GEOLOGY OF THE DENVER BASIN AQUIFERS

COLORADO DIVISION OF WATER RESOURCES

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Technical Appendix A

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INTRODUCTION

This report presents the results of an extensive hydrogeologic study prepared by the Colorado Division of Water Resources, Office of the State Engineer, for the purpose of promulgation of rules and regulations as required by Senate Bill 5 (Section 37-90-137(9)(a) C.R.S). This is the most comprehensive hydrogeologic study of the Denver Basin that has been completed. Information contained in this report describes the aquifers, sets forth the criteria used for hydrologic separation of the aquifers and includes a series of maps depicting the aquifer boundaries and thicknesses of permeable aquifer materials.

DESCRIPTION OF THE DENVER BASIN

The Denver ground water basin, hereinafter referred to as the Denver Basin, underlies an area of approximately 6,700 square miles. It extends southward from Greeley to a point approximately 25 miles southeast of Colorado Springs, and extends eastward from the Front Range to near Limon, Colorado. Four major bedrock aquifers occur in the Denver Basin. In descending order these are the Dawson, Denver, Arapahoe, and Laramie-Fox Hills Aquifers. These aquifers are known or potential sources of water to wells constructed for domestic, livestock, industrial, commercial, municipal, and irrigation purposes.

For the purposes of the rules and regulations for which the aquifer descriptions, hydrogeologic cross sections, and maps were prepared, the boundary of the Denver Basin is defined by the lower or outermost boundary of the Laramie-Fox Hills Aquifer and the South Platte River between the LaSalle area and the town of Masters in Weld County as shown on Figure 4B. The lower limit of the Denver Basin is not extended below the base of the Laramie-Fox Hills Aquifer because virtually all of the estimated groundwater in storage in the region's bedrock aquifers is contained in the Laramie-Fox Hills, Arapahoe, Denver, and Dawson Aquifers. Other bedrock formations outcrop along the westernmost edge of the Denver Basin but their structural characteristics limit their usefulness as aquifers to their respective outcrop areas. The South Platte River between the towns of LaSalle and Masters is the northern boundary because the river approximately parallels a geologic feature known as the Greeley Arch. This arch physically separates the Denver Basin on the south from the similar Cheyenne Basin on the north. Furthermore the Laramie-Fox Hills Aquifer is significantly thinned or is missing along the arch's crest. The aquifer descriptions include terms such as conglomerate, sandstone, siltstone, clay shale and claystone. These terms are utilized in a general descriptive sense rather than as an attempt to describe the precise nature of individual beds. The term clay shale is used to signify clay-sized sediments which lie in an intermediate stage between a plastic clay and a true shale. Claystone is used to denote unstructured clay shale with a higher degree of induration. Most of the strata encountered in the bedrock aquifers are only partly lithified, or converted to a consolidated rock. When exposed to atmospheric conditions all strata, except moderately cemented sandstones and conglomerates, are easily weathered and eroded.

HISTORY OF THE AQUIFER NOMENCLATURE

The Dawson, Denver, and Arapahoe Aquifers were not identified, mapped, and utilized as individual aquifers until the middle 1970's. In the late 1880's the names Denver and Arapahoe Formations were applied to strata which nearly coincide with current descriptions. Later the term Dawson Formation was applied to describe the entire sequence of strata generally lying between the base of the Castle Rock Conglomerate and the top of the Laramie Formation. The Denver and Arapahoe were classed as members of the Dawson Formation. Throughout the last 60 to 70 years, the Dawson Formation has been periodically described as having upper and lower parts and arkosic and andesitic members, with the names Denver and Arapahoe appearing periodically. Location of the stratigraphic boundaries of the parts or members are controversial because of complex intertonguing and facies changes associated with up to 2800 feet of strata over an area of about 4700 square miles.

In the early 1970's, Colorado Division of Water Resources personnel began to utilize geophysical logs of oil and gas exploration holes as a means of identifying and mapping the Laramie-Fox Hills Aquifer. It was soon recognized that rock strata overlying the Laramie-Fox Hills Aquifer exhibited electrical characteristics or signatures which could be traced from log to log. Further investigation revealed that in most cases the boundaries of each signatured section of log could be related to either Dawson, Denver, or Arapahoe rock types as described by earlier workers. Examination of lithologic logs of the then few deep water wells in the Denver Basin, and field investigations resulted in verification of this whereupon Colorado Division of Water Resources investigators were instructed to examine the possibility of dividing the Dawson Formation into distinct aquifers. By late 1972 it was shown that the characteristic signatured sections of logs could be traced throughout the Denver Basin. The names Dawson, Denver, and Arapahoe were applied and by mid 1974 Colorado Division of Water Resources description and maps of the Dawson, Denver, and Arapahoe Formations, each given aquifer status, were completed. These were the first descriptions and maps of the Dawson, Denver, and Arapahoe Aquifers.

The Laramie-Fox Hills Aquifer did not come into prominence until the late 1920's. At that time, however, the aquifer was commonly called the Fox Hills Sandstone; the term Laramie Sands was used only occasionally. The name Fox Hills Sandstone was used throughout the 1940's, 50's and 60's by most investgators including a large segment of the local oil and gas industry. Since the late 1960's additional information and data have been evaluated and the aquifer aquired its present name.

Updated versions of Denver Basin Aquifer maps were prepared during 1976 and 1977 and again in 1980. The 1980 versions were utilized by the U.S. Geological Survey in the Denver Basin Hydrologic Atlas series published in 1981. Since 1981, no basin wide hydrolgeologic studies of the Denver Basin have been published.

