Windy Hill Water Facility

Nontributary Determination Request

Prepared for:

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LIST OF ACRONYMS

bgs	below ground surface
C.R.S.	Colorado Revised Statutes
CCR	Colorado Code of Regulations
COGCC	Colorado Oil and Gas Conservation Commission
DWR	Colorado Division of Water Resources
ft/d	feet per day
gpm	gallons per minute
J-4 Sandstone	Dakota J-4 Sandstone
msl	mean sea level
Project	Windy Hill Gas Storage LLC Project
RMAG	Rocky Mountain Association of Geologists
Windy Hill	Windy Hill Gas Storage LLC

*Acronyms specific to equations are defined within the body of the report, immediately preceding or following presentation of the equation.

1.0 INTRODUCTION

This report provides technical information in support of a request for nontributary determination for ground water withdrawal from the Dakota J-4 Sandstone (J-4 Sandstone) at the location of the Windy Hill Gas Storage LLC (Windy Hill) project (the "Project") southeast of the City of Brush in Morgan County, Colorado (**Figure 1**). The information includes:

- A brief description of the Project, including identification of the Project land area boundaries, the source aquifer, and the amount, maximum rate, and use of the proposed ground water withdrawal (see Section 2.0),
- A description of the regional and local geology and hydrogeology as related to the Windy Hill Project (see Section 3.0),
- Demonstration that there is unappropriated water available in the Dakota J-4 Sandstone for withdrawal by the Windy Hill Project (see Section 4.0),
- Demonstration that the proposed Windy Hill water supply well location(s) are more than 600 feet from existing wells constructed in the same aquifer (see Section 4.0),
- Demonstration that the proposed ground water withdrawal will not materially injure vested water rights of others (see Sections 4.0 and 5.0), and
- Demonstration that the ground water proposed to be withdrawn from the Dakota J-4 Sandstone meets the criteria for classification as nontributary (see Section 5.0).

The information presented in this report was obtained from published reports regarding the regional geology and hydrogeology, publicly-available data from the Colorado Division of Water Resources (DWR) and the Colorado Oil and Gas Conservation Commission (COGCC), and reports on and information derived from on-site drilling, testing, and geophysical studies.

The approach taken in this report follows the *Statewide Nontributary Ground Water Rules* (2 Colorado Code of Regulations [CCR] 402-7) and Colorado Department of Natural Resources, DWR *Policy 2010-4 (Amended) Concerning Applications to the State Engineer to Make Determinations of Nontributary Ground Water in the Case of Applications for Well Permits to be Issued Pursuant to Section 37-90-137(4), C.R.S.* as modified on June 13, 2014.

2.0 PROJECT DESCRIPTION

The Windy Hill Project area encompasses 8,456.45 acres of land located southeast of the City of Brush, in Morgan County, Colorado (**Figure 1**). The Project contemplates the withdrawal of up to 1,268.47 acre-feet per year of nontributary ground water from the Dakota J-4 Sandstone for industrial purposes, including, but not limited to, hydraulic fracturing at off-site locations. The water would be withdrawn at rates up to 1,000 gallons per minute (gpm) from up to two wells constructed within the Project area boundary to withdraw ground water from only the Dakota J-4 Sandstone. The locations of the two wells are shown on **Figure 2**. Well 3-18WSW is an existing water supply well, and 1-18WSW would be a new well.

3.0 GEOLOGY AND HYDROGEOLOGY

This section describes the regional geology, the local geology, and the hydrogeologic properties of the Dakota Sandstone aquifer. The information was derived from publicly available literature, as well as geophysical studies and analysis of well logs from the Project area and in the Project vicinity.

3.1 Regional Geology

The Project area is on the eastern flank of the Denver Basin, one of the largest sedimentary basins formed during the Laramide Orogeny (Rocky Mountain Association of Geologists [RMAG] 1972). **Figure 3** shows a generalized west-to-east cross section through the Denver Basin east of the basin axis. The basin is asymmetric, with its axis close to and paralleling the mountain front. The western side of the basin is bounded by a 5- to 10-mile-wide zone of large-displacement faulting parallel to the mountain front, with vertical displacements on some faults exceeding 10,000 feet (Robson and Banta 1987). The western flank dips steeply to the east at 10 degrees or more near the mountain front, while the eastern flank of the basin dips gently to the west at approximately 0.5 to 1 degree (RMAG 1980).

The basin contains up to approximately 13,000 feet of sedimentary rocks above the Precambrian igneous and metamorphic basement rocks (Belitz and Bredehoeft 1988). The sedimentary rocks range in age from Cambrian to Tertiary, with the greatest thickness consisting of Cretaceous-age rocks.

Mississippian-aged rocks consisting of massive grey to brown cherty limestone and dolomite uncomformably overlie either Precambrian or Cambrian rocks in the Denver Basin and range from areas of non-deposition or erosion with no Mississippian rocks up to about 350 feet in thickness. They are uncomformably overlain by Pennsylvanian-aged rocks consisting of a basal sandstone and overlying thinly-bedded carbonates, sandstones, and shales. The rocks of Pennsylvanian age range in thickness from about 800 to about 1,700 feet (RMAG 1980).

Unconformably overlying the Pennsylvanian section are Permian carbonates, sandstones, and evaporites. The thickness of Permian deposits varies from 900 feet in the northern part of the basin to 1,200 feet in the southeastern part of the basin (Momper 1963, RMAG 1972, Robson and Banta 1987).

Triassic-aged rocks are represented by the Lykins Formation, also known as the Chugwater Formation, consisting of red to maroon or purple sandstone, siltstone, and shale. The Lykins/Chugwater overlies the Permian System in the western part of the basin, where it is up to 250 feet thickness, but has been removed by erosion in the eastern part of the basin (RMAG 1976).

The Triassic system is uncomformably overlain by the Jurassic-aged Morrison Formation, which consists of 50 percent to greater than 80 percent variegated shales and lesser amounts of siltstones, sandstone, and minor thin interbeds of limestone. The thickness of the Morrison ranges from approximately 200 to approximately 350 feet. The Morrison formation represents a confining layer with minimal water yields from sandstone lenses (Topper et al. 2003).

The Cretaceous-aged Dakota Group uncomformably overlies the Jurassic System. The Dakota consists of a basal member, the Plainview-Lytle sandstone, or its equivalent; a middle marine shale member, the Skull Creek Shale; and upper sandstone members, the "D" and "J" Sandstones (RMAG 1972, Robson and Banta 1987). The Dakota Group is recognized as a regionally extensive unit that outcrops in Kansas, Nebraska, South Dakota, the southeastern portion of the Denver Basin, and along the flank of the Front Range uplift from Colorado Springs north to Wyoming. The Dakota Group extends throughout the Denver Basin in the subsurface (RMAG 1972). The total Dakota Group thickness is generally about 250 to 350 feet (RMAG 1972, RMAG 1976, Robson and Banta 1987). The Windy Hill Project's proposed ground water withdrawal zone is within the J Sandstone, the lowermost sandstone of the Dakota. The J Sandstone is composed mainly of deltaic, distributary, and near-shore sandstones (Higley and Schmoker 1989) that are fine- to medium-grained. The Dakota Group is discussed in more detail in Section 3.3 below.

The Dakota Group is overlain by the Upper Cretaceous Colorado Group, which includes, in ascending order, the Graneros Shale, the Greenhorn Limestone, the Carlile Shale, and the Niobrara Formation. These units consist of shale, siltstone, and limestone, and are confining layers. The aggregate thickness of Colorado Group units ranges from about 700 to about 1,000 feet.

The Niobrara Formation is the thickest unit of the Colorado Group, with thicknesses ranging from approximately 300 feet near the mountain front to approximately 600 feet near the Kansas border (RMAG 1976). The Niobrara Formation represents a transgressive marine deposit formed when the Cretaceous Seaway was expanding in the interior of the United States (RMAG 1972). The Niobrara is composed of two members, the basal Fort Hayes Limestone and the overlying Smokey Hill Chalk. The Fort Hayes is the thinner unit, and the contact with the Smokey Hill is gradational (RMAG 1976). The Niobrara was evaluated in the Project area for its reservoir potential (The Discovery Group 2003) and found to be composed of chalk and organic-rich shale with high porosity (17 percent average) but very low permeability. The report found that the formation salinity averaged about 24,000 parts per million chlorides and concluded that the Niobrara in this area has "essentially no permeability to fluids" (The Discovery Group 2003).

The Niobrara Formation is uncomformably overlain by the late-Cretaceous-aged Pierre Shale. The Pierre Shale is a thick, widespread marine shale that consists of calcareous, silty, dense shale containing some thin lenses of siltstone and fine sandstone. The Pierre Shale exceeds 4,000 feet of thickness over much of the Denver Basin (RMAG 1972) and represents a low-permeability confining layer (Topper et al. 2003). The upper part of the Pierre Shale interfingers with regressive shoreline deposits of the Late Cretaceous Fox Hills Sandstone in the western third of the basin (RMAG 1972). The nonmarine Laramie Formation overlies the Fox Hills in the portion of the Denver Basin closest to the mountain front (RMAG 1972). In the Windy Hill Project area, the formations overlying the Pierre Shale have been removed by erosion.

The oldest Tertiary rocks present in the eastern portion of the Denver Basin are Oligocene. These rocks are of floodplain origin, and erosion has left only remnant deposits in the eastern part of the Denver Basin just east of the Windy Hill Project area (Miller 2000, RMAG 1976, RMAG 1972, Topper et al. 2003).

Unconsolidated Quaternary-aged deposits of alluvial and eolian sediments form the surficial geology over large areas of the Denver Basin (Topper et al. 2003, Scott 1978). In the area of the Windy Hill Project, the Pierre Shale is covered with a thin veneer of wind-deposited silt and fine sand (Scott 1978) up to about 100 feet thick.

3.2 Local Geology

The local geology within the Project area has been documented by studies of logs of oil wells within and surrounding the Project area (The Discovery Group 2003), including nine wells drilled within the Project area boundary and a geophysical study of the Project area and vicinity (Geostock 2008). The local stratigraphic sequence mimics the regional sequence and is summarized in **Figure 4**. The total thickness of sedimentary rocks beneath the Project area is approximately 8,000 feet (Belitz and Bredehoeft 1988).

The sedimentary strata dip to the northwest at 0.5 to 1 degree. No identified regional faults occur in the Project vicinity. The Project is located in an area of low seismicity, and there are no mapped Quaternary-aged faults within Morgan County (Widmann et al. 1998, Colorado Geological Survey 2015). Windy Hill conducted seismic testing in the Project area in January 2005, and the results confirmed that there are no expected displacements of the J Sandstone (Sandarusi 2005). Additional detail on the local geology is provided in Sections 3.3 and 3.4.

3.3 Dakota Group and Dakota Sandstone

The Dakota Group is a regional reservoir and aquifer that underlies a large area in the western interior of the United States. The outcrop belt east of the Rocky Mountains extends from the foothills along the Front Range north of Colorado Springs, east along the Apishapa Uplift on the southern flank of the Denver Basin and into Kansas, Nebraska, and South Dakota (RMAG 1972). The Dakota Group is present in the subsurface across the Denver Basin.

