [[36]](#footnote-37)36 Aquifer stresses create change in aquifer water levels that propagate through aquifer systems, which cause changes in flow patterns and corresponding depletions or accretions to surface water systems. [[37]](#footnote-38)37

[*II*](https://advance.lexis.com/api/document?collection=statutes-legislation&id=urn:contentItem:8T9R-T352-D6RV-H379-00000-00&context=1516831). PHYSICAL CLASSIFICATIONS OF GROUND WATER

In ***Colorado***, the three most common types of aquifers encountered include alluvial aquifers, sedimentary bedrock aquifers, and hard rock bedrock aquifers, discussed in more detail below. [[38]](#footnote-39)38

**[\*111]**

A. Alluvial Aquifers

Alluvial aquifers are relatively young aquifers in geologic time, created mostly during the Quaternary [[39]](#footnote-40)39 geologic period, and consist of unconsolidated sand and gravel material. [[40]](#footnote-41)40 Alluvial aquifers are relatively shallow and proximal to the surface stream systems that created the deposits . [[41]](#footnote-42)41 However, alluvial aquifers can be thin or absent in areas where the surface stream has eroded into, or is underlain by, bedrock. [[42]](#footnote-43)42 Some of the major ***rivers*** in ***Colorado***, and therefore, some of the major alluvial aquifer systems in ***Colorado***, include the South Platte ***River***, Arkansas ***River***, ***Colorado*** ***River***, Yampa ***River***, White ***River***, and Rio Grande ***River***. [[43]](#footnote-44)43 Alluvial aquifers have a strong connection to stream systems due to the unconsolidated aquifer material, relatively shallow depths, and proximity to surface streams. [[44]](#footnote-45)44

Well records from the ***Colorado*** Division of Water Resources indicate alluvial aquifers in ***Colorado*** range in thickness from tens of feet to a few hundred feet. [[45]](#footnote-46)45 Typically, the thickness of alluvial aquifers increases towards valley centers. Alluvial aquifers are typically unconfined. The specific yield of alluvial aquifer material ranges from 0.5 percent to 30 percent [[46]](#footnote-47)46 and hydraulic conductivity values range from 1 to 100,000 gallons per day per square foot. [[47]](#footnote-48)47 Due to their high specific yield, high hydraulic conductivity, and proximity to recharge sources (stream systems), alluvial aquifers are some of the most productive aquifers in ***Colorado***. [[48]](#footnote-49)48 Figure 4 presents the generalized locations of alluvial aquifer systems in ***Colorado***. [[49]](#footnote-50)49 **[\*112]**

 Figure 4

From GWA, supra note 10.

Figure 4 - Location map of alluvial aquifers in ***Colorado***.

B. Sedimentary Bedrock Aquifers

Sedimentary bedrock aquifers in ***Colorado*** consist primarily of conglomerate, sandstone, [[50]](#footnote-51)50 siltstone, [[51]](#footnote-52)51 and limestone [[52]](#footnote-53)52 of varying age and are located in structural basins containing multiple geologic layers. Many of these structural basins extend thousands of feet below the earth's surface. The major sedimentary bedrock aquifers in ***Colorado*** include the Denver Basin, Piceance Basin, Eagle Basin, Sand Wash Basin, Paradox Basin, San Juan Basin, Raton Basin, Dakota-Cheyenne aquifer, and the High Plains aquifer. Groundwater flow in sedimentary bedrock aquifers is influenced by various structural features such as dipping beds, [[53]](#footnote-54)53 fractures, [[54]](#footnote-55)54 and faults. [[55]](#footnote-56)55 In addition, groundwater flow in sedimentary bedrock aquifers **[\*113]** is influenced by geologic layering of different material within sedimentary bedrock formations, such as layered sandstone, siltstone, and shale. [[56]](#footnote-57)56 This layering is known as stratigraphy. As a result of the varying geology, depth, structural features and stratigraphy, sedimentary bedrock aquifers have varying degrees of connection to the stream system.

The Denver Basin is the most utilized, and subsequently, most studied sedimentary bedrock aquifer system in ***Colorado***. The administratively defined Denver Basin aquifer system generally extends north to south from Greeley to ***Colorado*** Springs and west to east from Golden to Limon. The geology of the Denver Basin consists of Tertiary [[57]](#footnote-58)57 and Cretaceous [[58]](#footnote-59)58 age sandstone, siltstone and shales resembling concentrically stacked asymmetrical bowls. [[59]](#footnote-60)59 Confining layers separate the individual hydrogeologic units, resulting in four separate statutory aquifers contained in the basin. In descending order, these aquifers include: the Dawson, Denver, Arapahoe and Laramie-Fox Hills aquifers. The unique administrative regulations for ground water in the Denver Basin have provided many Front Range metropolitan entities with an economically efficient and locally available water supply, enabling growth. However, many of these entities are now pursuing renewable water supplies to replace their nonrenewable Denver Basin water supplies.

The specific yield, hydraulic conductivity and well yield in sedimentary bedrock aquifers is typically less than alluvial aquifers. The specific yield of sedimentary bedrock aquifers typically ranges from 5-percent to 20-percent. [[60]](#footnote-61)60 Specific storage values are typically 0.0001 per foot or less. [[61]](#footnote-62)61 Hydraulic conductivity will typically range from 0.0001 to 10 gallons per day per square foot. [[62]](#footnote-63)62 Figure 5 presents the general location of sedimentary bedrock aquifer systems in ***Colorado***. [[63]](#footnote-64)63

**[\*114]**

 Figure 5

From GWA, supra note 10.

Figure 5 - Location map of sedimentary bedrock aquifers in ***Colorado***.

C. Hard Rock Bedrock Aquifers

Hard rock bedrock aquifers in ***Colorado*** are generally located in mountainous regions and consist of fractured igneous and metamorphic crystalline rock from the Precambrian [[64]](#footnote-65)64 era and Tertiary period. Folding and faulting has caused extensive joints and fracture systems within many of these formations. [[65]](#footnote-66)65 Primary porosity in these aquifers is very low while secondary porosity resulting from the fractures and faults can provide significant permeability within these aquifers. [[66]](#footnote-67)66 Hard rock bedrock aquifer wells are historically limited to 400 feet below ground surface because overburden pressures effectively close the fractures and reduce secondary porosity with depth, [[67]](#footnote-68)67 thereby reducing well yield potential at greater depths. However, productive wells have been constructed at greater depths. [[68]](#footnote-69)68 Hard rock bedrock aquifers generally have a strong connection with surface stream systems.

Hard rock bedrock aquifers are difficult to characterize because of non-uniform fractures and faults. As a result, well yields are difficult to predict until after the well has been drilled, constructed and tested. In Jefferson County, ***Colorado***, this uncertainty has led to the creation of the Jefferson County Mountain Ground Water Overlay District, which requires **[\*115]** demonstration of an adequate water supply through well testing prior to approval of a building permit, rezoning application, site development plan or special use and platting application not served by a water district. [[69]](#footnote-70)69

Hydraulic conductivity and well yields in hard rock bedrock aquifers are highly variable. The hydraulic conductivity of hard rock aquifer systems can range from 0.1 to 10,000 gallons per day per square foot, although lower hydraulic conductivity may occur if fractures are not present in the formation. [[70]](#footnote-71)70 Well records from the Division of Water Resources indicate hard rock bedrock aquifer well yields are generally only a few gallons per minute, but wells completed in fractured hard rock aquifers can produce up to 50 gallons per minute or more if they penetrate extensively fractured zones, fault zones, or shear zones. [[71]](#footnote-72)71 Topography impacts well yields, with wells in valleys and draws producing at a higher rate than wells on ridges, slopes, or saddles. [[72]](#footnote-73)72 This variation may be attributable to the proximity of faults or fracture zones that have influenced the resultant topography. [[73]](#footnote-74)73 Figure 6 presents the general locations of hard rock aquifer systems in ***Colorado***. [[74]](#footnote-75)74

 Figure 6

From GWA, supra note 10.

Figure 6 - Location map of hard rock aquifers in ***Colorado***.

**[\*116]**

[*III*](https://advance.lexis.com/api/document?collection=statutes-legislation&id=urn:contentItem:8T9R-T372-8T6X-731R-00000-00&context=1516831). SUMMARY OF ***COLORADO*** GROUND WATER LAW

There are three major pieces of legislation that provide the laws, rules and framework to manage and administer ground water in ***Colorado***, including, the 1957 Ground Water Laws [[75]](#footnote-76)75, 1965 Ground Water Management Act [[76]](#footnote-77)76 ("the 1965 Act") and the 1969 Water Rights Determination and Administration Act [[77]](#footnote-78)77 ("the 1969 Act"). In addition, other important legislation governing ground water includes Senate Bill 73-213, Senate Bill 85-5 and House Bill 72-1042. This legislation is discussed in more detail below.