HYDROGEOLOGIC INVESTIGATIONS FOR THE DENVER BASIN RULES AND REGULATIONS

In order to accurately map the horizontal and vertical extent of the aquifers and to assure that the aquifers boundaries are consistant based on hydrologic separation, it was necessary to correlate hydrogeologic units on a basin wide scale. This was done by first constructing a series of hyrogeologic cross sections based on geophysical logs and then constructing maps showing aquifer boundaries, structural contours and sandstone/siltstone isoliths. This work is the most comprehensive study of the Denver Basin Aquifers yet accomplished.

Structural contour and isolith maps for which the rules and regulations were prepared show areas which differ from prior HA series maps. The differences are due to a combination of refinement in aquifer boundary identification based on hydrologic separation of the aquifers and over a 100 percent increase in the number of logs analyzed. Most aquifer boundary changes from previous work occur east of metropolitan Denver. Extrapolation from the newly contructed type cross sections resulted in more consistant thicknesses of Laramie and Arapahoe strata. The newly mapped hydrologic boundaries led to substantial lowering of the Denver-Arapahoe and Arapahoe-Laramie boundaries. Sandstones and siltstones previously assigned to the Arapahoe Aquifer are now assigned to the Denver Aquifer.

The relationship of overall geophysical signatures to hydrologic and lithologic descriptions of specific sequences of rock strata formed the basis for dividing the Dawson Formation by early investigators into three separate aquifers. Each aquifer has a characteristic overall lithologic, hydraulic, and electrical (geophysical) property which can be mapped throughout the entire Denver Basin. In identifying and mapping the Dawson, Denver, and Arapahoe Aquifers, emphasis is placed on grouping geologic strata based on similar hydrologic and geophysical character. Hence, the mass of conglomeratic sandstones with interbedded clay shale and clay and exhibiting an overall high resistivity is designated as the Dawson Aquifer. The underlying 800 to 1000 feet of finer grained sandstone, siltstone, clay shale, and lignite, and which exhibits an overall low resistivity, is designated as the Denver Aquifer. Underlying the Denver Aquifer is a 400 to 600 foot sequence of sandstones and conglomerate with interbedded siltstone and clay shale which exhibits an overall high resistivity and is designated as the Arapahoe Aquifer.

The upper and lower boundaries of each aquifer do not necessarily coincide with formation boundaries located on the basis of inferred geologic history or time concepts. Instead, the aquifer boundaries are placed to segregate strata having similar geophysical and inferred hydraulic characteristics irrespective of the presence of pre-existing formation boundaries. Therefore, the Arapahoe Aquifer as identified by the Colorado Division of Water Resources may include Laramie Formation strata of other investigators. This concept is also applied to Dawson, Denver, and Laramie-Fox Hills Aquifer boundaries. Application of this concept is locally difficult because the boundaries of the Dawson, Denver, and Arapahoe Aquifers lie within zones of gradation. Difficulties associated with zones of gradation have been alleviated by identifying and using key beds or key horizons. In the case of the Denver-Arapahoe boundary, the key bed is a hydrologic boundary composed of a 20 to 50-foot thick bed of clay shale occasionally with subordinate siltstone. In most logs this key bed is easily recognized because it separates a distinct siltstone and clay shale sequence (Denver Aquifer) from a distinct sandstone sequence (Arapahoe Aquifer). In a few logs the distinction is not as apparent, and the key bed itself locally contains thin siltstone or silty shale layers. Identification of the key bed in such logs required stringent correlation procedures. The Denver-Arapahoe boundary is placed at the base of the key bed. The key bed separating the Denver Aquifer from the Dawson Aquifer is a 20 to 50 foot thick bed of clay shale and clay and, like the Denver-Arapahoe key bed, locally requires stringent correlation procedures for its identification. The Denver-Dawson boundary is placed at the top of this key bed. Once located on a number of type logs the key beds were laterally correlated to other parts of the Denver Basin.

Hydraulic separation is based upon overall differences in horizontal and vertical permeabilities of the aquifers. For example, strata of the Denver Aquifer are significantly finer grained (they contain a higher percentage of siltstone and clay shale) and are normally more unevenly distributed than those of the overlying and underlying Dawson and Arapahoe Aquifers. The effect of this characteristic is a significant reduction in regional horizontal and vertical permeabilities of the aquifer. Therefore, the Denver Aquifer can be classed as "self confining", that is, the effects of pumping are, for all practical purposes, restricted to the aquifer. Furthermore, the 800 to 1,000 feet of fine grained sediments with significant siltstone and clay shale serve as an effective barrier between the Dawson and Arapahoe Aquifers. Separation based on geophysical and hydraulic characteristics is reinforced by the use of mappable key beds of clay shale and clay.

Supporting technical information and data used in this investigation are on file at the State Engineer's Office. These include a number of technical reports on the Denver Basin, numerous core samples retrieved during exploration activities, results of analyses of core samples, about 1000 geophysical logs of water wells and oil and gas exploration holes, and a series of east-west and north-south hydrogeologic cross sections of the Denver Basin. Over 3,000 geophysical logs in the Denver Basin are on file at the Colorado Oil and Gas Conservation Commission Office.