The Dakota Group is composed of a basal marine sandstone (the Cheyenne, Lytle-Cheyenne, Plainview-Lytle, Purgatoire, or other stratigraphically equivalent sandstones) that is overlain by a widespread marine shale unit (the Skull Creek Shale) that is in turn overlain by a series of erratically-distributed, near-shore-marine, deltaic, and distributary sandstones (**Figure 3**). The lower sandstones are known as the J Sandstone (also called the Muddy), and the upper sandstone is known as the D Sandstone. In Morgan County, as many as four distinguishable sandstone beds (the J-1, J-2, J-3, and J-4) make up the J Sandstone, with the J-1 being the uppermost and the J-4 being the deepest. These sandstones are collectively known as the Dakota Sandstone.

Robson and Banta (1987) contoured the aggregate thickness of sandstone units within the Dakota Sandstone in the Denver Basin, based on logs of selected oil and gas wells in the area. They estimated that in the Project area the thickness ranges from slightly less than 100 feet to more than 150 feet, and that in the 82 miles between the Project area and the outcrop along the mountain front the thickness ranges from approximately 50 feet to more than 150 feet (**Figure 5**). More detailed studies and drilling at and in the immediate vicinity of the Project area (The Discovery Group 2003, Geostock 2008) have indicated that the total J Sandstone thickness in the Project area ranges from approximately 180 feet to 240 feet (**Figure 6**) and has an area-weighted average thickness of 224 feet. Depths to the top of the Dakota within the Project area range from about 5,000 feet to 5,200 feet below ground surface (bgs). The top of the J Sandstone in the Windy Hill #3-17D well was encountered at a depth of 5,110 feet bgs, and the base of the J Sandstone (top of the Skull Creek Shale) was at 5,310 feet bgs. Only the J-1, J-2, and J-4 Sandstones were present; the J-3 Sandstone was absent. The geophysical logs indicate that the D-1 Sandstone and the D-2 Sandstone are shaley, the J-1 Sandstone is cleaner sand but thin, and the J-4 Sandstone is thick and clean, with a gross sand thickness of 192 feet. Analysis of well logs by The Discovery Group (2003) shows that over 90 percent of the overall J Sandstone thickness is represented by the lowermost J-4 layer. Considering the J-4 Sandstone as 90 percent of the overall J Sandstone thickness, the thickness of the J-4 Sandstone within the Project area ranges from approximately 162 feet to 216 feet and averages 202 feet.

The elevation of the top of the J Sandstone ranges from about -3500 feet (relative to mean sea level [msl]) in the Denver area and northeast of Fort Collins, along the axis of the Denver Basin, to about -500 feet msl in the Project area (**Figure 7**), and about 750 feet msl at the Colorado/Nebraska border about 80 miles east of the Project area (Robson and Banta 1987). More detailed study of the Project area (Geostock 2008) showed that the top of the J Sandstone ranges from approximately -830 feet msl in the northwest corner to approximately -515 feet msl in the southeast (**Figure 8**), resulting in a dip of approximately one-half to one degree to the west-northwest.

The Dakota Sandstone is an important reservoir for oil and gas production throughout the Denver Basin (Ethridge and Dolson 1989, RMAG 1982). About two-thirds of the oil and one-half of the gas production in the basin have come from the D and J Sandstones in 355 fields across the basin (Higley and Cox 2007). Historical production from the D and J Sandstones in the Project vicinity includes the Pinneo North and Jubilee fields, located about 2 miles south of the southern boundary of the Project area. Although no historical production is recorded within the Project boundaries shown on **Figure 1**, oil was present in J Sandstone core from the John A Fries et al. (L-2768) #1 well (API #05-087-05996) in the northwest quarter of Section 17 (COGCC 2015).

3.4 Dakota Hydrogeology

The Dakota Sandstone is also known as the Dakota-Cheyenne aquifer in southeastern Colorado, where it occurs at relatively shallow depths and provides ground water to stock, domestic, and irrigation wells (Robson and Banta 1987, Topper et al. 2003) and is classified as a regional aquifer. In adjacent Kansas, it is called the Dakota aquifer and includes the Cheyenne Sandstone, Kiowa Formation and Dakota Formation (Whittemore et al. 2014). Regionally, the Dakota Sandstone is included in the Great Plains aquifer system as the Maha aquifer (Jorgensen et al. 1996); however, in Morgan County, where the Windy Hill project is located, the Dakota is not classified as a regional aquifer (Robson and Banta 1995). The petroleum industry terminology varies from this, not only geographically but also from person to person. The Dakota is frequently referred to as the Muddy Sandstone, which sometimes includes both the D and J Sandstones and other times only the J Sandstone. The J Sandstone is also called the Muddy “J” or Muddy (J), and in northeastern Colorado it is sometimes divided into the Horsetooth and Fort Collins Members rather than the J-1 through J-4 Sandstones. It has been acknowledged that the terminology has varied greatly over the years (Boyd 1993), but use of the term Dakota Sandstone is the generally accepted terminology (Higley and Schmoker 1989, Weimer and Sonnenberg 1989). For the purposes of this document, this unit is referred to as the Dakota Sandstone.

The most complete description of the Dakota Sandstone hydraulic properties is provided in a U. S. Geological Survey Water Resources Investigation (Robson and Banta 1987). The hydraulic conductivity of various units within the Dakota Sandstone ranges from 20 feet per day (ft/d) in well-sorted sandstones to less than 0.001 ft/d in poorly sorted, clay-rich, and highly compacted sediments. Hydraulic conductivities of 0.2 ft/d and greater are generally more prevalent in the eastern part of the Denver Basin, and lower hydraulic conductivities predominate toward the west and where the unit is deeply buried along the Denver Basin axis (**Figure 9**). In Morgan County, the average hydraulic conductivity is estimated to be 0.2 ft/d (Topper et al. 2003). **Table 1** summarizes data from J Sandstone oil wells within the Project area (The Discovery Group 2003) and testing of wells #3-17D and #3-18WSW in the Project area (Geostock 2007, 2008). The on-site data indicate hydraulic conductivities with a range of 0.03 ft/d to 2.24 ft/d and an average of 0.89 ft/d.

Table 1. Summary of Hydraulic Conductivity and Porosity Data for J Sandstone within Windy Hill Project Area

Well	Location (Township-Range-Section)	Well Type	Year Drilled	Hydraulic Conductivity (ft/d)	Porosity (percent)
1 Miller	3N-55W-21	Oil	1955	0.72	22.9
1 Mitchell	3N-55W-23	Oil	1958	0.03	15.8
1 Fries	3N-55W-17	Oil	1961	1.0	21.7
1-4 Federal	3N-55W-4	Oil	1971	0.40	21.1
1 Chvatal	3N-55W-18	Oil	1981	0.09	15.5
1 Bass	3N-55W-29	Oil	1983	2.24	24.4
1 Bewley Const	3N-55W-7	Oil	1986	0.77	23.3
1-17D	3N-55W-17	Disposal	2004	0.39	--
3-17D	3N-55W-17	Disposal	2007	1.64	--
3-18WSW	3N-55W-18	Water Supply	2007	1.66	--
				Average = 0.89	**Average = 20.7**

Data from oil wells within the Project area indicate that the J Sandstone has porosities ranging from 15.5 percent to 24.4 percent, with an average of 20.7 percent (**Table 1**) (The Discovery Group 2003). Between the Project area and the Dakota outcrop at the mountain front, the J Sandstone porosity is reported to range from about 16 percent to slightly less than 10 percent (Robson and Banta 1987) (**Figure 9**).

The Dakota Group is confined by the underlying Morrison Formation and the overlying Graneros Shale. The Graneros Shale consists of dark gray to black, fissile, noncalcareous shale. The Morrison Formation is composed of mudstones, shales, thin limestones, and sandstones. The permeability of both these units is very low. Also overlying the Dakota Sandstone are the confining units of the Niobrara Formation (greater than 300 feet thick) and the Pierre Shale (approximately 4,300 feet thick) based on the logs of wells in and near the Project area. These units hydraulically isolate the Dakota Sandstone from the surface and from deeper units in the Project area and region. Vertical conductivity in the Dakota Sandstone is negligible, and very little flow is thought to occur between the overlying and underlying units (Robson and Banta 1987, Topper et al. 2003).

Throughout the axial trough and the eastern side of the Denver Basin, the Dakota Sandstone is hydraulically underpressured, with a potentiometric surface elevation far below the land surface (Gibbons and Self 1978, Robson and Banta 1987, Belitz and Bredehoeft 1988). The cause of the subnormal formation pressure was attributed by Belitz and Bredehoeft (1988) to the combination of 1) isolation of higher-altitude recharge areas by faulting along the mountain front, 2) low permeability along the Denver Basin axis, and 3) increasing permeability toward the lower-altitude discharge areas in Kansas and Nebraska. Dakota outcrop areas between Boulder and Pueblo are detached from the main body of the Dakota farther east by faulting along the Front Range, which limits the eastward flow of groundwater recharge south of Boulder. As the J Sandstone dips toward the axis of the Denver Basin, it is buried more deeply (up to about 8,000 feet) and contains oil and gas. The deep burial along the axis of the basin and the presence of oil and gas (rather than complete saturation with water) result in an area of lower permeability, which restricts the flow of water eastward from the recharge area and has the effect of further isolating the recharge area from the areas east of the basin axis. East of the basin axis, the permeability increases by up to several orders of magnitude. The area with increased permeability extends to the outcrop areas in Kansas and Nebraska where the water discharges. Within the basin, the J Sandstone is capped by a thick sequence of low-permeability shales which provide isolation from the elevation head of the local water table. The combination of low permeability along the basin axis, higher permeability east to the discharge area, and isolation by the overlying shale sequence produces the under-pressured area within and east of the basin axis. The low permeability zone restricts eastward flow of groundwater, the overlying shales prevent vertical communication to the surface, and the higher-permeability area to the east readily allows discharge from the aquifer and lowers the hydraulic heads (pressures) east of the low-permeability basin axis.

A potentiometric surface map representing conditions prior to extensive oil and gas development and ground water extraction from the Dakota was prepared by Robson and Banta (1987), the northern part of which is shown here as **Figure 10**. The map indicates ground water flow generally toward the north and east from recharge areas on the southern and western margins of the Denver Basin. Northward flow predominated in the southern part of the basin, westward flow predominated in the northwestern part of the basin, and a gradual change of flow toward the northeast occurred across Morgan County, where the potentiometric surface elevation ranged from about 2,500 feet msl in the southwest to about 2,300 feet msl in the northeast. Hoeger (1968, shown in Nelson and Santus 2011), Gibbons and Self (1978), Pruit (1978), and Pearl (1982) prepared potentiometric maps for then-current conditions in the J Sandstone in the Denver Basin. These maps showed potentiometric surface slopes generally similar to that shown by Robson and Banta (1987), but also indicated local complexity. Complex interfingering of sandstones and shales restricts the movement of groundwater in many areas. Additionally, some growth faults in the Cretaceous section may affect ground water movement.