In 1957, the Ground Water Act established that (1) ground water users must file a statement of use with the State Engineer, (2) a well permit is required from the State Engineer prior to drilling a new well, (3) a well permit does not grant or confer a groundwater right to the user, (4) a ground water right's priority date shall not be postponed beyond its true date of appropriation due to the failure to conduct a surface right adjudication, and (5) critical ground water areas that "have approached, reached or exceeded the normal annual rate of replenishment" shall be identified by the ***Colorado*** Ground Water Commission. [[78]](#footnote-79)78

The 1965 Act provided authorization to the ***Colorado*** Ground Water Commission to (1) designate ground water basins where ground water lacks a substantial hydrogeological connection to a surface stream, (2) employ a permit system to allocate and regulate ground water within designated ground water basins according to a modified prior appropriation basis promoting economic development and maintaining reasonable pumping levels, and (3) to create local ground water management districts to regulate the designated ground water basins. [[79]](#footnote-80)79 Additionally, the 1965 Act reiterated that all new wells obtain a well permit from the State Engineer and the well permit "shall not have the effect of granting nor conferring a ground water right upon the user." [[80]](#footnote-81)80

The 1969 Act establishes that (1) the State Engineer shall administer tributary ground water according to the doctrine of prior appropriation and (2) shall protect vested surface water and tributary ground water rights according to their decreed priorities, (3) that non adjudicated wells have two years to file for their original appropriation date, and (4) augmentation plans, discussed in more detail below, may be decreed. [[81]](#footnote-82)81 The 1969 Act recognized the interaction between ground water and surface **[\*117]** water and the ability of well pumping to reduce streamflows relied upon by senior surface water rights. [[82]](#footnote-83)82

An augmentation plan allows out-of-priority depletions by providing replacement water to prevent injury to other vested water rights. [[83]](#footnote-84)83 For example, the withdrawal of tributary ground water through a well results in either decreased aquifer discharge to surface water or increased loss from surface water, both of which are depletions to the stream system. Depletions from well pumping typically do not occur instantaneously. Instead, there is a timing lag between the time that the well is pumped and the time that the depletion occurs to the surface water system. [[84]](#footnote-85)84 These depletions to the stream system are referred to as lagged depletions. Lagged depletions from wells occur after pumping has stopped, and are referred to as post-pumping depletions. Post-pumping depletions can occur over a period of months, years or longer. [[85]](#footnote-86)85

Wells differ from surface water diversions in that depletions do not stop when the diversions stop. [[86]](#footnote-87)86 Unlike direct flow surface water rights, tributary well pumping typically requires an augmentation plan because lagged pumping depletions occur after the well pump has shut off. [[87]](#footnote-88)87 A junior surface water right can be operated without an augmentation plan because it is feasible to stop a diversion at the time that a senior water right places a call. [[88]](#footnote-89)88 In contrast, lagged depletions from a well will continue after a ***river*** call is placed, resulting in out-of-priority depletions. Many high capacity irrigation wells have been drilled into alluvial aquifers since the 1950's, and must operate according to augmentation plans designed to prevent injury to senior water rights. [[89]](#footnote-90)89 Due to the costs associated with augmentation plans, special groups have been formed to assist with development and operation of these plans. One example is the Lower Arkansas Water Management Association (LAWMA), which is a member-owned corporation that provides replacement water to off-set depletions caused by the membership's ground water use. [[90]](#footnote-91)90

**[\*118]** As a result of the 1965 Act and 1969 Act, ***Colorado*** established two statutory classifications of ground water: tributary ground water and designated ground water. [[91]](#footnote-92)91 The legislature created two additional statutory classifications of ground water, nontributary and not-nontributary, in 1973 under Senate Bill 73-213 and in 1985 under Senate Bill 85-5, respectively. All ground water in ***Colorado*** falls under one of these four statutory classifications and must be administered accordingly. House Bill 72-1042 creates an exemption for certain uses of small-capacity wells designated as exempt wells. The four statutory classifications of ground water and exempt wells are discussed in more detail below.

The first classification, tributary ground water, involves water that has a hydrologic connection to surface streams. As a result of this connection, state authorities administer tributary ground water in conjunction with surface water, under the priority system. Users must follow an augmentation plan to replace the out-of-priority depletions. Alluvial and hard rock bedrock aquifers are typically classified as tributary. Figure 2 presents an idealized schematic of a well pumping tributary ground water. [[92]](#footnote-93)92

 Figure 2

Modified from GWA, supra note 10.

Figure 2 - Schematic diagram of an unconfined aquifer system.

The ***Colorado*** Ground Water Commission manages the second classification, designated ground water, under a modified prior appropriation system that only exists in locations that have been "designated" by the ***Colorado*** Ground Water Commission. Designated ground water has two definitions: (1) ground water "which in its natural course would not be available to and required for the fulfillment of decreed surface rights" and (2) ground water "in areas not adjacent to a continuously flowing natural stream wherein ground water withdrawals have constituted the principal **[\*119]** water usage for at least fifteen years." [[93]](#footnote-94)93 The ***Colorado*** Ground Water Commission can establish designated ground water basins based on compliance with either definition, however; compliance with the first definition may be difficult to meet due to hydrologic complexities. [[94]](#footnote-95)94 Currently eight designated ground water basins have been established in ***Colorado***: Kiowa Bijou, Southern High Plains, Upper Black Squirrel Creek, Lost Creek, Camp Creek, Upper Big Sandy, Upper Crow Creek and Northern High Plains. [[95]](#footnote-96)95

The third classification, nontributary ground water, encompasses water located outside the boundaries of any designated ground water basin that has little to no hydrologic connection to surface streams. Nontributary ground water is defined as ground water that when withdrawn will not deplete the flow of a natural stream within one hundred years of continuous withdrawal "at an annual rate greater than one-tenth of one percent of the annual rate of withdrawal." [[96]](#footnote-97)96 As a result of this disconnect, nontributary ground water is allocated based on overlying land ownership rather than according to the priority system. [[97]](#footnote-98)97 Natural recharge is very low in nontributary aquifers, and as a result, nontributary ground water is generally considered to be a non-renewable resource. In order to prolong use of the resource, Senate Bill 73-213 specified a minimum one hundred year aquifer life for nontributary aquifers. [[98]](#footnote-99)98 The mandated 100-year aquifer life effectively allocates the total available ground water entitlement based on 1-percent per year. [[99]](#footnote-100)99 Nontributary ground water is quantified based on the product of land area, aquifer saturated thickness, and specific yield, divided by 100 years. The Denver Basin aquifers comprise the primary nontributary ground water resource in ***Colorado***. An additional limitation on nontributary ground water specific to the Denver Basin allows no more than 98-percent of the water withdrawn annually to be consumed. [[100]](#footnote-101)100 Therefore, 2-percent of pumped nontributary Denver Basin ground water must be relinquished to the surface stream system. This 2-percent relinquishment is typically achieved through assignment of return flows. Figure 3 presents an idealized schematic of a well pumping nontributary ground water. [[101]](#footnote-102)101 **[\*120]**

 Figure 3

Modified from GWA, supra note 10.

Figure 3 - Schematic diagram of a confined aquifer system.

Not-nontributary ground water is water located within the Denver Basin that does not meet the statutory definition of nontributary ground water. [[102]](#footnote-103)102 However, pumping depletions remain attenuated over many decades and centuries. Facing these unique geologic and hydrologic characteristics and the great economic importance of the ground water resource, the ***Colorado*** Legislature declared that all Denver Basin ground water not meeting the definition of nontributary ground water would still be allocated in the same manner as nontributary ground water. Therefore the allocation of not-nontributary ground water is similarly based on overlying land ownership and a minimum one hundred year aquifer life. [[103]](#footnote-104)103 However, in recognition of the depletive effects pumping not-nontributary ground water may have on surface streams, the ***Colorado*** Legislature required the approval of an augmentation plan in order to pump not-nontributary ground water. [[104]](#footnote-105)104 The augmentation plan requires the replacement of depletions both during pumping and after pumping has stopped. The law requires the replacement of calculated actual depletion for ground water pumped from locations within one mile of the point of connection between a surface stream or its alluvium and the outcrop of the not-nontributary aquifer. Relinquishment of 4-percent of not-nontributary pumping is required at locations greater than one mile from the point of connection between the aquifer and the stream system. [[105]](#footnote-106)105

Exempt wells include "small-capacity wells for domestic, stock watering, and low-intensity commercial uses in locations where other [water] supplies are not available." [[106]](#footnote-107)106 ***Colorado*** allows exempt wells in tributary, **[\*121]** designated, nontributary and not-nontributary ground water aquifers, and largely exempts them from the rules and regulations covering these designations. [[107]](#footnote-108)107 Recognizing the social and economic benefit, the ***Colorado*** Legislature authorized exempt wells with the intent "to allow citizens to obtain a water supply in less densely populated areas...where other water supplies are not available." [[108]](#footnote-109)108 The ***Colorado*** Division of Water Resources has explained that in most cases, permits for exempt wells limit pumping rates to fifteen gallons per minute and require non-evaporative wastewater disposal systems. [[109]](#footnote-110)109 The disposal systems may include septic tank systems or leach field systems and must return the water to the same drainage basin in which the well is located. [[110]](#footnote-111)110 For example, one type of exempt well permit is for domestic and livestock uses on tracts of land 35 acres or more, allowing the well to serve up to three single-family dwellings, irrigate one acre of lawn or garden, and provide water for domestic and livestock animals. [[111]](#footnote-112)111 Other exempt well permit types depend on when a subdivision was platted and may include household use only wells and small-capacity commercial wells.