HYDROGEOLOGIC CROSS SECTIONS

A series of cross sections were completed to both accurately map the extent of each aquifer and to form the basis for correlation of geophysical logs within the basin. To begin the task of constructing cross sections and to confirm the basis for separation of aquifers a series of meetings were held in 1984 between the Division and the professional community. Also, an east-west section (now known as Section F-F') was distributed to approximately 25 individuals and firms representing the consulting community and the U.S. Geological Survey. The section contained no identification of any aquifers above the top of the Laramie-Fox Hills Aquifer. Individuals and firms were asked to identify aquifers and to return the cross section to the Division with their "picks" identified and an explanation of their choice. About five sections were returned.

Based on the discussions, meetings and cross sections, it was the general consensus that the Denver Basin contained a series of aquifers which can be hydrologically separated from each other and can be mapped throughout the Basin. It was also recognized that the aquifers may cross the classic time - stratigraphic formational boundaries but should be named the same as the formation for which they are most closely associated. This then became the basis for aquifer separation used by the Colorado Division of Water Resources, Office of the State Engineer.

Fifteen cross sections were constructed to provide hydrogeologic control; eleven oriented east-west and four oriented north-south. The sections were spaced at about six to eight mile intervals from north to south and approximately ten to twelve mile intervals east to west. Geophysical logs along these lines were selected from the logs on file with the Colorado Division of Water Resources and the Colorado Oil and Gas Conservation Commission. Logs were selected based on clarity and depth of investigation. Whenever possible logs which penetrated through the base of the Laramie-Fox Hills Aquifer and preferably through a well defined marker stratum in the upper Pierre Shale were selected. Later, additional logs were added to refine the detail of the sections. Approximately 250 logs were used to construct the cross sections.

Correlations were made by comparing the geophysical response or signture on the logs and matching this on a bed by bed basis. Aquifers were separated based on the descriptions previously developed and refined by the Colorado Division of Water Resources and the consulting community.

The final hydrogeologic cross sections were reviewed by the Division Staff and by a panel of three geologists from outside the Division. The panel consisted of Mr. W.C. Wells, an independent consultant recommended by the Colorado Groundwater Association; Mr. S. Robson of the U.S. Geological Survey; and Mr. R. Kirkham, an independent geologist.

DENVER BASIN AQUIFER MAPS

After construction of the cross sections, additional geophysical logs were analysed and locations, elevations of tops and bases of aquifer and sandstone/siltstone thicknesses were plotted on map bases at a scale of 1:100,000. Structural contour maps were then drawn showing the elevations for the top and base of all the Denver Basin Aquifers. Also, sandstone or sandstone/siltstone isolith maps were constructed for each aquifer.

To construct these maps, approximately 3000 geophysical logs were evaluated. Approximately half or 1500 logs were used as data points for the construction of the Laramie-Fox Hills Aquifer maps. Over 1000 logs were used as data points for the Arapahoe Aquifer maps. Five hundred data points were used for the Denver Aquifer and about 300 logs were selected as data points for the Dawson Aquifer maps.

The additional geophysical logs were examined by staff groundwater geologists, but these logs were not included in construction of aquifer maps for a variety of reasons. Mapping was based on a log density of one log per square mile. Some logs lacked sufficient quality to be interpreted. Other logs appeared to be mislocated and could not be used. Wells with the greatest depth of investigation were selected over shallow wells. Structurally complex areas near the basin boundaries required detailed studies beyond the scope of this investigation. These areas deferred to later studies are shown on aquifer maps.

Outcrop data were obtained from numerous sources which include published geologic and geohydrologic maps, theses, and original mapping by the Division Staff.

As with the cross sections, these maps were reviewed by the staff of the Colorado Division of Water Resources and by the panel of three geologists.

DESCRIPTIONS OF THE DENVER BASIN AQUIFERS

DAWSON AQUIFER

The Dawson Aquifer is the uppermost principal aquifer in the Denver Basin. The aquifer covers an area of approximately 1400 square miles and ranges in thickness from zero at its outer boundary to about 1200 feet in the central part of the Basin. The Dawson is at or near land surface throughout its entire areal extent with the exception of mesas and ridges in the Castle Rock region where it is overlain by the Castle Rock Conglomerate. The Dawson Aquifer is made up of predominantly conglomeratic, very coarse grained arkosic sandstones interbedded with clay shale and clay. The sandstones are generally poorly to moderately consolidated and vary from light to gray to yellowish brown in color. Deeply buried clay shales and clay are normally gray to occasionally pale green gray. Outcrop colors are frequently varicolored ranging fom white to red and purple. Near the western edge of the Denver Basin between Sedalia and Pikeview, the Dawson Aquifer consists of massive conglomeratic, arkosic sandstone with subordinate clay shale and clay. Toward the east, discontinuous clay shale and clay layers increase in thickness and number and interfinger with sandstones in an irregular pattern.

In the northern half of the area covered by the Dawson Aquifer, identification of a continuous mappable clay shale layer has resulted in subdividing the aquifer into upper and lower aquifer members. The clay shale layer, which functions as a hydrostratigraphic barrier within the Dawson Formation, varies from 50 to over 150 feet in thickness. The clay shale of this barrier grades laterally southward into sandstones and conglomerates. The southward change from a two aquifer system to one continuous aquifer occurs gradually throughout a zone two to three miles wide. Therefore the boundary of divided Dawson shown on Figure 1B, 1C, and 1D is actually the approximate center of a zone of gradation which may be two to three miles wide. Thickness of the upper member ranges from zero at the aquifer margins to about 600 feet, thickness of the lower member varies from 50 to over 400 feet.