In the Windy Hill Project area, the potentiometric surface elevation for the Dakota Sandstone, interpreted from down-hole pressure readings made during testing of three Windy Hill wells (#1-17D, #3-17D, and #3-18WSW) in Sections 17 and 18, Township 3 North, Range 55 West, ranges from approximately 1,920 feet msl on the southwest side of the Project area to approximately 1,893 feet on the southeast side of the Project area (**Figure 11**). The hydrodynamic gradient is to the northeast at approximately 5.6 feet per mile. The depth to the static water level is approximately 2,460 to 2,600 feet below the land surface, depending on the location within the Project area.

4.0 WATER RIGHTS

Tetra Tech searched the DWR (2015a) online water wells database to identify permitted water supply wells within the Windy Hill Project area. The search returned results showing 43 water well permits issued or active applications received, including 36 constructed water wells (**Table 2**). Note that the database does not accurately represent the status of Windy Hill's well 3-18WSW in Section 18, Township 3 North, Range 55 West, as that is a well that was constructed and completed in the Dakota aquifer under permit number 65080-F and for which new permit number 79176-F was issued in July 2015.

Of the other constructed wells in the Project area, the greatest reported well depth is 410 feet, and a total of eight reported depths are 172 feet or more. Those wells are drilled into the upper part of the Pierre Shale and terminate at depths at least 4,600 feet above the top of the Dakota Sandstone. Eight wells have reported depths of 109 to 120 feet and are likely completed in the uppermost part of the Pierre Shale. The remaining 19 wells with reported depths are thought to be completed in the Quaternary-aged surficial unconsolidated deposits that cover the Pierre Shale bedrock. All of the identified wells in the Project area, other than the one Windy Hill well completed in the Dakota aquifer, are hydraulically isolated from the Dakota J-4 Sandstone by at least several thousand feet of low-permeability shale. No permits are issued or pending for wells in the Dakota, other than those for Windy Hill.

Based on the information presented in this section and the preceding section of this report, unappropriated ground water is available in the Dakota J-4 Sandstone beneath the Windy Hill Project area. The absence of water wells completed in the Dakota aquifer within or near the Project area, and the hydraulic isolation of the J-4 Sandstone from shallower and deeper aquifers by substantial thicknesses of low-permeability shale, demonstrates that no existing water users would be harmed by the proposed withdrawal for the Windy Hill Project.

Table 2. DWR Records within Windy Hill Project Area

Receipt	Permit Number	Permit Suffix	Status Description	Well Name	Township	Range	Section	Qtr-Sec.	Qtr-Qtr-Sec.	UTM Coordinates		Uses			Aquifer Name	Well Depth (ft)	Perforation Depth (ft)		Pump Rate (gpm)	Static Water Level (ft)	Owner Name
										Easting	Northing						Top	Bottom			
C440475	475	WCB	Well Constructed		3 N	55 W	4			624423.8	4457142				ALL UNNAMED AQUIFERS	80					HANSELM HENRY
C440546	546	WCB	Well Constructed	BOXER JACK #2	3 N	55 W	4			624423.8	4457142				ALL UNNAMED AQUIFERS	120					BOXER JACK
C440547	547	WCB	Well Constructed	BOXER JACK #1	3 N	55 W	4			624423.8	4457142				ALL UNNAMED AQUIFERS	120					BOXER JACK
17246	17246	MH	Permit Issued; Completion Status Unknown		3 N	55 W	4	NW		624025	4457499	OTHER		MONITORING WELL	ALL UNNAMED AQUIFERS						BOOTH BROTHERS
19300	41349	F		WELL NO 8	3 N	55 W	4	NW	NE	624225.9	4457690	DOMESTIC	COMMERCIAL		ALL UNNAMED AQUIFERS						PINNO FEEDLOTS
17371	91087	VE	Permit Issued; Completion Status Unknown		3 N	55 W	4	NW	NW	623960.8	4457842	IRRIGATION			ALL UNNAMED AQUIFERS						PINNEO
0323956A	10539	R	Well Constructed	#2	3 N	55 W	4	NW	NW	624005.5	4457802	COMMERCIAL			ALL UNNAMED AQUIFERS	118			350	51	PINNEO FEEDLOTS
476914	10538	R	Well Constructed	#1	3 N	55 W	4	NW	NW	623756.7	4457841	COMMERCIAL			ALL UNNAMED AQUIFERS	109	39	109	350	60	PINNEO FEEDLOTS
9047348	10330	F	Well Constructed		3 N	55 W	4	NW	NW	623804.7	4456700	COMMERCIAL			ALL UNNAMED AQUIFERS	122			200	56	PINNEO FEEDLOTS
9047414	10538	R	Well Constructed		3 N	55 W	4	NW	NW	623828.5	4457681	COMMERCIAL			ALL UNNAMED AQUIFERS	117			350	45	PINNEO FEEDLOTS
9049747	111641		Well Constructed		3 N	55 W	4	SE	SW	624666.4	4456778	STOCK			ALL UNNAMED AQUIFERS	115			15	42	HANSEN LLOYD BOB & ED
112778	111641		Permit Issued; Completion Status Unknown		3 N	55 W	4	SE	SW	624666.4	4456778	STOCK			ALL UNNAMED AQUIFERS						HANSEN L
19302	41351	F		A18-1	3 N	55 W	4	SW	NE	624262.1	4457118	DOMESTIC	FIRE		ALL UNNAMED AQUIFERS						EBEN EZER LUTHERAN CARE CTR
9048506	31855		Well Constructed		3 N	55 W	5	NW	NW	622076.5	4457734	STOCK			ALL UNNAMED AQUIFERS	68	56	68	6	50	ODLE RUTH ANN
238783	132567		Well Constructed		3 N	55 W	5	NW	SE	622528.7	4457054	STOCK			ALL UNNAMED AQUIFERS	300	200	300	10	90	FRIES H C
0299546B	154645		Well Constructed	REPLACE LR	3 N	55 W	7	NW	SW	620601.5	4455549	DOMESTIC	STOCK	ISSUED UNDER PRESUMPTION 3b-IIA	ALL UNNAMED AQUIFERS	92	40	92	15	39	ODLE RUTH ANN
3605166C	269978		Well Constructed	MW-3	3 N	55 W	17	NE	NW	623044	4454533	OTHER		MONITORING WELL	ALL UNNAMED AQUIFERS	60	50	60			UNOCAL WINDY HILL GAS STORAGE LLC
46051	46051	MH	Well Constructed	MW-3	3 N	55 W	17	NE	NW	623038.9	4454449	OTHER		MONITORING WELL	ALL UNNAMED AQUIFERS	62	50	60			BOSS BRUCE B FAMILY LLP
46052	46052	MH	Well Constructed	MW-2	3 N	55 W	17	NW	NE	622605.2	4454522	OTHER		MONITORING WELL	ALL UNNAMED AQUIFERS	74					BOSS BRUCE B FAMILY LLP
3605166B	269977		Well Constructed	MW-2	3 N	55 W	17	NW	NE	622605	4454531	OTHER		MONITORING WELL	ALL UNNAMED AQUIFERS	72	62	72			UNOCAL WINDY HILL GAS STORAGE LLC
3605166A	269976		Well Constructed	MW-1	3 N	55 W	17	NW	NW	622159	4454488	OTHER		MONITORING WELL	ALL UNNAMED AQUIFERS	64	54	64			UNOCAL WINDY HILL GAS STORAGE LLC
46053	46053	MH	Well Constructed	MW-1	3 N	55 W	17	NW	NW	622159.2	4454488	OTHER		MONITORING WELL	ALL UNNAMED AQUIFERS	64	54	64			BOSS BRUCE B FAMILY LLP
46055	46055	MH	Well Constructed	MW-5	3 N	55 W	17	NW	SE	622717.2	4453904	OTHER		MONITORING WELL	ALL UNNAMED AQUIFERS	79	69	79			BOSS BRUCE B FAMILY LLP
3605166E	269980		Well Constructed	MW-5	3 N	55 W	17	NW	SE	622717	4453914	OTHER		MONITORING WELL	ALL UNNAMED AQUIFERS	79	69	79			UNOCAL WINDY HILL GAS STORAGE LLC
3605166F	269981		Well Constructed	MW-6	3 N	55 W	17	NW	SE	622796.2	4453998	OTHER		MONITORING WELL	ALL UNNAMED AQUIFERS	79	69	79			UNOCAL WINDY HILL GAS STORAGE LLC
3605166D	269979		Well Constructed	MW-4	3 N	55 W	17	NW	SW	622159	4454136	OTHER		MONITORING WELL	ALL UNNAMED AQUIFERS	88	78	88			UNOCAL WINDY HILL GAS STORAGE LLC
46054	46054	MH	Well Constructed	MW-4	3 N	55 W	17	NW	SW	622159.2	4454134	OTHER		MONITORING WELL	ALL UNNAMED AQUIFERS	88	78	88			BOSS BRUCE B FAMILY LLP
9048825	43892		Well Constructed		3 N	55 W	17	SE	SW	623050.2	4453250	STOCK			ALL UNNAMED AQUIFERS	45			10	30	FRIES HERBERT C
3669228B			Application Received	1-18WSW	3 N	55 W	18	NW	NW			INDUSTRIAL			DAKOTA						WINDY HILL GAS STORAGE LLC
0298913A	153783		Well Constructed		3 N	55 W	18	SE	SW	621603.9	4453081	STOCK			ALL UNNAMED AQUIFERS	120			15		BAUGHMAN ROY
0298913B	153783		Well Constructed		3 N	55 W	18	SE	SW	621599.4	4453084	STOCK			ALL UNNAMED AQUIFERS						STUTZMAN TIMOTHY J & LANA
3669228A			Application Received	3-18WSW	3 N	55 W	18	SW	NW			INDUSTRIAL			DAKOTA						WINDY HILL GAS STORAGE LLC
389426	189411		Well Constructed		3 N	55 W	19	SE	NW	621338.4	4451894	STOCK		ISSUED UNDER PRESUMPTION 3b-IIA	ALL UNNAMED AQUIFERS	380	170	370	5	126	FRAZIER JODY & BONNIE & CODY
9049808	121140		Well Constructed		3 N	55 W	19	SW	NE	621161.4	4451888	DOMESTIC			ALL UNNAMED AQUIFERS	310	140	310	5	110	FRAZIER CODY W & BONNIE CARPENTER
9049791	119570		Well Constructed		3 N	55 W	19	SW	SE	620834.8	4451807	DOMESTIC			ALL UNNAMED AQUIFERS	410			10	104	HOFFMAN CEDRIC C.
9046057	1137		Well Constructed		3 N	55 W	26	NE	NE	628207.4	4451359	DOMESTIC	STOCK		ALL UNNAMED AQUIFERS	44	32	44	6	32	MITCHELL DON
9048515	32306		Well Constructed		3 N	55 W	26	NE	NE	628207.4	4451359	DOMESTIC			ALL UNNAMED AQUIFERS	62	33	62	6	34	FORD WILLIAM DOUGLAS & SANDRA A
9048561	33717		Well Constructed		3 N	55 W	26	NW	NW	626969.8	4451497	STOCK			ALL UNNAMED AQUIFERS	60	45	60	3	31	FORD WILLIAM DOUGLAS & SANDRA A
9048593	35267		Well Constructed		3 N	55 W	26	NW	NW	627070.2	4451385	STOCK			ALL UNNAMED AQUIFERS	81	31	81	5	34	FORD WILLIAM DOUGLAS & SANDRA A
332687	162480		Well Constructed		3 N	55 W	30	NE	NW	621325.2	4451371	STOCK		ISSUED UNDER PRESUMPTION 3b-IIA	ALL UNNAMED AQUIFERS	402	362	402	10	105	BASS BRUCE
9049840	128026		Well Constructed		3 N	55 W	30	SE	NW	621291.1	4450422	DOMESTIC			ALL UNNAMED AQUIFERS	400			15	100	SCHILLING RANDALL L.
9048649	37548		Well Constructed		3 N	55 W	30	SE	SW	621350.3	4449920	DOMESTIC			ALL UNNAMED AQUIFERS	172			2	52	BASS L C
9049374	76545		Well Constructed		3 N	55 W	30	SE	SW	621488	4449844	DOMESTIC			ALL UNNAMED AQUIFERS	400			6	90	BASS L. C.