[*IV*](https://advance.lexis.com/api/document?collection=statutes-legislation&id=urn:contentItem:8T9R-T3H2-D6RV-H37G-00000-00&context=1516831). HYDROGEOLOGY, WELL-TO-WELL INTERFERENCE AND STREAM DEPLETIONS

A change to a ground water system in one location can impact surface water and ground water at other locations within an aquifer system. For instance, when a well pumps water, the cone of depression [[112]](#footnote-113)112 propagates outward reducing water levels in nearby wells constructed in the same aquifer. As a result, this reduction in water level can reduce available drawdown in nearby production wells and potentially limit yields and result in increased pumping costs. Water level changes in a well, caused by the operation of another well are generally known as well-to-well interference. In addition to localized interference resulting from a small number of wells, cones of depression from multiple wells in an aquifer can overlap and accentuate each other. For example, this occurs during the irrigation season in the Arapahoe aquifer of the Denver Basin, resulting in a greater seasonal well-to-well interference. [[113]](#footnote-114)113 In the Arapahoe aquifer, seasonal water level decline from the beginning of irrigation season **[\*122]** to the end of irrigation season can range from 125 to 200 feet. [[114]](#footnote-115)114 Similarly, regional water level decline rates occurring in the Arapahoe aquifer over time have ranged from 20 to just under 50 feet per year. [[115]](#footnote-116)115 This regional decline of water levels in the Denver Basin aquifers has emphasized the finite and limited nature of the aquifer system, and has caused many municipalities relying upon Denver Basin ground water to pursue costly alternative renewable water supplies. [[116]](#footnote-117)116

Ground water pumping and recharge may not only affect other wells but may also result in depletions or accretions to surface streams. The cone of depression resulting from a pumping well will ultimately propagate through an aquifer, and if the cone of depression extends to a surface water feature in connection with the aquifer, then the change in water level will induce a depletion to the stream. The interaction between ground water and surface water occurs at the streambed interface and impacts both gaining streams and losing streams. [[117]](#footnote-118)117

[*V*](https://advance.lexis.com/api/document?collection=statutes-legislation&id=urn:contentItem:8T9R-T3X2-8T6X-731X-00000-00&context=1516831). ***COLORADO*** REGULATORY FRAMEWORK

The focus of technical issues addressed by ground water experts is directed towards matters related to the ***Colorado*** water courts and the State Engineer's Office. These entities are tasked with prevention of injury to senior water rights or wells and quantifying legal water supply entitlements. Technical ground water investigations are also completed to determine the adequacy of a proposed water supply. For example, county governments may require water adequacy reviews for subdivisions or other zoning changes. [[118]](#footnote-119)118 As part of the coal mining approval process, ***Colorado*** statute requires the Division of Reclamation Mining and Safety (DRMS) to consider impacts to the "hydrologic balance." [[119]](#footnote-120)119

In the State of ***Colorado***, water rights adjudications occur in the seven water courts, which function in the seven primary drainage basins of ***Colorado***. [[120]](#footnote-121)120 Adjudications include filings for new ground and surface water rights, water rights augmentation plans, exchanges, and water rights changes, including changes of use, alternate points of diversion, and changes of location. [[121]](#footnote-122)121

**[\*123]** The State Engineer has the responsibility of administering water rights and well permits. [[122]](#footnote-123)122 On multiple occasions, the State Engineer has also been issued the authority to implement rules and regulations pertaining to ground water administration. [[123]](#footnote-124)123 Examples of rulemaking proceedings include the Denver Basin Rules, [[124]](#footnote-125)124 the Statewide Nontributary Ground Water Rules [[125]](#footnote-126)125 and the Produced Nontributary Ground Water Rules. [[126]](#footnote-127)126

[*VI*](https://advance.lexis.com/api/document?collection=statutes-legislation&id=urn:contentItem:8T9R-T4F2-D6RV-H37N-00000-00&context=1516831). ACTIVITIES POTENTIALLY RESULTING IN WATER RIGHTS INJURY

Listed below are examples of activities that may result in injury to surface water or ground water rights due to changes in the aquifer system.

1. Pumping of a water supply well may result in out-of-priority stream depletions, even after pumping has stopped.

2. Pumping of wells in an aquifer system may cause excessive drawdowns in an aquifer, thereby inhibiting senior wells from withdrawing their entitlements.

3. Pumping of wells in an aquifer system may cause drawdowns in an aquifer, resulting in deeper pump setting depths in nearby wells, greater pumping costs and lower achievable pumping rates. This type of well-to-well interference in not always considered to be injurious in ***Colorado*** water law. [[127]](#footnote-128)127

4. If a historical surface water right is changed through the ***Colorado*** court process and irrigation of historically irrigated lands is ceased, then historical return flows occurring through deep ground water percolation will no longer return to the stream system. Senior water rights have historically relied on those return flows and the interruption of the return flows may injure water rights. [[128]](#footnote-129)128

5. The operation of a ground water recharge plan may result in a rise of the water table, and thereby cause sub-irrigation of crops and increased consumption by phreatophytes. Failure to account for this increased consumption of ground water may overstate accretions of the returned water to the stream system.

6. In a gravel mining operation, impacts to neighboring water supply wells may result if a gravel pit is dewatered.

7. Under the Denver Basin Rules, ground water entitlements are quantified based on overlying land and the characteristics of the aquifer **[\*124]** system. [[129]](#footnote-130)129 Erroneous quantifications may result in an over appropriation of the aquifer, thereby accelerating the depletion of a limited resource.

Injury to water rights could result from the scenarios described above, and ground water analyses are needed to quantify the potential for injury. With these considerations in mind, ground water experts are skilled in estimating impacts to stream systems, wells, and aquifer systems, specifically to determine the following:

1.The timing, location, and amount of stream depletions and accretions.

2.Changes in aquifer water levels resulting from various aquifer stresses, including: well pumping, aquifer dewatering or recharge.

3.Changes in ground water / surface water interaction resulting from an aquifer stress. For example, well pumping in some aquifer systems has potential to dry up nearby stream systems.

4.The sustainability of an aquifer system.

5.The amount of ground water in storage or flowing through an aquifer system.

6.The amount of ground water available for appropriation from an aquifer system.

7.Changes to water quality resulting from an aquifer stress.

The findings of ground water investigations are frequently used to develop terms and conditions for inclusion in water rights decrees or well permits. Examples of terms and conditions that may be specified in ***Colorado*** water court decrees are provided below.

1.In fractured rock aquifers, water level monitoring may be required to ensure that well pumping does not interfere with the ability of nearby wells to produce their pumping entitlements. [[130]](#footnote-131)130

2.In an alluvial aquifer system, water level monitoring may be required to ensure that water level drawdowns resulting from one entity's pumping do not interfere with another entity's ability to pump their ground water entitlements. In Lochbuie, trigger water level elevations were established; if the trigger water levels were measured as a result of the applicants' pumping, then mitigation was required to maintain aquifer water levels above the water levels trigger elevations. [[131]](#footnote-132)131

3.In a ground water recharge plan, volumetric limits may be specified to prevent excessive water level rises and consumptive use resulting from shallow ground water levels. [[132]](#footnote-133)132

**[\*125]** 4. Water rights augmentation plans may require the delivery of augmentation water or recharge water at specific times and locations to ensure that ground water accretions to surface streams occur when and where they are needed to prevent injury to vested downstream water rights.

[*VII*](https://advance.lexis.com/api/document?collection=statutes-legislation&id=urn:contentItem:8T9R-T4S2-D6RV-H37V-00000-00&context=1516831). METHODS FOR EVALUATING GROUND WATER

When evaluating ground water resources, ground water experts must first understand the recharge, discharge and flow patterns of the ground water system. Such information may be obtained from mapping, published literature and well records. In addition to these sources, field work including flow measurements, well water level measurements, pumping tests and water quality testing may be implemented to characterize the local hydrogeology. After data are collected, it can be used to evaluate ground water movement through the use of modeling techniques or by applying ground water equations. Ground water experts rely on ground water equations and models to analyze ground water flow systems and predict the behavior of flow systems in the future. These tools can be used to complete simulations of ground water systems and predict such things as aquifer characteristics, water levels, well-to-well interference, and location and magnitude of surface stream impacts.

A. Pumping Tests

Pumping tests can be conducted on a well after the well(s) has been drilled and constructed. [[133]](#footnote-134)133 These tests provide data to determine local aquifer characteristics such as transmissivity, storage coefficient, and to identify boundary conditions. [[134]](#footnote-135)134 Boundary conditions can include recharge or barrier (negative) boundaries. [[135]](#footnote-136)135 A recharge boundary may include a stream or lake and can limit drawdown during pumping. [[136]](#footnote-137)136 However, a barrier or negative boundary, such as a low-permeability formation at the aquifer edge, can increase drawdown during pumping. [[137]](#footnote-138)137 In addition, pumping tests can be used to determine the efficiency of a well structure. [[138]](#footnote-139)138

Pumping tests involve the pumping of a well under controlled pumping conditions, while measuring static and pumping water levels in the pumping well and nearby observation wells if feasible. [[139]](#footnote-140)139 Typically, water level measurements are collected at specified time intervals during pumping and during the recovery period after pumping has stopped. [[140]](#footnote-141)140 The two **[\*126]** most common pumping tests conducted on wells include the step test and long-term constant discharge test. [[141]](#footnote-142)141 A step test consists of increasing the well pumping rate at regular intervals. [[142]](#footnote-143)142 For example, the well may be pumped at a rate of 50 gallons per minute for 30 minutes and then the pumping rate is increased to 100 gallons per minute for the next 30 minutes and so on for several more steps. Data collected during the step test can be used to estimate the efficiency of a well structure. [[143]](#footnote-144)143 A long-term constant discharge test consists of pumping a well at a constant rate, typically for 24-hours or longer. [[144]](#footnote-145)144 This type of test provides an accurate analysis of aquifer characteristics and boundary conditions. [[145]](#footnote-146)145 Ideally, observation wells should be identified or installed at appropriate distances from the pumping well to collect data at a distance in the aquifer. However, due to cost considerations, location, and project timing, observation wells are not always viable. It should be noted that storage coefficients calculated from pumping well data alone are generally not reliable. [[146]](#footnote-147)146 Therefore, if no observation wells are available to collect data, other means of determining the storage coefficient should be utilized, such as data from nearby pumping tests or published values for similar aquifer types. [[147]](#footnote-148)147