Lithologically the Dawson Aquifer is distinguished from the Denver Aquifer by its predominantly light gray to yellowish brown, very coarse grained to conglomeratic arkosic sandstone. Dawson sandstones are generally moderately to poorly consolidated and friable; resistant iron oxide cemented sandstones exist in some areas. Quartz particles are occasionally frosted with iron oxide and feldspars are locally highly weathered to a white clay-like material (kaolinized feldspar). Contrasted with Dawson colors are the predominantly finer grained olive and green to brown lignitic strata of the Denver Aquifer. The color contrasts are particularly noticeable in surface exposures along the eastern half of the Denver Basin. They are not as marked in the Sedalia-Castle Rock-Monument area.

The top of the Dawson Aquifer is present only where mesas and high ridges are capped by the highly resistant Castle Rock Conglomerate. In such areas moderately to poorly consolidated conglomeratic, arkosic sandstone with interbedded clay shale and clay of the Dawson Aquifer are overlain by 50 to 100 feet or more of highly resistant reddish-brown conglomeratic arkose of the ridge-forming Castle Rock Conglomerate. The base of the Dawson Aquifer is defined as that horizon below which the rock strata consist of predominantly olive green, and brown colored, very fine to medium grained sandstones and siltstones interbedded with similarly colored clay shales and claystone, and which are fossiliferous and lignitic, and exhibit an overall low resistivity on a geophysical log. Above this the rock strata are predominantly very coarse grained to conglomeratic light gray to yellowish brown arkosic sandstones interbedded with predominantly gray, and greenish gray, clay shale and clay, and which exhibit an overall high resistivity on a geophysical log. Outcropped clays are locally varicolored.

Identification of the Dawson-Denver boundary in the borehole can be made by use of geophysical logs and reference to hydrogeologic cross sections and maps on file at the State Engineer's Office (cross sections and Figs. 1A, and 2A). Geophysical logs of the Dawson aquifer normally indicate that the generally massive, conglomeratic, and arkosic sandstones have an overall higher resistivity than the finer grained rocks of the underlying Denver Aquifer.

The predominant water-yielding strata of the Dawson Aquifer are saturated conglomeratic, arkosic sandstones. These water-yielding beds locally are irregularly shaped and distributed; hence, yields of wells located in one area might differ from wells located in an adjacent area. Wells properly completed in the Dawson Aquifer yield small to large quantities of water depending upon well location and hydraulic properties of the saturated material penetrated. In some areas the lower member of the Dawson Aquifer might not contain sufficient sandstone to insure a reliable water supply. Generally, higher capacity wells can be expected along the western edge of the Denver Basin between Sedalia and Pikeview.

DENVER AQUIFER

The Denver Aquifer consists of a series of interbedded clay shale, claystone, siltstone, and sandstone lenses in which fossilized plant remains and coal are common. The aquifer overlies an area of about 3500 square miles and its thickness ranges from zero at the outer boundary to between 800 and 1000 feet. Distinctive characteristics of the aquifer are its predominantly fine-grained character, widespread olive, green and brown coloration, an abundance of fossilized plant remains, and numerous carbonaceous and lignitic beds. Throughout most of the Denver Aquifer's areal extent, siltstone, clay shale, and claystone are the most abundant rock types. Siltstones occur in irregular beds ranging from a few inches to 40 feet thick, and are composed of quartz grains, dark mineral grains derived from volcanic activity, clay, fossilized plant matter and lignite fragments. Clay shale and claystone occur in beds ranging in thickness from thin laminae to 30 or 40 feet and normally contain fossilized plant matter and lignite particles. Sandstones form irregular beds ranging from a few inches to generally less than 40 feet thick. They are very fine to medium grained, and are composed of quartz, interstitial clay and silt, and dark mineral grains derived from andesitic and basaltic lavas. Denver Aquifer lignite forms beds ranging from about one foot to several feet thick, with some beds 15 to 30 feet thick. Net lignite thickness in some areas is 40 to 60 feet.

Due to the irregular nature of the lenses and beds which make up the main body of the Denver Aquifer and the lateral changes in these beds, it is not possible to correlate them over any distance. Because of this discontinuous nature and interfingering of permeable materials, the Denver Aquifer is considered to be hydrologically connected througnout its entire vertical and horizontal extent with the exception of the continuous confining clays and clay shales which form the top and base of the aquifer.

The distinctive olive, green and brown coloration does not extend continuously throughout the aquifer's areal extent. In some areas, light to medium gray beds may predominate. In such areas, color of sediments cannot be used as a reliable guide for identifying aquifer boundaries.

Within its 3500 square miles of areal extent, the Denver Aquifer exhibits noticeable variations in textural and structural characteristics. Extending eastward from the Rampart Range between Sedalia and Pikeview is a four to six mile wide strip of Denver Basin strata within which conglomerate and sandstone layers are so numerous and closely spaced that distinction between the Dawson, Denver, and Arapahoe Aquifers is difficult. Available data indicate there are no distinctive differences in color of the buried strata and coals are absent. Within this area, boundaries of the Denver Aquifer are determined by extrapolation from areas to the east and identification of key beds. Extending northward, eastward, and southward from the Sedalia - Pikeview strip, Denver sandstone beds thin and become finer grained, and the aquifer attains its olive, green and brown coloration and lignitic character.

The Denver - Arapahoe boundary is relatively easy to identify because siltstones and shales generally predominate in lower Denver strata, whereas sandstones and siltstones generally predominate in upper Arapahoe strata. Hydraulic separation is reinforced by the presence of a 20 to 50 foot thick bed of clay shale and clay at the base of the Denver Aquifer. Identification of the Denver-Dawson boundary is based upon the same principle: the Denver aquifer is composed of predominantly fine grained sediments whereas the Dawson Aquifer is composed of predominantly coarser grained sediments. Hydraulic separation is also reinforced by a mappable clay shale bed ranging in thickness from 20 to 50 feet thick.