Notes:
In several cases the DWR database contains duplicate entries for a given well.

5.0 NONTRIBUTARY DETERMINATION

Nontributary ground water is defined [Colorado Revised Statutes (C.R.S.) 37-90-103(10.5)] as "that ground water, located outside the boundaries of any designated ground water basins in existence on January 1, 1985, the withdrawal of which will not, within one hundred years of continuous withdrawal, deplete the flow of a natural stream, including a natural stream as defined in sections 37-82-101(2) and 37-92-102(1)(b), at an annual rate greater than one-tenth of one percent of the annual rate of withdrawal." Landowners have the right to withdraw the amount of ground water, exclusive of artificial recharge, underlying their land or land owned by another who has consented to the withdrawal [C.R.S. 37-90-137(4)] on the basis of an aquifer life of one hundred years. This section of the report presents information to demonstrate that the water proposed to be withdrawn from the Dakota J-4 Sandstone for the Windy Hill Project meets the definition of nontributary ground water.

5.1 Designated Basins

The Project area is located outside of any DWR-designated ground water basin or ground water management district. The nearest designated basin is the Camp Creek Basin (DWR 2015b), located about ¾-mile east of the easternmost part of the Project area (**Figure 12**).

5.2 Ground Water Volume

The Windy Hill Project area encompasses 8,456.45 acres in Township 3 North, Range 55 West, Sixth Principal Meridian (**Figure 1**). This land area is sufficient to provide ground water to meet the proposed withdrawal rate of 1,268.47 acre-feet per year, as demonstrated below.

The volume of ground water available in the Dakota J-4 Sandstone beneath the Project area can be calculated from the land area, the saturated thickness of the aquifer, and the specific yield of the aquifer. The applicable equation is:

$$V = A \times m \times Sy$$

where:

V = ground water volume in acre-feet,

A = land area in acres,

m = aquifer saturated thickness in feet, and

Sy = aquifer specific yield (unitless).

Table 3 summarizes the values assigned to the various input parameters for the calculation and the basis for those values. More detailed information regarding the geological foundation for the information is provided in Sections 3.3 and 3.4 of this report.

Table 3. Summary of Input Parameters for Calculation of Available Ground Water Volume

Equation Input Parameter	Assigned Value	Basis for Assigned Value
A, land area	8,456.45 acres	Land area within boundaries of Windy Hill Project area.
m, aquifer saturated thickness	150 feet	The area-weighted average thickness of Dakota J Sandstone within Project area is 224 feet. The J-4 Sandstone comprises over 90 percent of Dakota J Sandstone thickness within Project area (The Discovery Group 2003). 224 feet x 90 percent = 201.6 feet The assigned value is approximately three-quarters of the actual value, so will produce a very conservative result.
Sy, aquifer specific yield	0.1 (10 percent)	Specific yield is defined as the ratio of the volume of water which an aquifer will yield by gravity to the volume of the aquifer. It is sometimes referred to as drainable porosity. The average porosity of the J Sandstone within the Project area is 0.207, or 20.7 percent (The Discovery Group 2003). The assigned value is less than half of the average measured porosity, so will produce a very conservative result.

Applying the values presented in **Table 3** to the equation yields the following result:

$$V = A \times m \times Sy$$
$$= 8{,}456.45 \text{ acres} \times 150 \text{ feet} \times 0.1$$
$$= 126{,}846.75 \text{ acre-feet}$$

The calculated volume of ground water available from the Dakota J-4 Sandstone beneath the Project area is 126,846.75 acre-feet. The allowable annual appropriation is one percent of the total volume of ground water available, or 1,268.47 acre-feet. The use of very conservative values for saturated thickness and specific yield gives a calculated volume much less than the actual volume of ground water present. The actual volume present, based on the full saturated thickness and the actual porosity is 352,897.82 acre-feet, more than twice the conservatively-calculated volume stated above. Consequently, the annual appropriation of 1,268.47 acre-feet that is requested for the Windy Hill Project is very reasonable.

5.3 Glover Modeling

Tetra Tech used the Glover model (Glover and Balmer 1954) to determine that ground water in the Dakota J-4 Sandstone in the Project area, withdrawn at the annual appropriation rate of 1,268.47 acre-feet per year, is classified as nontributary. The calculations and the derivation of the values used as input to the model are summarized below.

Glover and Balmer (1954) developed an equation to calculate stream flow depletion from pumping a well near a river. The equation calculates the stream flow depletion as a fraction of the well pumping rate. The equation is:

$$q/Q = erfc\left\{r/\left(2\sqrt{\alpha \cdot t}\right)\right\}$$

where:

q = stream flow depletion rate [length {L}^{3}/time {T}],

Q = well pumping rate [L^3/T],

r = distance from well to stream bank [L],

$\alpha = (K \cdot m) / Sy$ [L^2/T],

K = aquifer hydraulic conductivity [L/T],

m = aquifer saturated thickness [L],

Sy = aquifer specific yield [dimensionless],

$erfc$ = error function, and

t = time since pumping started [T].

The Colorado Revised Statutes, in the definition of nontributary groundwater, limit q/Q to a maximum of one-tenth of one percent, or 0.001. The derivation of the values used for the input parameters to the equation is described below. Note that the input parameters can be in any consistent units; in this case, the units employed are feet and days. Thus, lengths are in feet, volumes in cubic feet, time in days, and pumping or flow rates in cubic feet per day.

The Dakota J-4 Sandstone is overlain and isolated from the land surface and any surface streams near the Project area by several thousand feet of shale with very low permeability, so ground water withdrawals would not affect any surface waters in the vicinity of the Project area. The closest point of hydraulic communication between the Dakota Sandstone and surface water would be at the Dakota Sandstone outcrop, the nearest of which is along the Front Range west of Loveland, approximately 82 miles from the western edge of the Project area (**Figure 5**).

Because the Glover model calculation is to be applied over the intervening distance between the Project area and the mountain front, the aquifer properties used for input to the equations should represent average conditions between those points. The values used as input for hydraulic conductivity, saturated thickness, and specific yield were averaged over the cross-section extending from the Project area to the nearest Dakota outcrop. Derivation of the values was based on maps presented by Robson and Banta (1987) showing contours of aggregate Dakota Sandstone thickness and porosity and zoned hydraulic conductivity. The relevant portions of those maps were presented as **Figure 5** (sandstone thickness) and **Figure 9** (porosity and hydraulic conductivity).

The weighted-average aquifer thickness was calculated as the sum of the contoured thicknesses times the proportion (percentage) of the total distance occupied by each thickness range, as summarized in **Table 4**. The greater thickness of J-4 Sandstone observed in the Project area was not factored into the calculation, considering that the applicable distance is between the western boundary of the Project area and the outcrop, and excludes the Project area. The weighted average thickness used as input to the Glover model calculations was 121 feet.

Table 4. Calculation of Average Saturated Aquifer Thickness

Contoured Thickness Range (feet)	Thickness Applied for Calculation (feet)	Percent of Total Distance along Cross-Section	Thickness x Percentage of Distance (feet)
50	50	13.6%	7
50-100	75	24.3%	18
100-150	125	25.7%	32
>150	175	36.4%	64
		Weighted-Average Thickness	121

Similarly, the weighted average porosity was calculated as the sum of the contoured porosities times the proportion (percentage) of the total distance occupied by each porosity range, as summarized in **Table 5**. The greater average porosity observed within the Project area was not factored into the calculation. The weighted average porosity was 10.8 percent. The porosity was rounded down to 10 percent (0.10) to approximate the specific yield used as input to the Glover model calculations.

Table 5. Calculation of Average Aquifer Porosity

Contoured Porosity Range (Percent)	Porosity Applied for Calculation (Percent)	Percent of Total Distance along Cross-Section	Porosity x Percentage of Distance (Percent)
<10%	8.0%	40.2%	3.2%
10 – 15%	12.5%	56.9%	7.1%
>15%	16.0%	2.9%	0.5%
		Weighted-Average Porosity	10.8%

The effective hydraulic conductivity was calculated using the principle applied to the conductance term used in the finite-difference ground water flow model code MODFLOW. The conductance (C) equals the hydraulic conductivity (K) times the cross sectional area (A) divided by the cell length (L), or C = KA/L. The effective conductance of a series of cells, which in this case comprises the three hydraulic conductivity zones mapped by Robson and Banta (1987, **Figure 9**), is the inverse of the sum of the inverses of the individual hydraulic conductivity zone conductances, or $1/C = 1/C_1 + 1/C_2 + 1/C_3$. The cross-sectional areas were based on the average thickness of the aquifer within each hydraulic conductivity zone and an arbitrary width of one foot. The lengths were the distances occupied by each hydraulic conductivity zone along the line from the Project area to the outcrop. The calculation of effective conductance is summarized in **Table 6**.

Table 6. Calculation of Effective Conductance and Effective Hydraulic Conductivity

Hydraulic Conductivity Zone (ft/d)	Length of Zone along Cross Section (feet)	Average Aquifer Thickness in Zone (feet)	Conductance Term (ft^2/d)
0.2	70977	175	4.93×10^{-4}
0.03	209382	125	1.79×10^{-5}
0.001	152601	75	4.91×10^{-7}
		Effective Conductance	4.78×10^{-7}
		Effective Hydraulic Conductivity (ft/d)	0.00171

The effective hydraulic conductivity was calculated by rearranging the conductance equation, C = KA/L, to solve for K (K = CL/A), where L is the 82-mile (432,960 feet) distance from the Project area to the outcrop area and A is the area-weighted thickness (121 feet) times one foot. The effective hydraulic conductivity used in the Glover model was 0.00171 ft/d.

Table 7 summarizes the input parameter values incorporated into the Glover model calculations and the basis for those values.