B. Monitoring Programs

Ground water impacts resulting from changes to aquifer systems can be measured by monitoring water levels and water quality. Monitoring programs are frequently implemented as part of other aquifer analyses or modeling projections. [[148]](#footnote-149)148 Monitoring programs provide information to understand changes that occur in an aquifer system under natural or static conditions, and can function as an early warning system if unfavorable aquifer conditions are expected to occur. [[149]](#footnote-150)149 As summarized below, monitoring programs are sometimes included as a requirement in ***Colorado*** water court decrees or stipulations as a protective term and condition. [[150]](#footnote-151)150

C. Conceptual Models

A conceptual model is a description of an aquifer system, which includes inflows, outflows, storage, aquifer extent, and hydraulic properties. [[151]](#footnote-152)151 Conceptual models are the simplest form of model and act as a **[\*127]** basis for any additional modeling. [[152]](#footnote-153)152 Conceptual models are frequently described with cross-sections or other visual means. Other types of conceptual models may include flow charts or simple written descriptions of the ground water system. Conceptual models are important tools for understanding ground water systems; however, they are stationary and unable to make predictions of future behavior. [[153]](#footnote-154)153

D. Ground Water Equations (Analytical Models)

Analytical models rely on mathematical methods to arrive at a solution. These mathematical methods are typically applied based on a simplified set of assumptions. To rely on analytical modeling, the assumptions inherent to the ground water equations should be considered to ensure they are suitable for the question at hand and to ensure that applying a simplified representation of the aquifer system will provide an adequate solution. Types of analytical models may include Darcy's law, the Theis equation, the Cooper-Jacob equation, and the Glover equation. These analytical models are discussed in more detail below.

Darcy's law was developed in 1856 by a French engineer named Henri Darcy and is used to quantify ground water flow. [[154]](#footnote-155)154 Darcy found that the rate of flow between two points in a porous medium is proportional to the difference in head and inversely proportional to the flow length. [[155]](#footnote-156)155 Inputs to Darcy's law include hydraulic gradient, flow rate, cross-sectional area, and hydraulic conductivity.

C.V. Theis developed the Theis equation in 1935. [[156]](#footnote-157)156 This equation is most commonly used to predict drawdown and flow rates over time. In addition, the Theis equation is commonly used to calculate aquifer characteristics from pumping test data. Parameters in the Theis analyses include drawdown, pumping rate, transmissivity, distance from the center of the pumping well to the point where drawdown is measured, storage coefficient, and time since pumping started. The Theis equation assumes an idealized set of aquifer conditions, such as an infinite and homogeneous aquifer. [[157]](#footnote-158)157 Physical world aquifer systems are more complex, but the equation can be applied to estimate how an aquifer will respond to an imposed stress.

The Cooper-Jacob equation, also known as the modified non-equilibrium equation, was developed by H.H. Cooper and C.E. Jacob in 1946. [[158]](#footnote-159)158 This equation is a simplified version of the Theis equation and can be relied upon in many instances without significant error. The inputs, **[\*128]** assumptions, and uses for the Cooper-Jacob equation are the same as the Theis equation.

The Glover equation was developed by R.E. Glover and G.E. Balmer in 1954 to estimate the timing and magnitude of impact from pumping or recharge on a stream system. [[159]](#footnote-160)159 Inputs to the Glover equation include the distance from the simulated well to the simulated stream, distance from the well to no-flow boundary, distance from the no-flow boundary to the ***river***, transmissivity, and specific yield. In ***Colorado***, ground water experts often rely on the Integrated Decision Support Alluvial Water Accounting System (IDS AWAS) software, which is a graphic user interface for the Glover equation. [[160]](#footnote-161)160 Similar to the Theis equation, the Glover equation assumes an idealized set of aquifer conditions. [[161]](#footnote-162)161

F. Numerical Models

Numerical models simulate aquifer flow by breaking the aquifer into a grid of points or cells. Numerical models rely on mathematical methodologies to simulate flow between the grid cells. Numerical models can be operated in both transient and steady state modes to predict behavior in ground water systems. Due to their complexity and time commitment, numerical models are generally utilized only if analytical modeling is not appropriate, for instance, with regional aquifers containing complex geometry and heterogeneous aquifer characteristics and thickness. One example of a numerical modeling tool is MODFLOW, developed by the United States Geological Survey. MODFLOW is a numerical finite difference program, which is capable of simulating a number of parameters: ground water and surface water flow, aquifer parameters, water levels in aquifers and surface water features, evapotranspiration, aquifer recharge, and boundary conditions. Numerical models can be operated in many different modes with various input and output parameters. Also, numerical models can be operated to simulate both simplistic and very complex conceptual models. As is the case with any modeling procedure, the accuracy of the results depends on the accuracy of the input data.

**[\*129]**

[*VIII*](https://advance.lexis.com/api/document?collection=statutes-legislation&id=urn:contentItem:8T9R-T502-8T6X-7323-00000-00&context=1516831). EXAMPLES OF GROUND WATER PROBLEMS AND METHODS APPLIED

In order to illustrate the technical approaches that ground water experts typically apply, we provided various examples of actual case studies involving technical ground water analysis. In each example the approach was selected based on a number of factors, including the matter in question, the complexity of the aquifer system, available aquifer data, stakeholder concerns, administrative and water rights sensitivities, and project budget and schedule.

Example A - Alluvial augmentation plan for a water supply well, South Platte ***River*** basin - Division 1 Case No. 03CW025

An alluvial water supply well produces from the alluvium of the South Platte ***River*** and its tributaries. The lithology of the alluvial aquifer is relatively homogenous and the South Platte ***River*** is never dry at this location. The case involved an augmentation plan to replace depletions resulting from the pumping well. The augmentation source was nontributary ground water delivered to the alluvial aquifer near the point of depletion. The Glover equation was selected to determine the timing, location, and amount of stream depletions resulting from the operation of the alluvial water supply well; the timing, location, and amount of the delivery of return flows; and augmentation deliveries to the stream system. Inputs for the calculations in the Glover analysis included aquifer characteristics obtained from pumping test data on the water supply well and aquifer boundary conditions obtained from existing hydrogeologic mapping by the U.S. Geological Survey and others.

Example B - Alluvial augmentation plan for water supply wells, Cherry Creek basin - Division 1 Case No. 95CW277

Case No. 95CW277 involved an augmentation plan for water supply wells producing from the Cherry Creek alluvial aquifer. In this portion of the Cherry Creek drainage, the creek becomes dry during most years. When the stream is dry and alluvial water supply wells operate, the aquifer is depleted, resulting in a lowering of the water table in the aquifer. The dry stream condition and simultaneous well pumping result in the creation of a "hole" [[162]](#footnote-163)162 in the aquifer. Well-pumping depletions to the aquifer increase the size of the "hole" and result in a prolonged period of a dry stream condition when the hole fills. The enlarged "hole" causes depletions to occur at periods of runoff when the water in the stream effectively fills the "hole" instead of flowing downstream. This condition is more complicated than can be simulated using the Glover equation, and therefore, a more robust tool was used in order to determine the timing and location of stream depletions. In Case No. 95CW277, a MODFLOW ground water model and a spreadsheet water balance model were employed to determine the timing and location of stream depletions. **[\*130]** This hydrologic condition is an example of a condition in which the Glover equation was not used to estimate the timing and location of stream depletions.

Example C - Gravel Pit Mining Operation - Arkansas ***River*** Basin - Quantification of Impacts to Water Supply Wells.

During gravel mining operations, alluvial sand and gravel are sometimes mined from the saturated portion of the alluvium. Operators frequently dewater the mine pit to provide dry access to the sand and gravel product. As the mine is dewatered, it results in a lowering of the water table in the vicinity of the mine pit, which can be detrimental to neighboring water supply wells.

Analytical calculations such as the Theis equation can be used to estimate water level changes from mining dewatering activities, [[163]](#footnote-164)163 but for this mine a MODFLOW ground water model was developed and used to simulate water level changes that may result from the mining activities. [[164]](#footnote-165)164

To minimize the pumping needed to dewater the mine and to provide for water storage after mining is completed, operators sometimes install low permeability ground water barriers, such as slurry walls, around the mine pit. The low permeability barriers serve to protect nearby wells from the dewatering impacts of mining operations, but can result in other concerns. Low permeability barriers sometimes result in the mounding [[165]](#footnote-166)165 of ground water, or a rise of water level in the aquifer on the upstream side of the barrier. Rises in water level can be detrimental to neighboring basements and septic systems if shallow ground water conditions exist close to such structures and if the structures are sensitive to changes in water levels.