The top of the Denver Aquifer, therefore, is defined as that horizon below which rock strata consist of a series of predominantly olive, green and brown colored very fine to medium grained sandstone and siltstones interbedded with similarly colored clay shale and claystone, and which are fossiliferous, lignitic and exhibit an overall low resistivity on geophysical logs. Above this the rock strata are predominantly very coarse grained to conglomeratic, arkosic, light gray to yellowish brown sandstones, interbedded with predominantly gray to green clay shale and which exhibit an overall high resistivity on geophysical logs. The base of the Denver Aquifer is defined as that horizon below which the rock strata are predominantly light to medium gray fine to coarse grained quartzose sandstones with subordinate beds of similarly colored clay shale. Carbonaceous beds are minor to absent. The underlying strata exhibits an overall high resistivity on geophysical logs.

Identification of the Denver Aquifer is facilitated by the use of geophysical logs, hydrogeologic cross sections and maps on file at the State Engineer's Office (cross sections and Figures 2A, and 2B). Resistivity logs of the aquifer normally indicate the presence of numerous closely - spaced beds in which siltstone, clay shale, and claystone predominate. Because finer grained sediments predominate in the aquifer, overall formation or aquifer resistivity is lower than that of the overlying Dawson Aquifer and underlying Arapahoe Aquifer. Higher resistivity beds in the Denver Aquifer are normally interpreted either as coarser grained sediments or coal.

The predominant water yielding strata of the Denver Aquifer are saturated sandstones and siltstones irregularly dispersed in clay shale and claystone. The meandering, irregularly shaped and distributed sandstone and siltstone bodies form a complex pattern of interconnected beds of permeable and relatively impermeable sediments that differ in their capacity to store, transmit, and yield water to wells. Yields of wells located within relatively small areas may differ substantially because of this irregular, unevenly distributed layering. Wells properly completed in the Denver Aquifer generally yield small to moderate quantites of water depending on location and hydraulic properties of the saturated material penetrated. Additional technical information and data are on file at the State Engineer's Office.

ARAPAHOE AQUIFER

The Arapahoe Aquifer consists of a series of interbedded conglomerates, sandstones, siltstones, and clay shales. Thickness of the Arapahoe Aquifer ranges from zero at the outer boundary to between 400 and 600 feet in central parts of the Denver Basin. Sandstones are quartzose, fine to coarse grained, locally conglomeratic, and commonly silty and shaley. Carbonaceous clay shale and sandstone with carbonaceous inclusions may be present near the aquifers boundary with the overlying Denver Aquifer and underlying Laramie Formation. Individual sandstone and siltstone bodies are in the form of irregular blankets and lenses which range in thickness from a few inches to 30 or 40 feet. In some central and western parts of the basin, beds are so closely spaced they form a massive sandstone/siltstone body 200 to 300 feet thick.

Deeply buried conglomerates, sandstones, and siltstones are normally gray, to brownish and olive gray in color. Clay shales are normally gray but may be greenish or olive in the upper part of the aquifer and along the southwestern boundary. Outcrop colors of conglomerate, sandstone and siltstone are various shades of brown and yellow, whereas clay shales retain their relatively gray, brown, and greenish colors. Deeply buried Arapahoe strata normally are only partly indurated. Exposed strata are soft, and weather and erode rapidly.

Within its 4700 square mile extent the Arapahoe Aquifer exhibits significant lateral variations in textural and structural characteristics. Extending northward, eastward, and southeastward from the west-central part of the Denver Basin the conglomerate, sandstone, and siltstone content of the aquifer decreases and the clay shale content increases. In the Littleton - Castle Rock - Colorado Springs region conglomerate, sandstone, and siltstone form 60 percent or more of the total aquifer thickness. In northern, eastern and southeastern parts of the area occupied by the Arapahoe Aquifer, conglomerate, sandstone, and siltstone form only 30 to 50 percent of the total aquifer thickness, and clay shale forms 50 to 70 percent.

In the northern part of the area occupied by the Arapahoe Aquifer, conglomerate, sandstone, and siltstone are distributed in distinct upper and lower aquifer members. The upper and lower aquifers are 150 to 200 feet thick, interbedded with clay shale, and separated from each other by a 50 to 150 feet of clay shale, occasionally with minor siltstone, which forms a hydrostratigraphic barrier. This barrier grades laterally southward and eastward into massive sandstones and conglomerates of the more productive region of the Arapahoe Aquifer. Gradation from a two aquifer system to a single aquifer occurs over a distance of one to three miles. Therefore, the boundary of divided Arapahoe shown on Figure 3C, 3D, and 3F is actually the approximate center of a zone of gradation which may be one to three miles wide.

The upper confining bed for the Arapahoe is formed by a bed of clay shale normally 20 to 50 feet thick and which is considered part of the Denver Aquifer. The lower confining bed for the Arapahoe Aquifer is formed by 200 to 400 feet of gray to black shale of the Laramie Formation which contains thin beds of gray sandstone and siltstone and seams of lignitic through sub-bituminous coal. In the southeastern part of the Denver Basin the Arapahoe Aquifer's lower confining bed locally thins to about 100 feet thick.