Table 7. Summary of Glover Model Input Parameters

Equation Input Parameter	Assigned Value	Basis for Assigned Value
Q, well pumping rate	151,382 ft^3/day	Conversion of 1,268.47 acre-feet per year, the appropriation calculated in Section 5.2.
r, distance from well to stream bank	432,960 ft	Conversion of 82 miles, the distance from the Project area to the nearest outcrop area.
K, aquifer hydraulic conductivity	0.00171 ft/d	Effective hydraulic conductivity, as described above and in Table 6.
m, aquifer saturated thickness	121 ft	Weighted-average aquifer thickness, as described above and in Table 4.
Sy, aquifer specific yield	0.10 (10 percent)	Average porosity (Table 5) rounded down to 0.10 (10 percent) to approximate the specific yield.
α, parameter in Glover equation	2.07 ft^2/d	$\alpha = (K \cdot m) / Sy$
t, time since pumping started	36,500 days	Statutory aquifer life of 100 years

Applying the input parameters to the Glover model equation:

$$q/Q = erfc\left\{r/\left(2\sqrt{\alpha \cdot t}\right)\right\}$$
$$= erfc\left\{432{,}960\ ft/\left(2\sqrt{2.07\ ft^2/d \cdot 36{,}500\ days}\right)\right\}$$
$$= 0$$

The result indicates that no stream flow depletion will occur, even after 100 years of pumping.

Because the specific yield value represents unconfined aquifer conditions, which are not likely given the hydrogeologic setting of the Dakota J-4 Sandstone (i.e., static water levels significantly above the top of the unit and confining layers above and below the unit), Tetra Tech performed the Glover model calculation again using an estimated storage coefficient (S) typical of a confined aquifer. A reasonable estimate of confined-aquifer storage coefficient can be made from multiplying the aquifer saturated thickness (m) times a specific storage (Ss) of 1 x 10^{-6}/ft (Weight and Sonderegger 2001). For the weighted average thickness of 121 feet, the storage coefficient calculation is:

$$S = m \times Ss$$
$$= 121\,ft \times 1\,x\,10^{-6}/ft$$
$$= 1.21\,x\,10^{-4}$$

Applying this S value to calculate α gives

$$\alpha = (K \cdot m)/S$$
$$= (0.00171\,ft/d \times 121\,ft)/1.21\,x\,10^{-4}$$
$$= 1{,}711.5\,ft^2/d$$

Substituting this value of α into the Glover model equation produces:

$$q/Q = erfc\,\{r/(2\sqrt{\alpha \cdot t})\}$$
$$= erfc\left\{432{,}960\,ft/\left(2\sqrt{1{,}711.5\ ft^2/d \cdot 36{,}500\,days}\right)\right\}$$
$$= 0$$

The results of Glover modeling at the proposed annual withdrawal rate for both confined and unconfined aquifer conditions indicate that no stream flow depletion would occur within 100 years.

Sensitivity analysis was performed to determine critical values of aquifer hydraulic conductivity, saturated thickness, specific storage, and distance from the pumping well to the stream that would result in the stream flow depletion q/Q exceeding 0.1 percent. With aquifer thickness and specific storage held constant at 121 feet and 1 x 10^{-6}/ft, respectively, the stream flow depletion would exceed 0.1 percent only if the hydraulic conductivity were to exceed 0.237 ft/d, which is more than 100 times the effective hydraulic conductivity. With the hydraulic conductivity held at 0.00171 ft/d and the aquifer thickness constant at 121 feet, the stream flow depletion would exceed 0.1 percent if the specific storage were less than about 7 x 10^{-9}/ft, a value that is unrealistically low (Weight and Sonderegger 2001). With the hydraulic conductivity, saturated thickness, and specific storage held constant at 0.00171 ft/d, 121 feet, and 1 x 10^{-6}/ft, respectively, the stream flow depletion would exceed 0.1 percent if the distance from the pumping well to the stream were less than about seven miles. The Dakota J-4 Sandstone is separated from all surface streams and other surface water bodies by several thousand feet of low-permeability shale for a distance of more than 80 miles.

The conclusion supported by the Glover model calculations and the sensitivity analysis is that withdrawal of the proposed volume of 1,268.47 acre-feet of ground water annually from the Dakota J-4 Sandstone beneath the Windy Hill Project area would not result in any stream flow loss. Because the Windy Hill Project area is outside of the boundaries of any designated ground water basin and the proposed water withdrawal will not, with 100 years of continuous withdrawal, deplete the flow of a natural stream at an annual rate greater than 0.1 percent of the annual rate of withdrawal, the J-4 Sandstone ground water under the proposed withdrawal scenario meets the definition of nontributary groundwater.

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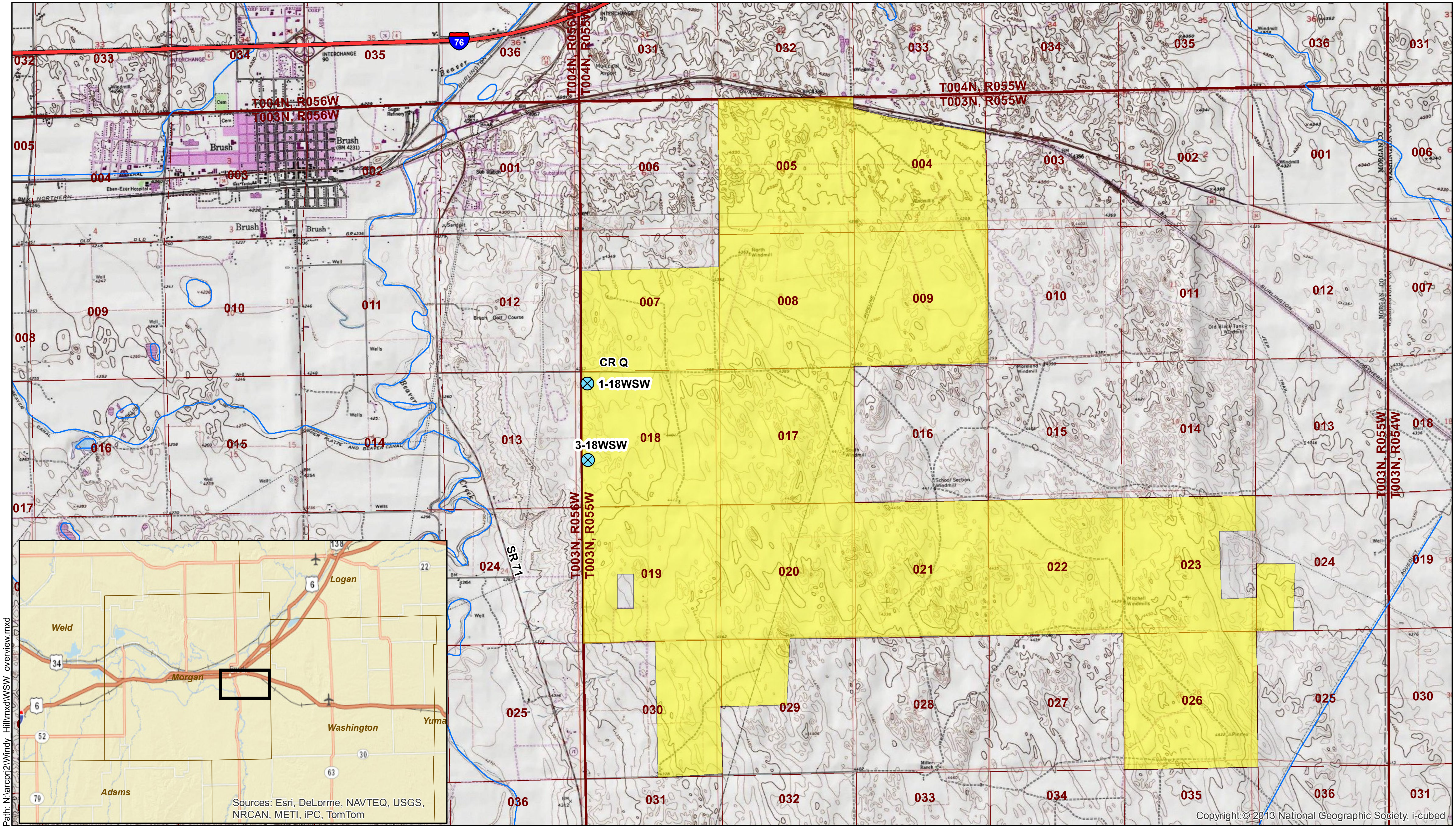
7.0 FIGURES