The MODFLOW model developed for this gravel pit was capable of simulating the change in water level that resulted from the sloping water table interacting with the low permeability barrier. [[166]](#footnote-167)166 Furthermore, water level monitoring programs are frequently implemented as part of DRMS and State Engineer gravel pit well-permitting processes to quantify such water level changes and to function as an early warning system in case detrimental water level changes occur. Water level monitoring data can also be used to project future water level changes in aquifer systems if new aquifer stresses are planned in the future. Examples of mining operations during which ground water models and water level monitoring programs have been implemented include the Pueblo East Pit in the Arkansas **[\*131]** ***River*** alluvium [[167]](#footnote-168)167 and the Lyons Pit in the alluvium of the St. Vrain ***River***. [[168]](#footnote-169)168

Example D - Augmentation Plan for Municipal Well in Fractured Rock Environment

Fractured rock aquifer systems, such as those that exist along the Front Range of ***Colorado***, typically contain minimal ground water storage. As a result, cones of depression resulting from pumping wells can extend for long distances from pumping wells, potentially impacting water levels in nearby wells. Furthermore, water supply wells completed in these types of aquifer systems often do not result in high pumping rates and cannot tolerate water level changes as effectively as wells completed in other aquifer systems. Aquifer systems of this type frequently rely on recharge from precipitation; therefore, water levels in the aquifer are sensitive to drought conditions.

Division 1 Case Nos. 94CW277 and 03CW217 involved water rights augmentation plans for two municipal water supply wells producing from the fractured bedrock aquifer in Gilpin County, ***Colorado***. The wells are located in a mountainous setting with numerous residential water supply wells located within a quarter-mile radius of the municipal water supply wells. As a result of concerns regarding potential impacts to these wells, in-depth field investigations were completed as part of Case No. 94CW277 to measure water level impacts resulting from the well pumping. The field investigations included two four-day pumping tests and long-term monitoring of water levels in the production wells and nearby residential water supply wells. In addition, projections were made of water level impacts to nearby wells using the Theis equation, based on aquifer characteristics determined from the pumping wells, including observation well data. In this case, the field investigations were utilized to quantify water level impacts resulting from the operation of the municipal water supply wells. The decree entered in Case No. 94CW277 included terms and conditions requiring the monitoring and reporting of water levels. [[169]](#footnote-170)169

Analytical calculations of water level impacts provided estimates of water level drawdowns. The aquifer parameters used in the Theis analyses were derived from the pumping test data involving both pumping wells and monitoring wells. In other words, actual water level changes measured in the aquifer resulting from well pumping were used to project water level changes resulting from other pumping scenarios.

Example E - Produced Nontributary Ground Water Rules

During the rulemaking process for the Produced Nontributary Ground Water Rules, [[170]](#footnote-171)170 a process was established by which proponents could petition the State Engineer to determine that the ground water in **[\*132]** specific oil and gas producing formations at specific locations is nontributary. The Rules identify specific methodologies for the purposes of determining whether or not a formation at a particular location is nontributary. [[171]](#footnote-172)171 The three methods include analytical modeling such as the Glover equation, numerical modeling such as MODFLOW, and alternate approaches such as geologic isolation of a formation from a surface water system. Each of these methods was successfully used to support Proposed Alternate Rules in the rulemaking process.

The Glover equation and simplified MODFLOW models were applied to essentially determine the distance to nontributary ground water from the point of connection between the oil and gas producing formations and the points of connection with surface streams. Both methodologies were determined to be acceptable by the Hearing Officer overseeing the rulemaking process. One Proposed Alternate Rule relied on the geologic isolation of a formation from any surface stream in ***Colorado***. The Sussex Sandstone of the D-J Basin was determined to be nontributary based on the fact that it does not outcrop anywhere in ***Colorado***, and therefore cannot interact with a surface stream. [[172]](#footnote-173)172

[*IX*](https://advance.lexis.com/api/document?collection=statutes-legislation&id=urn:contentItem:8T9R-T532-D6RV-H381-00000-00&context=1516831). TECHNICAL CHALLENGES, CONSIDERATIONS AND CONCLUSIONS

Ground water experts are faced with the challenge of developing quantitative solutions for ground water problems involving the flow of water beneath the ground surface where it typically cannot be measured or directly quantified. Ground water experts rely on available data to provide professional estimates of hydrologic impacts that may result from changes imposed to aquifer systems. Estimated impacts must be completed in the context of specific project budgets and schedules. Summarized below are the challenges frequently encountered in the field of hydrogeology as it relates to water resources in ***Colorado***.

A. Data Availability

Available information on aquifer systems is sometimes limited to well records and occasional published reports on the hydrogeology of a local ground water system. Information contained in well records is limited to well depths, geologic logs, water levels, and simple static and pumping water levels from when the wells were initially tested. Well records do not contain formal pumping test data that can be used to determine aquifer characteristics. Frequently published reports are not available that provide meaningful aquifer information for the purposes of ground water flow calculations. In these circumstances, it is necessary to characterize the aquifer system based on field investigations, which can be a time intensive and costly process; or in the alternative, it may be necessary to **[\*133]** rely on well records and estimates of aquifer parameters based on the local geology. As summarized below, the findings of ground water analyses can be very sensitive to aquifer parameters, and as a result it is imperative to have reliable aquifer characteristics, which can sometimes be difficult to achieve.

B. Sensitivity of Aquifer Parameters

As shown in Figure 1, aquifer hydraulic conductivities for the same type of aquifer materials can range over orders of magnitude. For example, the published range of hydraulic conductivity of sandstone can range from 10-3 to 10 gpd/ft2. Based on Darcy's Law, the flow of ground water through an aquifer system is directly proportional to the hydraulic conductivity of the aquifer material. Therefore, in this example, the calculated flow through a sandstone aquifer system can range over three orders of magnitude depending on the hydraulic conductivity value. This example illustrates the variability that may result from a range of aquifer characteristics and the importance of determining appropriate values, representative of the aquifer system in question. Ground water experts rely on field data, published reports, and their professional judgment to determine the most practical representative aquifer characteristics, but because of the range of values that may exist in a system, there is potential for variability in the results of ground water analyses.

C. Budgetary and Scheduling Constraints

Ground water field investigations and modeling projects can be very expensive to implement and the schedule and budget is a direct result of the modeling approach selected for a given project. The modeling approach is typically a function of the technical question that needs to be answered, but budgetary and time constraints can greatly impact the magnitude of a modeling effort. In general, simplified approaches can be applied to arrive at an answer to a ground water problem, but the accuracy of the result can be greatly impacted if limited data are available to accurately characterize a system, and if adequate budget and time are not available to study the system in detail. Estimates based on simplified analytical approaches may or may not be adequate to address the question at hand. If simplified approaches are used to arrive at a solution to a complex ground water problem as a result of budget and time constraints, then it is appropriate to clarify the limitations of the experts' results.

D. Variability of Aquifer Parameters Provides Room for Argument

A ground water expert may go through industry-accepted methods and arrive at what appears to be a reasonable answer to a ground water problem. However, a different expert may analyze the same information to address the same question and arrive at a different answer. This variability may result from differing assumptions in conceptual models, differing **[\*134]** assumptions in aquifer parameters, or different modeling approaches. The differences in the results may or may not be significant. Thus because of this variability, ground water modeling projects are easy to scrutinize and criticize. This is particularly true for numerical modeling projects, which include numerous inputs and assumptions. For example, in Division 1 Case No. 96CW14, multiple days of trial testimony occurred focusing on modeling approaches and technical arguments about the validity of the applicants' modeling approach. Ultimately, the ***Colorado*** water court dismissed the case because the applicant's "model generated information that is not sufficient to support the experts' or the court's reliance on modeling results … ." [[173]](#footnote-174)173

E. Technical Communications

Ground water experts need to communicate technical issues to a non-technical audience. The work product produced by ground water experts is sometimes a tangible water supply, but at other times, the work product is a technical report related to a ***Colorado*** water court case, well permit application, or DRMS permitting process. The readers of the technical reports are sometimes other technical experts, but also include judges, attorneys, regulatory agencies, or other stakeholders. In the case of ***Colorado*** water court proceedings, it is the judge that determines the outcome of the case. Attorneys and stakeholders also play a significant role in the ***Colorado*** water court process. As a result, ground water experts must be skilled not only at completing technical analyses, but also communicating their findings and methodologies to a non-technical audience. These communications occur in the form of technical reports, verbal communications, and testimony.

In summary, ground water problems need to be addressed on a case-by-case basis. The best methods must be selected based on the ground water expert's professional judgment. There is no "one size fits all" approach for any ground water problem, and many factors need to be considered to determine the most appropriate method to produce the information needed to resolve a ground water problem. Ground water flow analysis is not an exact science, and the outcome of ground water investigations are influenced by the physical field data, the modeling approach, and the expertise of the ground water expert. As a result, it is imperative that ground water experts apply the best technical science, judgment, and integrity; as well as clearly communicate their results, assumptions, and the limitations of their findings.