The top of the Arapahoe Aquifer is defined as that horizon below which the rock strata are predominantly gray to brownish sandstone and siltstone beds, carbonaceous beds are minor to absent, and the strata exhibit an overall high resistivity on geophysical logs. Above this horizon the rock strata generally become finer grained and individual beds are thin, closely spaced, frequently exhibit gray green color, and include numerous lignite seams and fossilized plant remains. They exhibit an overall low resistivity on geophysical logs. The base of the Arapahoe Aquifer is defined as that horizon below which the rock strata consist of predominantly gray to black shale and contains lignitic through sub-bituminous coal. Above this horizon the rock strata becomes coarser. Sandstones are locally conglomeratic, and lignitic and sub-bituminous coal seams are minor to absent. The overlying strata exhibits an overall high resistivity on geophysical logs.

Identification of the Arapahoe Aquifer is facilitated by use of geophysical logs and reference to hydrogeologic cross sections and maps on file in the State Engineer's Office (cross sections and Figures 3A, 3B, 3C, and 3D). Resistivity logs of Denver Basin strata reveal in general the resistivity of sediments of the Arapahoe Aquifer are higher than those of the overlying Denver Aquifer and underlying Laramie Formation. In addition, such logs generally reveal the preponderance of sandstone over clay shale. In areas where these characteristics are not prominent Arapahoe Aquifer boundaries were determined by identifying a key bed and extrapolating from logs and cross sections.

The predominant water-yielding strata of the Arapahoe Aquifer are saturated conglomerate, sandstone, and siltstone (Figures 3E, 3F). Within the central and westernmost part of the Denver Basin conglomerate, sandstone, and siltstone beds are very closely spaced and form 60 percent or more of the total aquifer thickness. In such areas the aquifer has a relatively high capacity to store and transmit large quantities of water, and yield water to wells. Generally small to large quantities of water can be obtained from water wells properly constructed in such strata. Within the northern, eastern and southern parts of the Denver Basin, conglomerate, sandstone, and siltstone beds are widely spaced and form only 30 to 50 percent of the total aquifer thickness. In these regions the ability of particular sandstones to store and transmit water is overshadowed by the existance of thick beds of interlayered clay shale and a proportional reduction of net sandstone and siltstone. Wells completed in such strata normally yield small to occasionally moderate quantities of water depending upon the number and water-yielding properties of the conglomerate, sandstone, and siltstone beds encountered.

LARAMIE-FOX HILLS AQUIFER

The Laramie-Fox Hills Aquifer, hereinafter referred to as the L-F Aquifer is the lowermost major aquifer of the Denver Basin. The aquifer consists of principally lower sandstone units of the Laramie Formation, and sandstone and siltstone units of the underlying Fox Hills Sandstone. The aquifer underlies an area of approximately 6700 square miles and it's thickness ranges from zero at the outer boundary to between 250 and 350 feet in the central part of the Denver Basin. The Laramie part of the L-F Aquifer consists of 100 to 150 feet of fine to medium grained sandstone with subordinate siltstone and carbonaceous beds. These Laramie sandstones normally are in the form of one or two closely spaced beds 50 to 80 feet thick. In the absence of intervening shale a single sandstone bed 100 to 150 feet thick may be present. The Laramie part of the L-F Aquifer grades transitionally into shale, coaly strata, and minor sandstone beds of the overlying upper part of the Laramie Formation. The Fox Hills part of the aquifer normally consists of 100 to 200 feet of very fine, silty sandstone and sandy to shaley siltstone with several 5 to 20 feet thick interbeds of silty shale. In many areas within the Denver Basin the sandstone forms a distinct 30 to 50 foot thick bed on top of the siltstone sequence. In some areas the lower half of the Fox Hills part of the aquifer includes siltstone beds occasionally assigned to the uppermost part of the Pierre Shale. These siltstones are included with the L-F Aquifer.

Core samples from the L-F Aquifer in the northwestern part of the Denver Basin indicate the Laramie part of the aquifer includes interstitial silt and clay, finely disseminated pyrite, thin carbonaceous films, and bioturbated, fossiliferous shale. Disseminated pyrite is also present in the Fox Hills part of the aquifer but to a lesser degree. Deeply buried sandstones and siltstones are friable and generally light to medium gray. Outcrops of the aquifer are normally well consolidated and colored various shades of brown and orange.

In many parts of the Denver Basin the lower sandstone units of the Laramie Formation are markedly irregular in thickness and areal distribution. The interval normally occupied by 100 to 150 feet of sandstone in the form of one or two beds is locally occupied by two or three beds of sandstone only 10 to 20 feet thick separated by shale beds 10 to 30 feet thick. The shales are commonly lignitic and accompanied by lignite or sub-bituminous coal seams. Such changes in stratigraphy commonly occur over distances of less than one mile. This property may locally impair the chemical and physical quality of ground water in the upper part of the L-F Aquifer. In areas where lower Laramie sandstones have given way to shale and coal beds the top of the L-F Aquifer is placed on the first major sandstone bed below the shaley-coaly zone.

The upper confining bed for the L-F Aquifer is the Laramie shale. This part of the Laramie Formation consists predominantly of gray to black shale, with numerous seams of lignitic through sub-bituminous coal. The lower confining bed for the L-F Aquifer is formed by the gray to black marine Pierre Shale which is about 5000 to 8000 feet thick.

The top of the L-F Aquifer is defined as that horizon below which the rock strata consists of one or more well defined beds of light to medium gray sandstone of non-marine origin and which contains subordinate shale and lignitic beds, and above which the rock strata consists of gray to black non-marine shale and sandy shale with subordinate sandstone and siltstone, frequently accompanied by seams of lignitic to sub-bituminous coal. The base of the L-F Aquifer is defined as that horizon below which the rock strata is predominantly gray to black shale and of marine origin and above which the rock strata is composed of light gray to medium gray sandy to shaley siltstone of marine origin.