Legend

Proposed Water Supply Well

Windy Hill Project Area Boundary

SCALE IN FEET

0 2,000

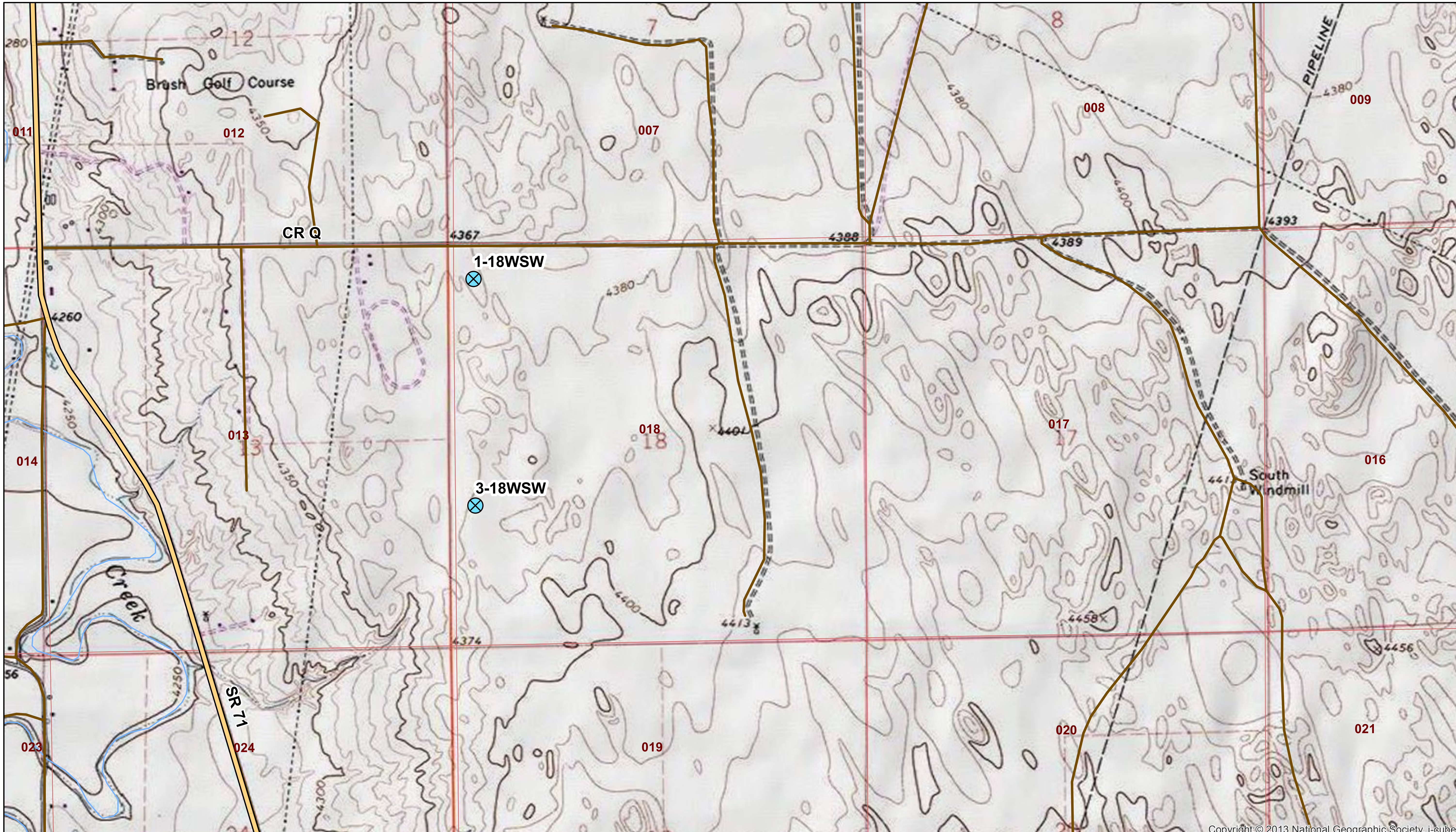
September, 2015

Figure 1

Project Location Map

Windy Hill Gas Storage LLC

114-910338



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Legend

Proposed Water Supply Well

SCALE IN FEET

0 2,000

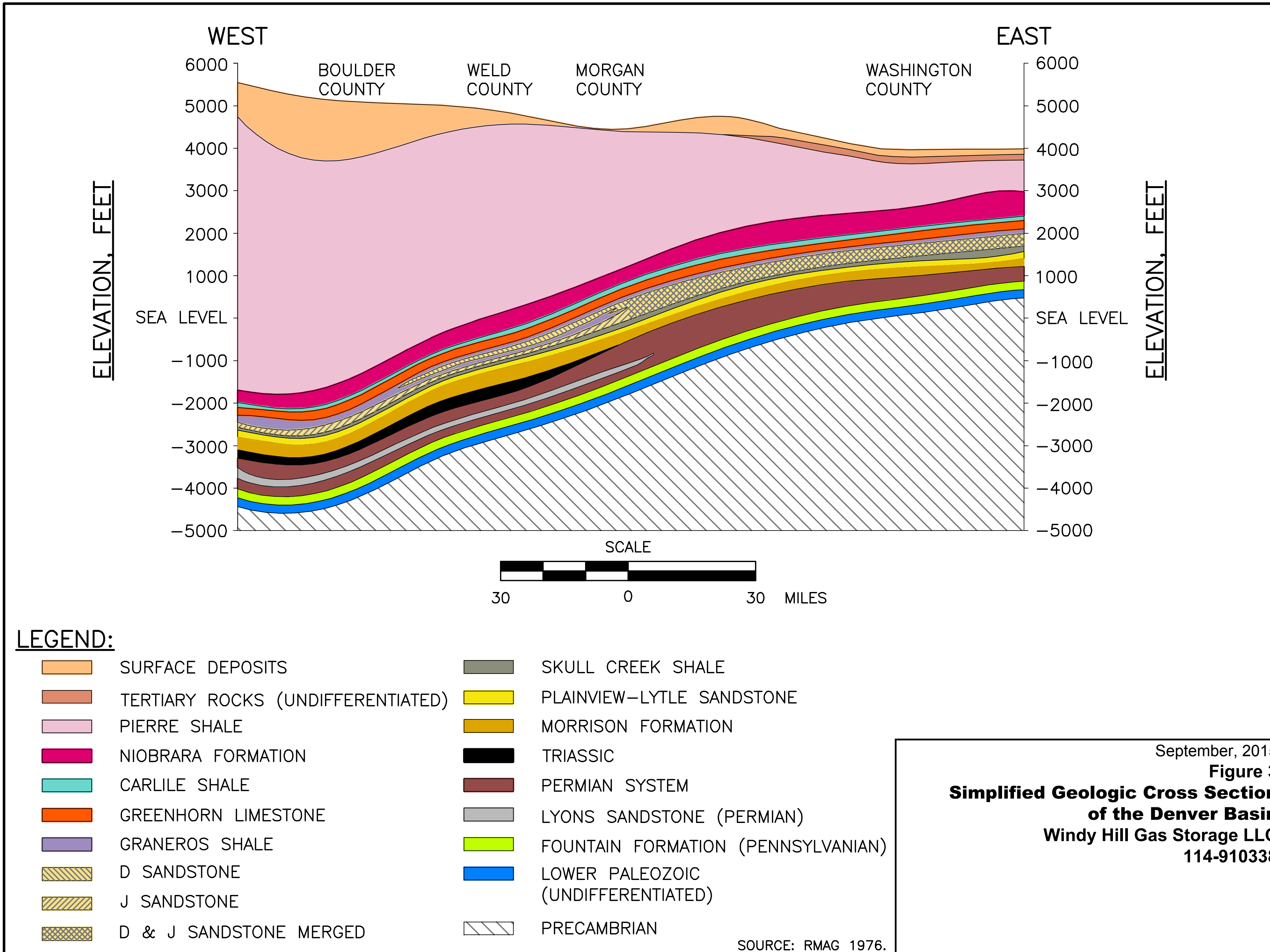
September, 2015

Figure 2

Locations of Proposed Water Supply Wells

Windy Hill Gas Storage LLC

114-910338



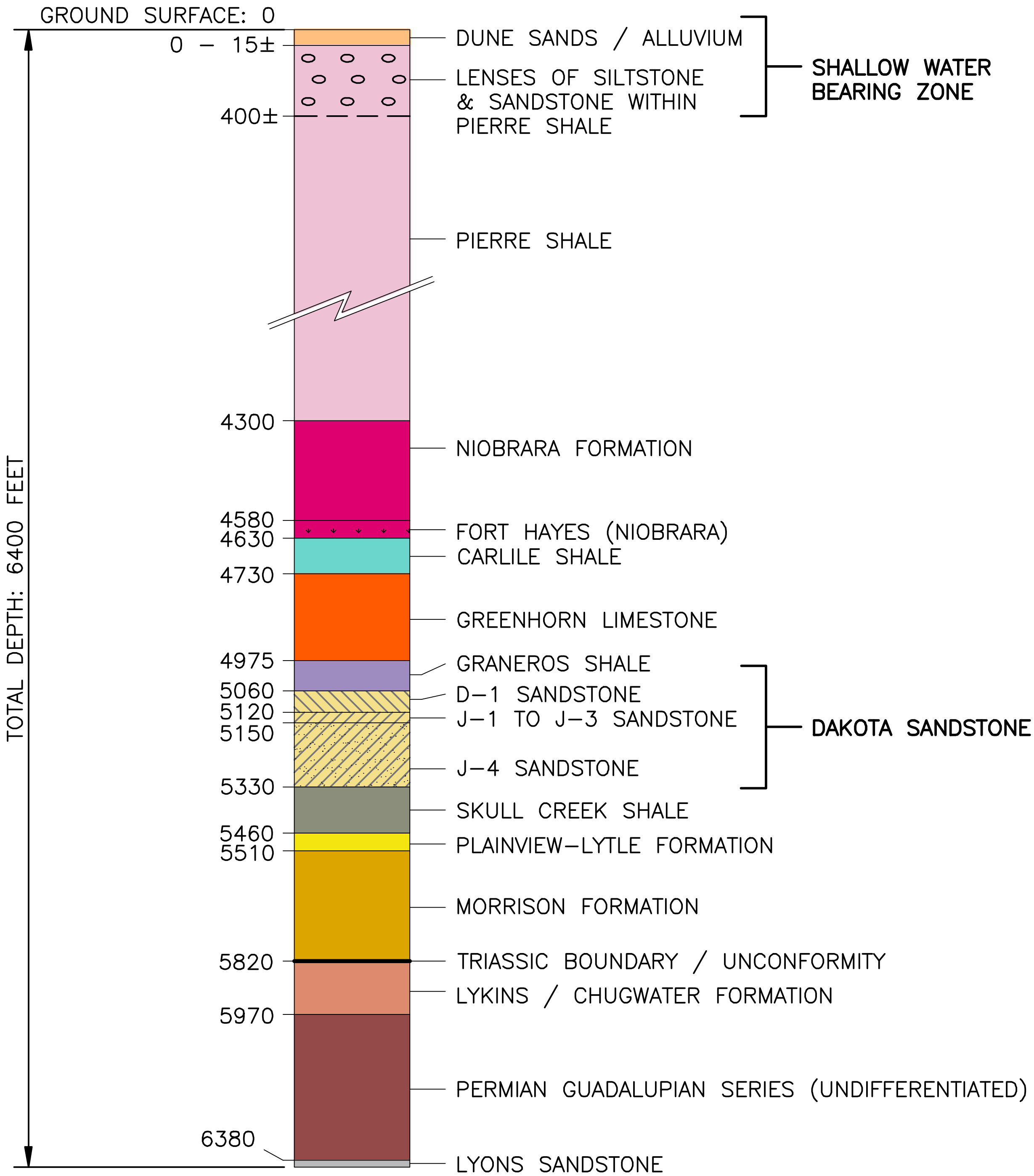
September, 2015

Figure 3

Simplified Geologic Cross Section of the Denver Basin

Windy Hill Gas Storage LLC

114-910338



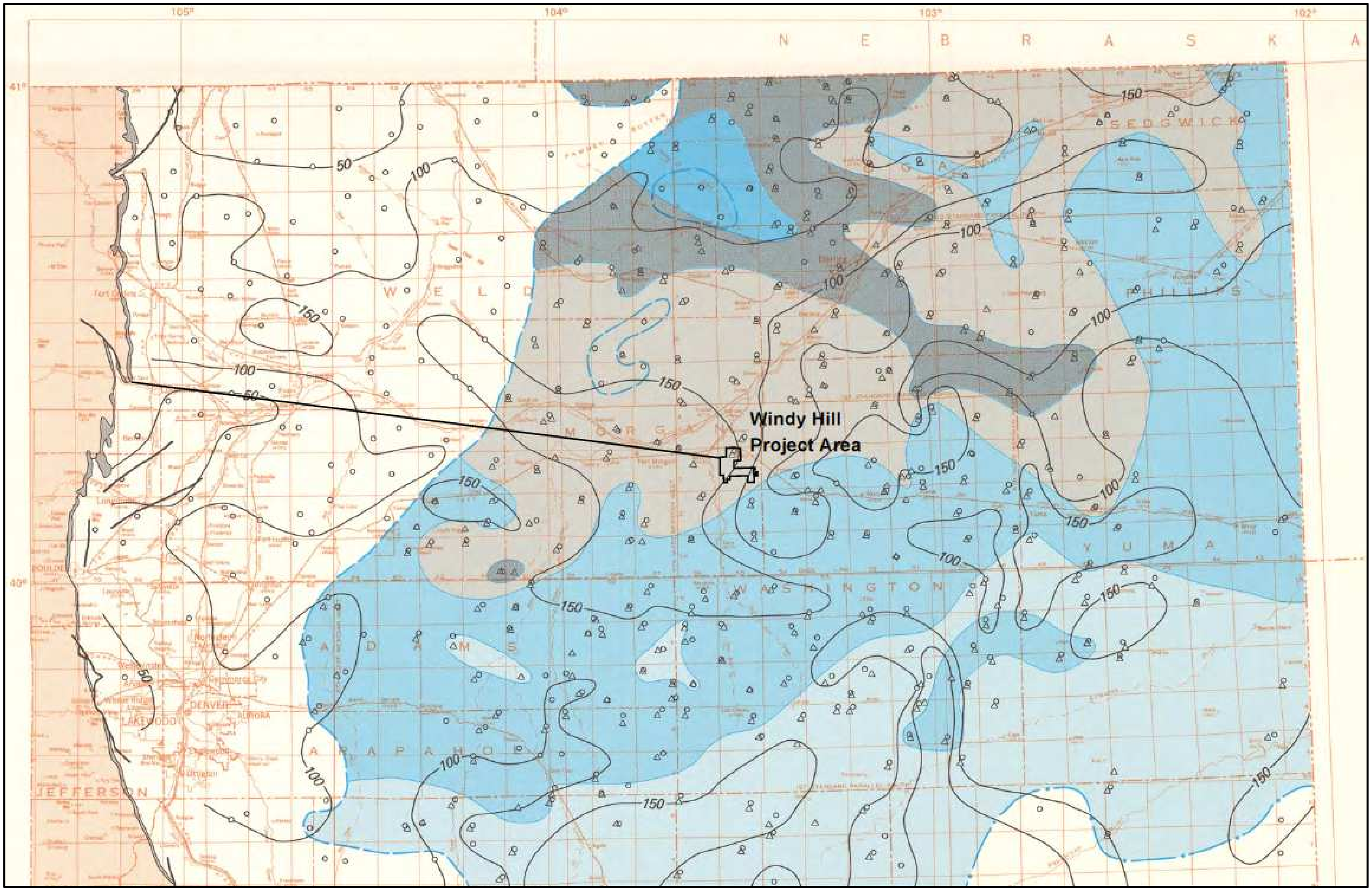