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1. 1 ***Colo.*** Rev. Stat. [*§ 37-90-103(19)*](https://advance.lexis.com/api/document?collection=statutes-legislation&id=urn:contentItem:68BY-DJC3-GXF6-82XJ-00000-00&context=1516831) (2011). [↑](#footnote-ref-2)
2. 2 Ralf Topper & Bob Raynolds, ***Colo.*** Found. for Water Educ., Citizen's Guide to Denver Basin Groundwater 6 (2007) [hereinafter Groundwater Guide]. [↑](#footnote-ref-3)
3. 3 C.W. Fetter, Applied Hydrogeology 64 (1980). [↑](#footnote-ref-4)
4. 4 Id. (defining secondary porosity as the porosity that has been caused by fractures or weathering in a rock or sediment after it has been formed). [↑](#footnote-ref-5)
5. 5 See F.G. Driscoll, Groundwater and Wells 891 (2nd ed. 1986) (defining water table as the surface of a body of unconfined ground water at which the pressure is equal to that of the atmosphere, and static water level as the level of water in a well that is not being affected by withdrawal of ground water). [↑](#footnote-ref-6)
6. 6 See Fetter, supra note 5, at 94. [↑](#footnote-ref-7)
7. 7 See ***Colo.*** Rev. Stat. [*§ 37-90-103(2)*](https://advance.lexis.com/api/document?collection=statutes-legislation&id=urn:contentItem:68BY-DJC3-GXF6-82XJ-00000-00&context=1516831) (2011) (defining an aquifer as a formation, group of formations, or part of a formation containing sufficient saturated permeable material that could yield a sufficient quantity of water that may be extracted and applied to beneficial use). [↑](#footnote-ref-8)
8. 8 Ralf Topper et al., ***Colo.*** Geological Survey Div. of Minerals and Geology, Ground Water Atlas of ***Colo.*** 17 (Special Publ'n 53 2003) [hereinafter GWA]. [↑](#footnote-ref-9)
9. 9 Id. [↑](#footnote-ref-10)
10. 10 Fetter, supra note 5, at 555. [↑](#footnote-ref-11)
11. 11 GWA, supra note 10, at 19. [↑](#footnote-ref-12)
12. 12 Fetter, supra note 5, at 100. [↑](#footnote-ref-13)
13. 13 Id. at 560. [↑](#footnote-ref-14)
14. 14 GWA, supra note 10, at 17. [↑](#footnote-ref-15)
15. 15 Driscoll, supra note 7, at 206. [↑](#footnote-ref-16)
16. 16GWA, supra note 10, at 17. [↑](#footnote-ref-17)
17. 17 Id. at 16. [↑](#footnote-ref-18)
18. 18 Groundwater Guide, supra note 4, at 32. [↑](#footnote-ref-19)
19. 19 GWA, supra note 10, at 16. [↑](#footnote-ref-20)
20. 20 Fetter, supra note 5, at 559 (defining specific yield as "the ratio of the water a rock or soil will yield by gravity drainage to the volume of the rock or soil. Gravity drainage may take many months to occur"). [↑](#footnote-ref-21)
21. 21 Id. at 553 (defining a confining layer as a "body of material of low hydraulic conductivity that is stratigraphically adjacent to one or more aquifers. It may above or below the aquifer"). [↑](#footnote-ref-22)
22. 22 GWA, supra note 10, at 16. [↑](#footnote-ref-23)
23. 23 Id. [↑](#footnote-ref-24)
24. 24 Id. [↑](#footnote-ref-25)
25. 25 Driscoll, supra note 7, at 890 (defining potentiometric surface as an imaginary surface representing the total head of ground water in a confined aquifer that is defined by the level to which water will rise in a well). [↑](#footnote-ref-26)
26. 26 Id. at 886 (defining an artesian well as a well deriving it water from a confined aquifer in which the water level stands above the ground surface synonymous with flowing artesian well). [↑](#footnote-ref-27)
27. 27 GWA, supra note 10, at 16. [↑](#footnote-ref-28)
28. 28 Fetter, supra note 5, at 559 (defining specific storage as "the volume of ground water that an aquifer absorbs or expels from a unit volume when the pressure head decreases or increases by a unit amount"). [↑](#footnote-ref-29)
29. 29 Driscoll, supra note 7 at 888. [↑](#footnote-ref-30)
30. 30 GWA, supra note 10, at 206 (defining hydraulic gradient as "the slope of the water table or potentiometric surface"). [↑](#footnote-ref-31)
31. 31 Driscoll, supra note 7, at 887. [↑](#footnote-ref-32)
32. 32 Id. (defining cone of depression as "a depression in the ground water table or potentiometric surface that has the shape of an inverted cone and develops around a well from which water is being withdrawn, which defines the area of influence of a well"). [↑](#footnote-ref-33)
33. 33 GWA, supra note 10, at 17-18. [↑](#footnote-ref-34)
34. 34 P. Andrew Jones & Tom Cech, ***Colorado*** Water Law for Non-Lawyers 22 (2009). [↑](#footnote-ref-35)
35. 35 See id. [↑](#footnote-ref-36)
36. 36 See id. at 24-25; see also Topper et al., supra note 10, at 18-20. [↑](#footnote-ref-37)
37. 37 See GWA, supra note 10, at 19. [↑](#footnote-ref-38)
38. 38 See Jones & Cech, supra note 36, at 22. [↑](#footnote-ref-39)
39. 39 What is Quaternary, U.S. Geological Survey, [*http://geomaps.wr.usgs.gov/sfgeo/quaternary/stories/what\_is.html*](http://geomaps.wr.usgs.gov/sfgeo/quaternary/stories/what_is.html) (last modified Aug. 18, 2006) (explaining that the Quaternary geologic period represents approximately the last 2 million years). [↑](#footnote-ref-40)
40. 40 Introduction to Hydrogeology of ***Colorado***, ***Colo.*** Geological Survey, [*http://geosurvey.state.****co****.us/apps/wateratlas/chapter4page1.asp*](http://geosurvey.state.co.us/apps/wateratlas/chapter4page1.asp) (last visited Oct. 24, 2011). [↑](#footnote-ref-41)
41. 41 See Jones & Check, supra note 36, at 23. [↑](#footnote-ref-42)
42. 42 Brogden, R.E., and Giles, T.F. 1977, Reconnaissance of ground-water resources in part of Yampa ***River*** basin between Craig and Steamboat Springs, Moffat and Routt Counties, ***Colorado***: U.S. Geological Survey Water-Resources Investigations 77-4, sheet. [↑](#footnote-ref-43)
43. 43 Jones & Check, supra note 36, at 22. [↑](#footnote-ref-44)
44. 44 See id.; see also GWA, supra note 10, at 31. [↑](#footnote-ref-45)
45. 45 See, e.g., ***Colorado*** Division of Water Resources, [*http://www.dwr.state.****co****.us/WellPermitSearch/default.aspx*](http://www.dwr.state.co.us/WellPermitSearch/default.aspx) (last visited Oct. 20, 2011) (the Well Construction and Test Reports for well permit nos. 46864-F and 36535-F-R indicate total well depths of 70 feet and 185 feet, respectively. Both wells are constructed into alluvial aquifers). [↑](#footnote-ref-46)
46. 46 Driscoll, supra note 7, at 67. [↑](#footnote-ref-47)
47. 47 Id. at 75. [↑](#footnote-ref-48)
48. 48 GWA, supra note 10, at 5. [↑](#footnote-ref-49)
49. 49 Id. at 33. [↑](#footnote-ref-50)
50. 50 Id. at 208 (explaining that sandstone is a sedimentary rock formed by the compaction and/or cementing of sand). [↑](#footnote-ref-51)
51. 51 Id. (explaining that silt is a rock fragment or mineral particle with a diameter smaller than a very fine sand grain and larger than coarse clay). [↑](#footnote-ref-52)
52. 52 Driscoll, supra note 7, at 889 (defining limestone as "a sedimentary rock consisting chiefly of calcium carbonate primarily in the form of mineral calcite"). [↑](#footnote-ref-53)
53. 53 Oil Field Glossary, Schlumberger, [*http://www.glossary.oilfield.slb.com/Display.cfm?Term=dipping%2*](http://www.glossary.oilfield.slb.com/Display.cfm?Term=dipping%2) 0bed (last visited 11/8/11) (defining a dipping bed as "a layer of rock or sediment that is not horizontal"). [↑](#footnote-ref-54)
54. 54 Jean-Michel Lemieux, Donna Kirkwood, and Rene Therrien, Fracture Network Analysis of the St-Eustache Quarry, Quebec, Canada, for Groundwater Resources Management, 46 Can. Geotech. J. 828 (2009) (defining a fracture as "any discrete brittle discontinuity in the rock mass along which cohesion is lost"). [↑](#footnote-ref-55)
55. 55 Driscoll, supra note 7, at 888 (defining a fault as "a fracture or zone of fractures along which there has been displacement of the sides relative to one another parallel to the fracture"). [↑](#footnote-ref-56)