Identification of the L-F Aquifer is easily facilitated by use of geophysical logs and reference to geologic cross sections and maps on file in the State Engineer's Office (cross sections and Figures 4A, and 4B).

The L-F Aquifer will normally yield small, and occasionally moderate quantities of ground water to wells throughout most of the Denver Basin. Sandstones of the Laramie part of the aquifer, and uppermost Fox Hills part are believed to furnish about 75 percent or more of the water yielded to wells. Siltstones of the Fox Hills part are more highly consolidated and silty and are believed to furnish 25 percent or less of the water yielded to wells. In some areas, however, the Laramie sandstones grade laterally into shales, and pyritic and coaly strata thereby reducing the water yielding capacity of the aquifer. This adverse characteristic is compounded by the likelyhood that such strata may yield undesirable substances such as methane and hydrogen sulfide. In southwestern Weld, southeastern Boulder, and northeastern Jefferson Counties the L-F Aquifer has been dislocated by a wide northeast trending fault zone. Water wells unintentionally located near a fault or within an isolated fault block in this area may yield only a very limited supply of water.

DESCRIPTION OF THE DENVER BASIN AQUIFER MAPS

UPPER AND LOWER DAWSON AQUIFERS:

It has been recognized that north of T.10.S, the Dawson Aquifer can be divided into an upper and lower aquifer separated by a middle clay shale layer which ranges in thickness from 50 to 150 feet. Thus, the aquifer was divided into an upper and lower aquifer north of the line designating the area in which the aquifer can be separated as shown on Figures 1B, 1C, and 1D. The Dawson south of this line cannot be separated into upper and lower aquifers and the Dawson in this area is referred to as the Upper Dawson Aquifer or sometimes the undefferentiated Dawson Aquifer.

Figure 1A - Structural Contour Map of the Base of the Dawson Aquifer

This map shows the elevation of the base of the Dawson Aquifer everywhere it exists. South of the line which shows separation into an upper & lower aquifer, it defines the base of the undifferentiated or Upper Dawson Aquifer. North of the line it defines the base of the Lower Dawson Aquifer. It also represents the top of the Denver Aquifer.

Figure 1B - Structural Contour Map of the Top of the Lower Dawson Aquifer

This map shows the elevation of the top of the Lower Dawson Aquifer which is the base of the middle clay shale layer. The difference in elevation between Figure 1A and Figure 1B represents the total thickness of the Lower Dawson Aquifer.

Figure 1C - Sandstone Isolith Map for the Lower Dawson Aquifer

This map shows the net sandstone thickness for the Lower Dawson Aquifer in feet. These thicknesses were obtained from geophysical logs.

Figure 1D - Structural Contour Map of the Base of the Upper Dawson Aquifer

This map shows the base of the Upper Dawson Aquifer north of the line defining the area where the Dawson can be separated into an upper and lower aquifer. The thickness of the Upper Dawson Aquifer is the difference between the elevation as shown on this map and the ground surface.

Figure 1E - Sandstone Isolith Map for the Upper Dawson Aquifer

This map shows sandstone thicknesses for the Upper Dawson Aquifer south of the line defining the area in which the Dawson can be separated into an upper and lower aquifer. North of the line it shows the sandstone thickness of the Upper Dawson Aquifer. This map does not represent the entire sandstone section but only that portion below the surface casing in the logged well or below the fluid level in the well. As such it should only be used as a general guide. This map was used to obtain ratios of sandstone to shale so that a approximate saturated thickness map could be created in the numerical model.

DENVER AQUIFER:

Figure 2A - Structural Contour Map of the Top of the Denver Aquifer

This map shows the elevation of the top of the Denver Aquifer and is equivalent to the base of the Dawson Aquifer (Figure 1A).

Figure 2B - Structural Contour Map of the Base of the Denver Aquifer

This map shows the elevation of the base of the Denver Aquifer and is equivelent to the top of the Arapahoe Aquier (Figure 3A). The difference in elevation between Figure 2A and 2B represents the thickness of the aquifer.

Figure 2C - Sandstone/Silstone Isolith Map of the Denver Aquifer

This map shows the thickness of sandstone and siltstone for the Denver Aquifer in feet. These thicknesses were obtained from geophysical logs.

UPPER AND LOWER ARAPAHOE AQUIFERS:

North of T.6.S. and west of R.64.W. the Arapahoe Aquifer can be divided into an upper and lower aquifer separated by a middle clay shale layer 50 to 150 feet thick. Thus the aquifer was divided into an upper and lower aquifer north of the line designating the area in which the aquifer can be separated as shown on Figures 3C, 3D, and 3F. South and east of this line the Arapahoe cannot be separated into upper and lower aquifers and is referred to as the upper or undifferentiated Arapahoe Aquifer.

Figure 3A - Structural Contour Map of the Top of the Arapahoe Aquifer

This map shows the elevation of the top of the Arapahoe Aquifer and is the equivelent of the base of the Denver Aquifer (figure 2B).

Figure 3B - Structural Contour Map of the Base of the Arapahoe Aquifer

This map shows the elevation of the base of the Arapahoe Aquifer. The difference in elevation between Figure 3A and Figure 3B represents the total thickness of the Arapahoe Aquifer and includes both the Upper and Lower Arapahoe Aquifers as well as the middle shale member.