September, 2015

Figure 4

Stratigraphic Column

Windy Hill Gas Storage LLC

114-910338



Source: Robson and Banta (1987)

150 Sandstone Thickness (ft)

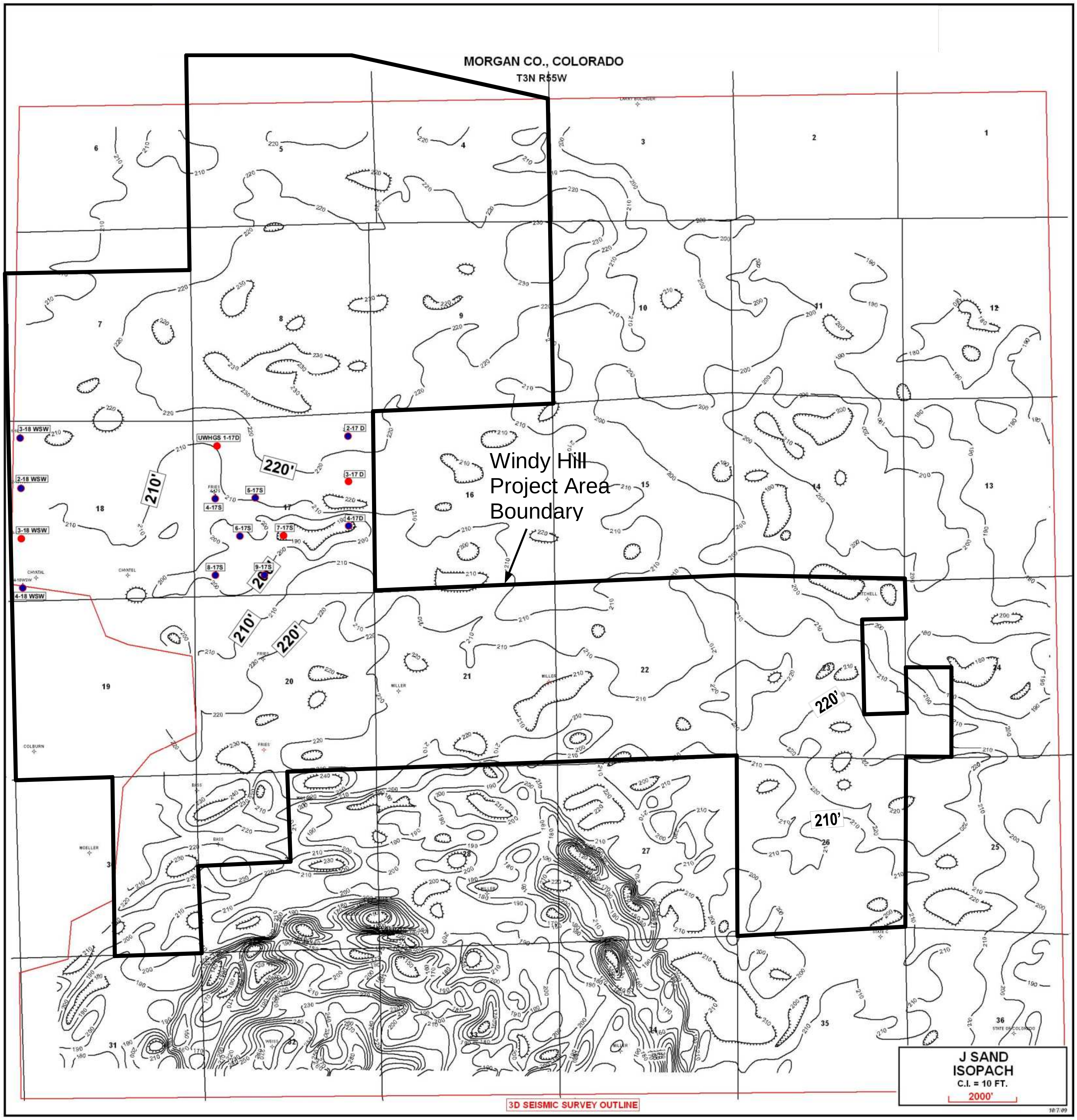
Line of Thickness Porosity Calculation

September, 2015

Figure 5

Aggregate Sandstone Thickness for the Dakota Sandstone in Northern Denver Basin

Windy Hill Gas Storage LLC
114-910338



Source: Geostock (2008)

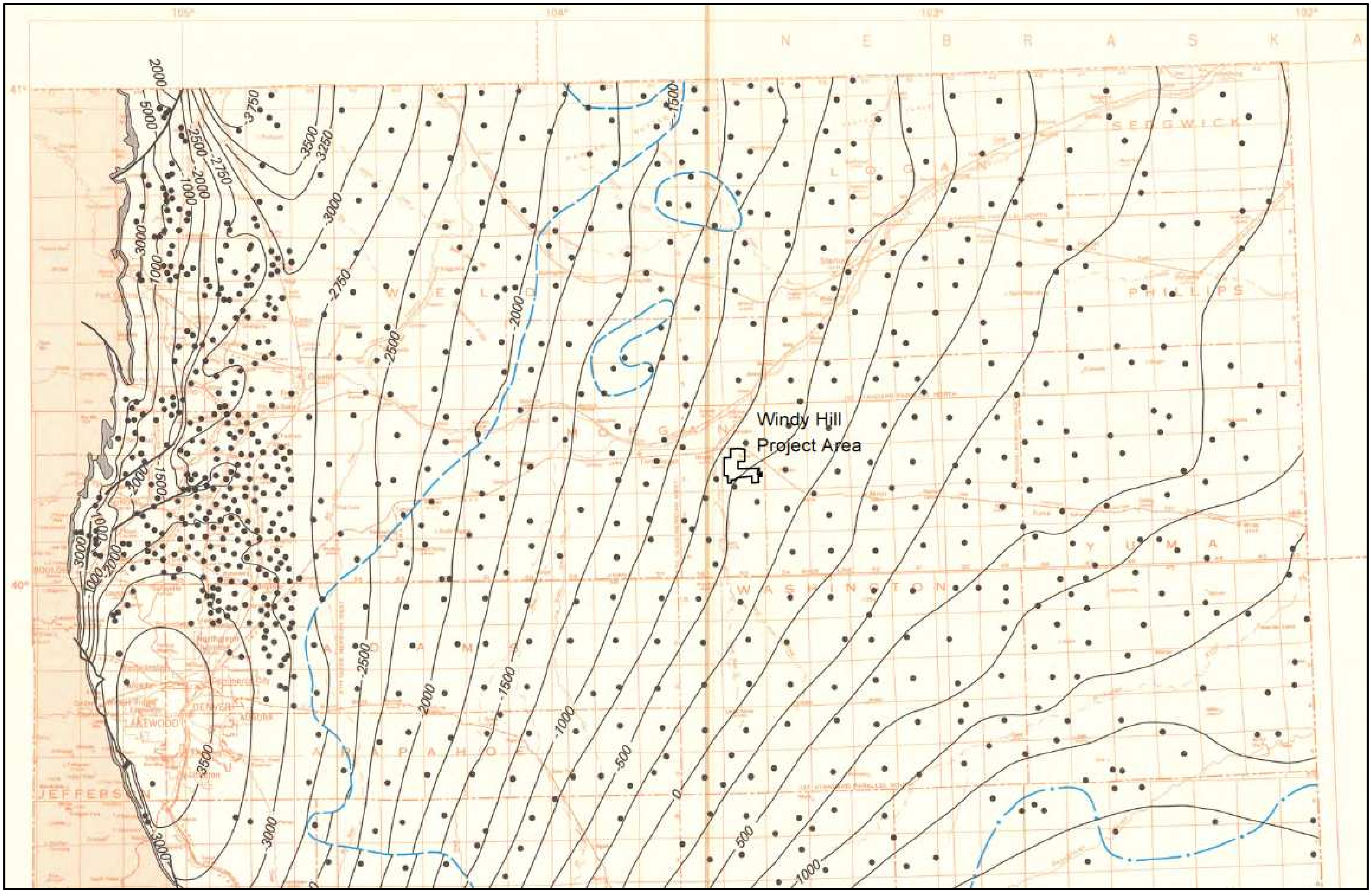
September, 2015

Figure 6

Dakota J Sandstone Thickness in Windy Hill Project Area

Windy Hill Gas Storage LLC
114-910338

220' Dakota J Sandstone Thickness (feet)



Source: Robson and Banta (1987)

-1500 Dakota Sandstone Elevation (ft msl)