56. 56 GWA, supra note 10, at 208 (explaining that shale is a rock that is often impervious to water but rather soft, brittle, and easily eroded. Shale is the result of compaction of silt or mud. Much of the Permian and Pennsylvanian strata in ***Colorado*** consist of various shales, often brightly colored). [↑](#footnote-ref-57)
57. 57 Id. at 3 (explaining that the Tertiary geologic period represents the time period from approximately 65 million years ago to approximately 2 million years ago). [↑](#footnote-ref-58)
58. 58 Id. (explaining that the Cretaceous geologic period represents the time period from approximately 144 million years ago to approximately 65 million years ago. The end of the Cretaceous Period was marked by the rise of the modern day Rocky Mountains). [↑](#footnote-ref-59)
59. 59 Denver Basin Aquifers, Douglas Cnty., [*http://www.douglas.****co****.us/water/Denver\_Basin\_Aquif*](http://www.douglas.co.us/water/Denver_Basin_Aquif) ers.html (last visited 11/8/11). [↑](#footnote-ref-60)
60. 60 ***Colo.*** Code Regs. § 402-6 (2011) (identifying specific yields for the Denver Basin aquifers ranging between 15-percent and 20-percent); Driscoll, supra note 7, at 67 (identifying specific yields for sandstone range from 5-percent to 15-percent). [↑](#footnote-ref-61)
61. 61 Fetter, supra note 5, at 101. [↑](#footnote-ref-62)
62. 62 Driscoll, supra note 7, at 75. [↑](#footnote-ref-63)
63. 63 GWA, supra note 10, at 34. [↑](#footnote-ref-64)
64. 64 Id. at 3 (illustrating that the Precambrian geologic era spans the time period from the origin of the Earth, estimated to be approximately 4.6 billion years old, to approximately 543 million years ago). [↑](#footnote-ref-65)
65. 65 Id. at 193. [↑](#footnote-ref-66)
66. 66 Id. at 194. [↑](#footnote-ref-67)
67. 67 Id. at 195. [↑](#footnote-ref-68)
68. 68 Id. [↑](#footnote-ref-69)
69. 69 Section 54: Mountain Ground Water (M-G) Overlay District, Jefferson Cnty. Planning Comm'n, 1-2 (Feb. 8, 2011), [*http://jeffco.us/jeffco/planning\_uploads/zoning/zr\_*](http://jeffco.us/jeffco/planning_uploads/zoning/zr_) 2\_8\_11/zr\_54.pdf. [↑](#footnote-ref-70)
70. 70 Driscoll, supra note 7, at 5. [↑](#footnote-ref-71)
71. 71 GWA, supra note 10, at 196. [↑](#footnote-ref-72)
72. 72 Id. [↑](#footnote-ref-73)
73. 73 Id. [↑](#footnote-ref-74)
74. 74 Id. at 33. [↑](#footnote-ref-75)
75. 75 ***Colo.*** Rev. Stat.§§147-9-1 to -15 (Supp. 1960), repealed by S. 367, 45th Gen. Assemb., 1st Reg. Sess. (***Colo.*** 1965). [↑](#footnote-ref-76)
76. 76 ***Colorado*** Ground Water Management Act, ch. 319, 1965 ***Colo.*** Sess. Laws 1246 (codified at ***Colo.*** Rev. Stat. [*§§37-90-101*](https://advance.lexis.com/api/document?collection=statutes-legislation&id=urn:contentItem:61P5-WY01-DYDC-J3C1-00000-00&context=1516831) to -143 (1997)). [↑](#footnote-ref-77)
77. 77 ***Colo.*** Rev. Stat. [*§§37-92-101*](https://advance.lexis.com/api/document?collection=statutes-legislation&id=urn:contentItem:61P5-WY01-DYDC-J3FM-00000-00&context=1516831) to -602 (2011). [↑](#footnote-ref-78)
78. 78 Hobbs, supra note 79, at 12. [↑](#footnote-ref-79)
79. 79 Id. [↑](#footnote-ref-80)
80. 80 Id. [↑](#footnote-ref-81)
81. 81 Id. at 13. [↑](#footnote-ref-82)
82. 82 Id. (noting that previous legislation created two types of groundwater: groundwater that was connected to streams and groundwater that had little or no connection to stream flow). [↑](#footnote-ref-83)
83. 83 Id. at 15. [↑](#footnote-ref-84)
84. 84 See, e.g., [*Well Augmentation Subdistrict of Cent.* ***Colorado*** *Water Conservancy Dist. v. City of Aurora, 221 P.3d 399, 412 (****Colo.*** *2009)*](https://advance.lexis.com/api/document?collection=cases&id=urn:contentItem:7X58-H3W0-YB0K-Y019-00000-00&context=1516831) ("Because groundwater depletions can lag behind surface water conditions by many years, the effects of a groundwater depletion may not be felt by surface waters for long periods of time."). [↑](#footnote-ref-85)
85. 85 See [*id. at 412*](https://advance.lexis.com/api/document?collection=cases&id=urn:contentItem:7X58-H3W0-YB0K-Y019-00000-00&context=1516831) (noting pre-2003 depletions were having a continuing effect on surface water levels). [↑](#footnote-ref-86)
86. 86 See Hobbs, supra note 79, at 17. [↑](#footnote-ref-87)
87. 87 Id. [↑](#footnote-ref-88)
88. 88 See, e.g., [*SRJ I Venture v. Smith Cattle, Inc., 820 P.2d 341, 343 n.3 (****Colo.*** *1991)*](https://advance.lexis.com/api/document?collection=cases&id=urn:contentItem:3RX4-0JH0-003D-91N2-00000-00&context=1516831) ("A call is placed on a ***river*** when a senior appropriator forces upstream juniors to let flow sufficient water to meet the requirements of the senior priority."). [↑](#footnote-ref-89)
89. 89 See Hobbs, supra note79, at 15. [↑](#footnote-ref-90)
90. 90 Lower Arkansas Water Management Association, [*www.lawma.net*](http://www.lawma.net) (last visited Oct. 25, 2011). [↑](#footnote-ref-91)
91. 91 Hobbs, supra 79, at 13. [↑](#footnote-ref-92)
92. 92 GWA, supra note 10, at 19. [↑](#footnote-ref-93)
93. 93 ***Colo.*** Rev. Stat. [*§ 37-90-103(6)*](https://advance.lexis.com/api/document?collection=statutes-legislation&id=urn:contentItem:68BY-DJC3-GXF6-82XJ-00000-00&context=1516831) (2011). [↑](#footnote-ref-94)
94. 94 Jones & Cech, supra note 36, at 156. [↑](#footnote-ref-95)
95. 95 Designated Basins and Ground Water Management, ***Colo.*** Div. of Water Res., [*http://water.state.****co****.us/groundwater/CGWC/Pages/ManagementDistr*](http://water.state.co.us/groundwater/CGWC/Pages/ManagementDistr) icts.aspx (last visited 11/8/11). [↑](#footnote-ref-96)
96. 96 ***Colo.*** Rev. Stat. [*§ 37-90-103(10.5)*](https://advance.lexis.com/api/document?collection=statutes-legislation&id=urn:contentItem:68BY-DJC3-GXF6-82XJ-00000-00&context=1516831) (2011). [↑](#footnote-ref-97)
97. 97 Id. [*§ 37-92-305(11)*](https://advance.lexis.com/api/document?collection=statutes-legislation&id=urn:contentItem:61P5-WY01-DYDC-J3G3-00000-00&context=1516831). [↑](#footnote-ref-98)
98. 98 Id. [*§ 37-90-137(4)*](https://advance.lexis.com/api/document?collection=statutes-legislation&id=urn:contentItem:689F-SN93-GXF6-81VM-00000-00&context=1516831). [↑](#footnote-ref-99)
99. 99 GWA, supra note 10, at 23. [↑](#footnote-ref-100)
100. 100 ***Colo.*** Rev. Stat. [*§ 37-90-137(9)(b)*](https://advance.lexis.com/api/document?collection=statutes-legislation&id=urn:contentItem:689F-SN93-GXF6-81VM-00000-00&context=1516831) (2011). [↑](#footnote-ref-101)
101. 101 GWA, supra note 10, at 19. [↑](#footnote-ref-102)
102. 102 ***Colorado*** State Water Law, Douglas Cnty., [*http://www.douglas.****co****.us/water/****Colorado****\_State\_Wat*](http://www.douglas.co.us/water/Colorado_State_Wat) er\_Law.html (last visited 11/11/11). [↑](#footnote-ref-103)
103. 103 ***Colo.*** Rev. Stat. [*§§37-90-137(4)*](https://advance.lexis.com/api/document?collection=statutes-legislation&id=urn:contentItem:689F-SN93-GXF6-81VM-00000-00&context=1516831), -92-305(11) (2011). [↑](#footnote-ref-104)
104. 104 Id. [*§ 37-90-137(9)(c)*](https://advance.lexis.com/api/document?collection=statutes-legislation&id=urn:contentItem:689F-SN93-GXF6-81VM-00000-00&context=1516831). [↑](#footnote-ref-105)
105. 105 Id. [↑](#footnote-ref-106)
106. 106 Jones & Cech, supra note 36, at 181. [↑](#footnote-ref-107)
107. 107 Id. at 179. [↑](#footnote-ref-108)
108. 108 ***Colo.*** Rev. Stat. [*§ 37-92-602(6)*](https://advance.lexis.com/api/document?collection=statutes-legislation&id=urn:contentItem:662M-XJW3-CGX8-03F8-00000-00&context=1516831) (2011). [↑](#footnote-ref-109)
109. 109 ***Colo.*** Div. of water Res., Guide to ***Colorado*** Well Permits, Water Rights and Water Administration, (Jan. 2008), available at water.state.***co***.us/dwripub/documents/wellpermitguide.pdf. [↑](#footnote-ref-110)