Figure 3C - <u>Structural Contour Map of the Base of the Upper Arapahoe Aquifer</u>

This map shows the elevation of the base of the Upper Arapahoe Aquifer. The difference in elevation between Figure 3C and Figure 3A represents the thickness of the Upper Arapahoe Aquifer in the area where the aquifer can be divided into upper and lower aquifer members.

Figure 3D - <u>Structural Contour Map of the Top of Lower Arapahoe Aquifer</u>

This map shows the elevation of the top of the Lower Arapahoe Aquifer. The difference in elevation between Figure 3D and Figure 3B represents the thickness of the Lower Arapahoe Aquifer. Figure 3D also represents the base of the middle shale member.

Figure 3E - <u>Sandstone/Siltstone Isolith Map of the Arapahoe Aquifer</u>

This map represents the total sandstone/siltstone thickness for the Arapahoe Aquifer and includes both the upper and lower aqifers where they can be subdivided. These thicknesses were obtained from geophysical logs.

Figure 3F - <u>Sanstone/Siltstone Isolith Map of the Lower Arapahoe Aquifer</u>

This map represents the thickness of sandstone/siltstone for the Lower Arapahoe Aquifer as defined on Figures 3B and 3D. To obtain the thickness of sandstone/siltstone for the Upper Arapahoe Aquifer, the thickness as shown on Figure 3F must be subtracted from the thickness shown on Figure 3E.

<u>LARAMIE-FOX HILLS AQUIFER</u>:

Figure 4A - <u>Structural Contour Map of the Top of the Laramie-Fox Hills Aquifer</u>

This map shows the elevation of the top of the Laramie-Fox Hills Aquifer.

Figure 4B - Structural Contour Map of the Base of the Laramie-Fox Hills Aquifer

This map shows the elevation of the base of the Laramie-Fox Hills Aquifer and is equivelent to the top of the Pierre Shale. It also defines the extent of the Denver Basin.

Figure 4C - Sandstone/Siltstone Isolith Map for the Laramie-Fox Hills Aquifer

This map shows the total thickness of sandstone/siltstone for the aquifer in feet. Thicknesses were obtained from geophysical logs.

GLOSSARY

This glossary is intended for use with this report only. The following definitions are not intended to replace or be formal revisions of definitions established by other governmental or private institutions.

Andesitic - The property of containing one or more of the dark minerals biotite, hornblende, augite, etc., and soda-lime feldspars predominate over alkalic-feldspars, andesitic sandstones and siltstones are commonly dark gray through various shades of green.

Aquifer - A geological formation, group of formations, or part of a formation that contains or transmits water, or that is capable of containing or transmitting water.

Arkose, arkosic - A variety of sandstone containing more than 25 or 30 percent of feldspar and usually derived from the disintegration of granite or similar rocks of granular texture. Arkose or arkosic rocks are commonly, but not universally pink or reddish in color.

Bedrock - The more or less solid, undisturbed rock in place either at land surface or beneath superficial deposits of soil, sand, or gravel.

Correlation - Demonstration of the equivalence of two or more geologic phenomena in different areas.

Facies change - A lateral or vertical change or gradation of the lithologic charactor of contemperaneous deposits (deposits laid down at the same time).

Geophysical log - A record of the response of a sensing device lowered and then raised in a borehole. The record can be interpreted in terms of characteristics of the rocks, the fluids contained within them, and the construction of the well or borehole.

Greeley Arch - An uplift of anticlinal nature having a east-west tranding crest and flanks gently sloping toward the Denver Basin on the south and Cheyenne Basin on the north.

Hydrostratigraphic barrier - A sheet or blanket of low permeability clay, clay shale, claystone, or shale which functions as a confining layer or hydraulic barrier.

Intertongued - The lateral disappearance of sedimentary bodies in laterally adjacent masses owing to splitting into many thin tongues. Individual tongues may pinch out, interlock, or overlap other tongues.

Isolith - An imaginary line connecting points of equal aggregate thickness of a given lithologic facies within an aquifer or formation.

Key bed - A well defined and easily recognizable bed that serves to facilitate correlation in geologic work. The term is used interchangeably with key horizon.

Lithified, lithification - The consolidation of fluid or loose materials into solid rock. The term includes compaction or cementing of loose sediments into rock.

Lithologic - Pertaining to the lithology or types of rocks encountered in the borehole.

Marine - Sedimentary deposits laid down in the sea.

Permeability - The property of allowing fluids to pass through under the pressure ordinarily found in earth materials.

Pick - In the interpretation of geophysical logs, the selection of an event; i.e., the base of a body of shale, the top of the L-F Aquifer, etc.

Resistivity - Pertainiang to a measure of the electrical resistivity of earth materials under the appliation of an electric current or induced electric current.

Signature (electrical characteristic) - A characteristic form, pattern, or shape exhibited on a geophysical log and formed by the response of a sensing device in the borehole.

Strata - Layers of homogeneous or gradational lithology. They are separated from adjacent strata or cross strata by surfaces of erosion, non-deposition, or abrupt changes in character.

Structural contour - A contour that portrays a structural surface such as an aquifer or formation boundary.

Type cross section - Cross Section F-F' of the illustrations accompanying this report. Cross section F-F' serves as a standard or foundation from which all other cross sections have been correlated, and structural contour-maps based.

Type log - A geophysical log from which the ultimate description of a geologic or hydrogeologic unit is based.

Zone of gradation - A limited thickness of strata which grade transitionally into a dominating rock type, i.e., gradation of a predominantly sand series to a predominantly siltstone and shale series.

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