110. 110 Id. [↑](#footnote-ref-111)
111. 111 ***Colo.*** Rev. Stat. [*§§37-90-105*](https://advance.lexis.com/api/document?collection=statutes-legislation&id=urn:contentItem:61P5-WY01-DYDC-J3C5-00000-00&context=1516831), -92-602 (2011). [↑](#footnote-ref-112)
112. 112 Driscoll, supra note 7, at 887 (defining a cone of depression as a "depression in the groundwater table or potentiometric surface that has the shape of an inverted cone and develops around a well from which water is being withdrawn. It defines the area of influence of a well"). [↑](#footnote-ref-113)
113. 113 Victor Ponce, Groundwater Utilization and Sustainability, San Diego State Univ. (Mar. 2006), [*http://groundwater.sdsu.edu/*](http://groundwater.sdsu.edu/). [↑](#footnote-ref-114)
114. 114 Daniel Niemela & Harun Ahmed, Bishop-Brogden Assocs., Inc., Irrigation Season Water level Changes in Municipal Arapahoe Aquifer Wells, Douglas County, ***CO*** (Oct. 28-31, 2007), [*http://gsa.confex.com/gsa/2007AM/finalprogram/abstract\_1*](http://gsa.confex.com/gsa/2007AM/finalprogram/abstract_1) 31260.htm (follow "Presentation Handout" hyperlink). [↑](#footnote-ref-115)
115. 115 Groundwater Guide, supra note 4, at 19. [↑](#footnote-ref-116)
116. 116 See Why is the Northern Project Important?, East Cherry Creek Valley Water and Sanitation Dist., [*http://www.eccv.org/view/61*](http://www.eccv.org/view/61) (last visited Oct. 18, 2011). [↑](#footnote-ref-117)
117. 117 GWA, supra note 10, at 18. [↑](#footnote-ref-118)
118. 118 ***Colo.*** Rev. Stat. [*§ 30-28-106(3)(a)(IV)*](https://advance.lexis.com/api/document?collection=statutes-legislation&id=urn:contentItem:65RT-9463-CGX8-03KB-00000-00&context=1516831) (2011). [↑](#footnote-ref-119)
119. 119 ***Colo.*** Rev. Stat. [*§ 34-33-114(2)(c)*](https://advance.lexis.com/api/document?collection=statutes-legislation&id=urn:contentItem:61P5-WXJ1-DYDC-J33W-00000-00&context=1516831) (2011). [↑](#footnote-ref-120)
120. 120 Groundwater Guide, supra note 4, at 12. [↑](#footnote-ref-121)
121. 121 Id. [↑](#footnote-ref-122)
122. 122 Id. at 17. [↑](#footnote-ref-123)
123. 123 See, e.g. ***Colo.*** Rev. Stat. [*§ 37-90-137(9)(a)*](https://advance.lexis.com/api/document?collection=statutes-legislation&id=urn:contentItem:689F-SN93-GXF6-81VM-00000-00&context=1516831) (authorizing the State Engineer to adopt rules and regulations pertaining to the administration of ground water). [↑](#footnote-ref-124)
124. 124 ***Colo.*** Code Regs. § 402-6(1) (2011). [↑](#footnote-ref-125)
125. 125 Id. § 402-7(1). [↑](#footnote-ref-126)
126. 126 Id. § 402-17.1. [↑](#footnote-ref-127)
127. 127 Justice Greg Hobbs, An Overview of ***Colorado*** Groundwater Law, ***Colo.*** Water, Oct.-Nov. 2007, at 2, 3 [↑](#footnote-ref-128)
128. 128 See id. at 2. [↑](#footnote-ref-129)
129. 129 See ***Colo.*** Code Regs. § 402-6(5), (7) (2011). [↑](#footnote-ref-130)
130. 130 See, e.g., In re. Application for Water Rights & Plan for Augmentation of the Bd. of Cnty. Comm'rs of Gilpin, Case No. 94CW277, at 15 (***Colo.*** Dist. Ct. Water Div. 1 1997). [↑](#footnote-ref-131)
131. 131In re. Applications for Water Rights of Farmers Reservoir & Irrigation ***Co***., Case No. 02CW404, at 3-4 (***Colo.*** Dist. Ct. Water Div. 1 2011) ("Stipulation Between Applicants and the Town of Lochbuie"). [↑](#footnote-ref-132)
132. 132 See, e.g., In re. Application for Water Rights of Cent. ***Colo.*** Water Conservancy Dist., Case No. 05CW331, at 24 (***Colo.*** Dist. Ct. Water Div. 1 2011) ("Stipulated Draft Decree"). [↑](#footnote-ref-133)
133. 133 Driscoll, supra note 7, at 202; see also Fetter, supra note 5, at 210. [↑](#footnote-ref-134)
134. 134 See Driscoll, supra note 7, at 203; see Fetter, supra note 5, at 210. [↑](#footnote-ref-135)
135. 135 Fetter, supra note 5, at 208. [↑](#footnote-ref-136)
136. 136 Id. [↑](#footnote-ref-137)
137. 137 Id. [↑](#footnote-ref-138)
138. 138 Driscoll, supra note 7, at 204. [↑](#footnote-ref-139)
139. 139 See Fetter, supra note 5, at 210, 212. [↑](#footnote-ref-140)
140. 140 See id. [↑](#footnote-ref-141)
141. 141 Driscoll, supra note 7, at 203. [↑](#footnote-ref-142)
142. 142 Id. [↑](#footnote-ref-143)
143. 143 Id. at 204. [↑](#footnote-ref-144)
144. 144 Id. at 203. [↑](#footnote-ref-145)
145. 145 Id. [↑](#footnote-ref-146)
146. 146 Id. at 221-22. [↑](#footnote-ref-147)
147. 147 Id. at 203. [↑](#footnote-ref-148)
148. 148 See, e.g., In re. Applications for Water Rights of Farmers Reservoir & Irrigation ***Co***., Case No. 02CW404, at 3 (***Colo.*** Dist. Ct. Water Div. 1 2011). [↑](#footnote-ref-149)
149. 149 See, e.g., id. at 3-4 [↑](#footnote-ref-150)
150. 150 See, e.g., id. [↑](#footnote-ref-151)
151. 151 See Fetter, supra note 5, at 514-515. [↑](#footnote-ref-152)
152. 152 See id. [↑](#footnote-ref-153)
153. 153 Id. at 514-15. [↑](#footnote-ref-154)
154. 154 Driscoll, supra note 7, at 73. [↑](#footnote-ref-155)
155. 155 Fetter, supra note 5, at 81. [↑](#footnote-ref-156)
156. 156 Id. at 153. [↑](#footnote-ref-157)
157. 157 Driscoll, supra note 7, at 218. [↑](#footnote-ref-158)
158. 158 Fetter, supra note 5, at 173-75. [↑](#footnote-ref-159)
159. 159 S.S. Papadopulos & Assocs. & ***Colo.*** Geological Survey, Coalbed Methane Stream Depletion Assessment Study - Piceance Basin, ***Colorado*** 37 (2008), available at [*http://geosurvey.state.****co****.us/water/CBM%20Water%20Depletion/Docu*](http://geosurvey.state.co.us/water/CBM%20Water%20Depletion/Docu) ments/Piceance\_Final\_Report.pdf. [↑](#footnote-ref-160)
160. 160 Integrated Decision Support Group, ***Colo.*** State Univ., [*http://www.ids.colostate.edu/projects.php?project=awas&*](http://www.ids.colostate.edu/projects.php?project=awas&) breadcrumb=IDS+AWAS (last visited Oct. 15, 2011). IDS AWAS was developed in 2003 by the Integrated Decision Support System at ***Colorado*** State University in response to requests of the South Platte Advisory Committee. Id. [↑](#footnote-ref-161)
161. 161 S.S. Papadopulos & Assocs. & ***Colo.*** Geological Survey, supra note 167. [↑](#footnote-ref-162)
162. 162 In this context a "hole" in the aquifer refers to a region of the alluvial aquifer in which the water level is lowered. [↑](#footnote-ref-163)
163. 163 Fetter, supra note 5, at 154. [↑](#footnote-ref-164)
164. 164 Dep't of Reclamation, Mining and Safety, Permit No. M-1986-015, Exhibit G at 2 (2011). [↑](#footnote-ref-165)
165. 165 Definition Result, Ala. State Water Program, [*http://www.aces.edu/waterquality/glossary/glossary\_resul*](http://www.aces.edu/waterquality/glossary/glossary_resul) ts.php3?rowid=2228 (last visited Nov. 9, 2011) (defining groundwater mounding as "an outward and upward expansion of the free water table caused by shallow re-injection, percolation below an impoundment, or other surface recharge method."). [↑](#footnote-ref-166)
166. 166 Dep't of Reclamation, supra note 170. [↑](#footnote-ref-167)
167. 167 Dep't of Reclamation, supra note 170. [↑](#footnote-ref-168)
168. 168 Boulder Cnty. Res. 98-32 (1998). [↑](#footnote-ref-169)
169. 169 In re Application for Water Rights and Plan for Augmentation of the Bd. of Cnty. Comm'rs of the Cnty. of Gilpin, No. 94-CW-277 (***Colo.*** Dist. Ct. Water Div. 1 1998). [↑](#footnote-ref-170)
170. 170 ***Colo.*** Code Regs. § 402-17.3(B) (2011). [↑](#footnote-ref-171)
171. 171 Id. § 402-17.3(C). [↑](#footnote-ref-172)
172. 172 See id. § 402-17.3(D). [↑](#footnote-ref-173)
173. 173 In re Application for Water Rights: The Park Cnty. Sportsmen's Ranch, No. 96-CW-14 (***Colo.*** Dist. Ct. Water Div. 1 June 1, 2001) (order dismissing application). [↑](#footnote-ref-174)