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Figure 7

Elevation of the Top of the Dakota Sandstone in Northern Denver Basin

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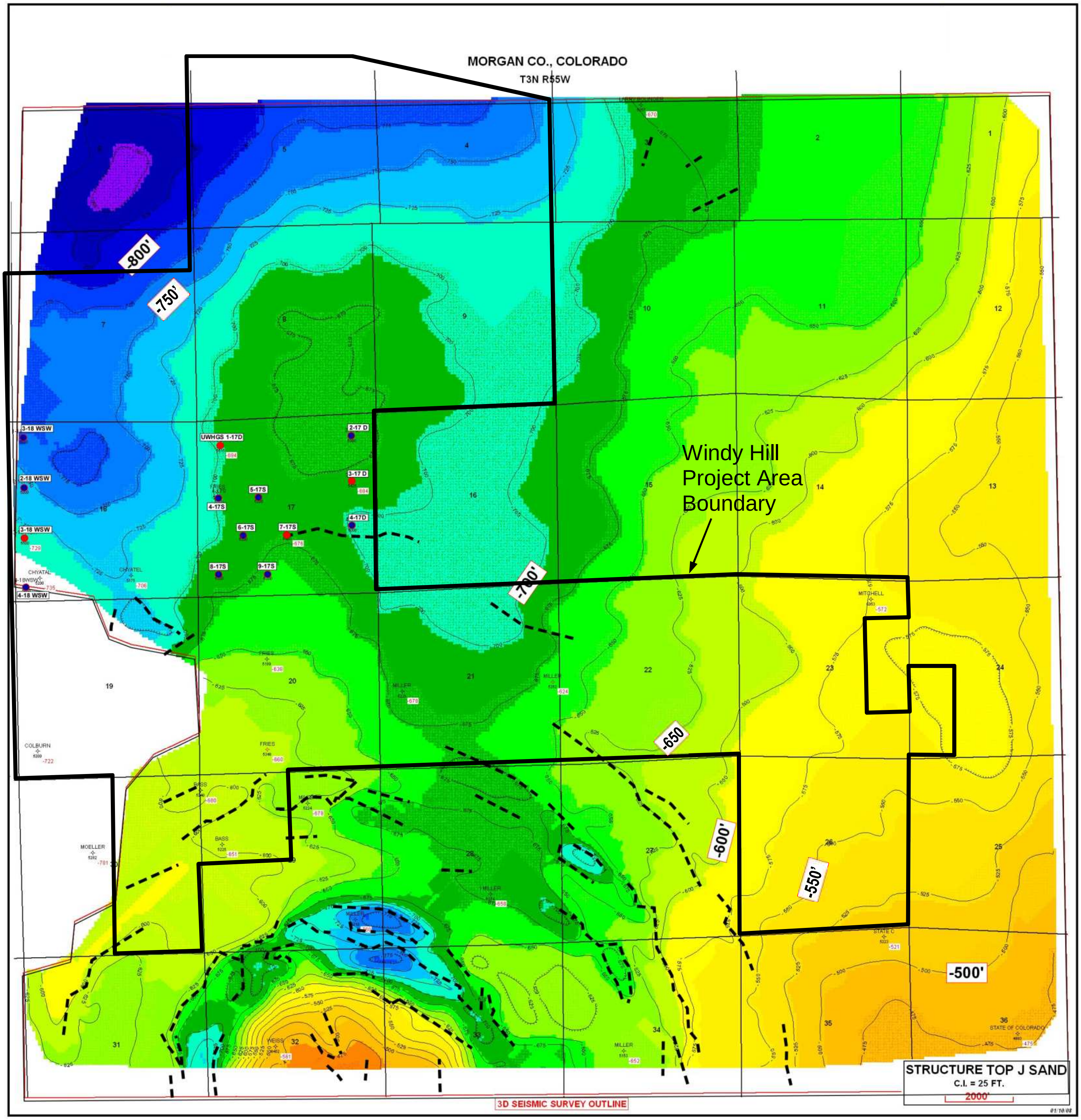


Source: Geostock (2008)

September, 2015

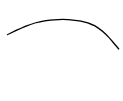
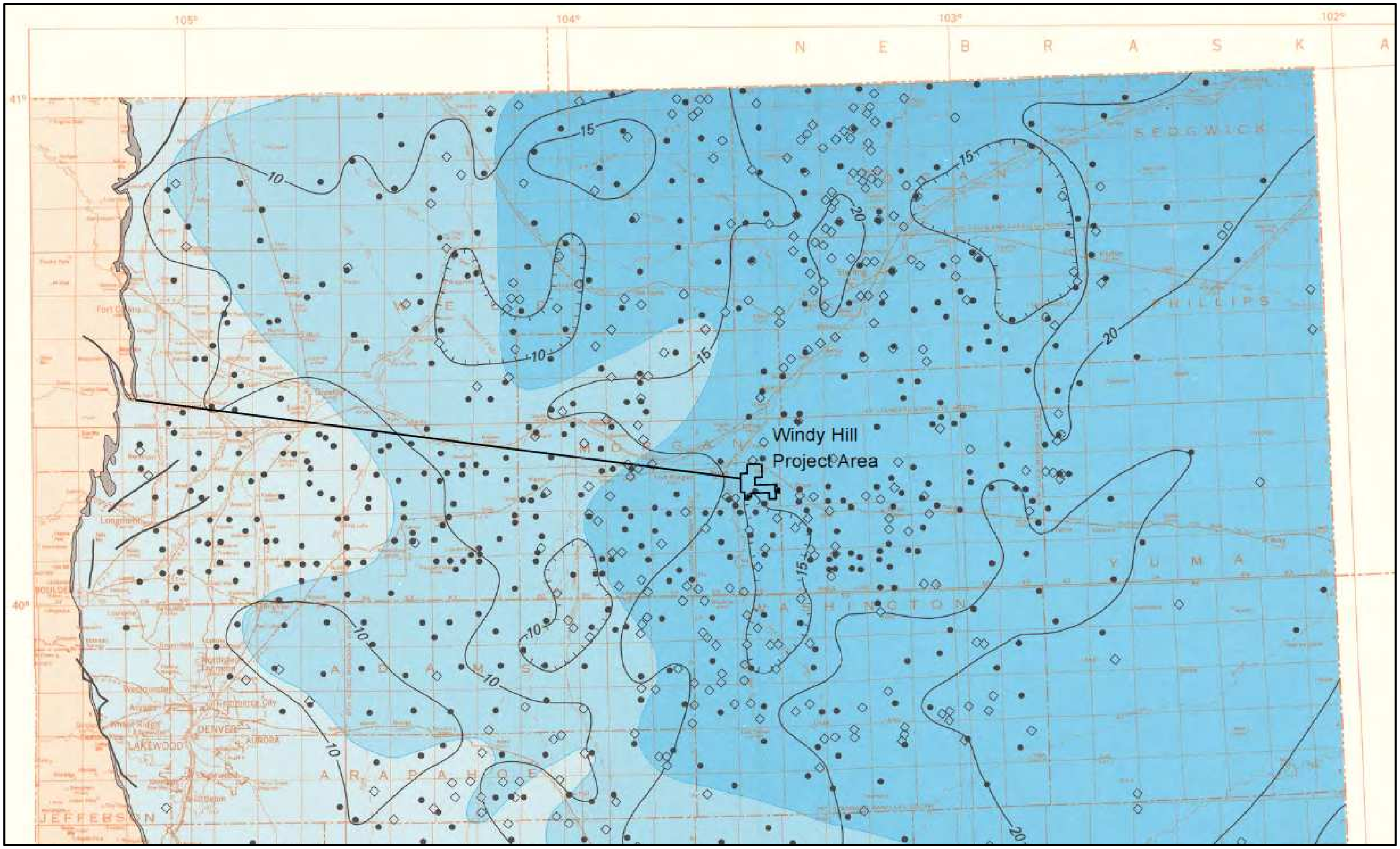


Figure 8

Elevation of the Top of the Dakota Sandstone in Windy Hill Project Area

Windy Hill Gas Storage LLC
114-910338



Source: Robson and Banta (1987)

K = 0.001 ft/d

K = 0.03 ft/d

K = 0.2 ft/d

15 Percent Porosity

Line of K and Porosity Calculations

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Figure 9

Dakota Sandstone Hydraulic Conductivity and Porosity Distribution in Northern Denver Basin

Windy Hill Gas Storage LLC
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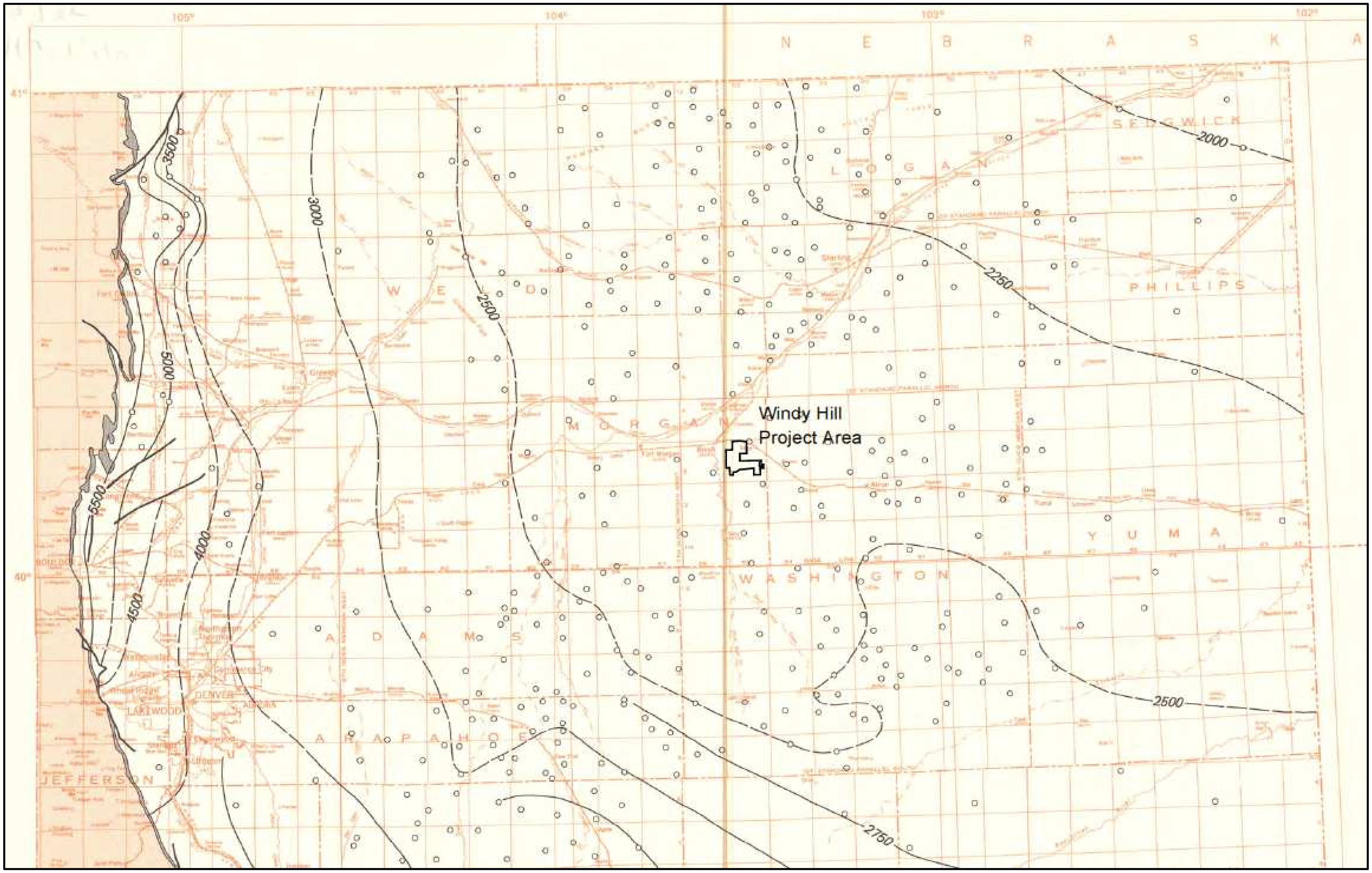

Source: Robson and Banta (1987)

2500 Potentiometric Surface Elevation (ft msl)

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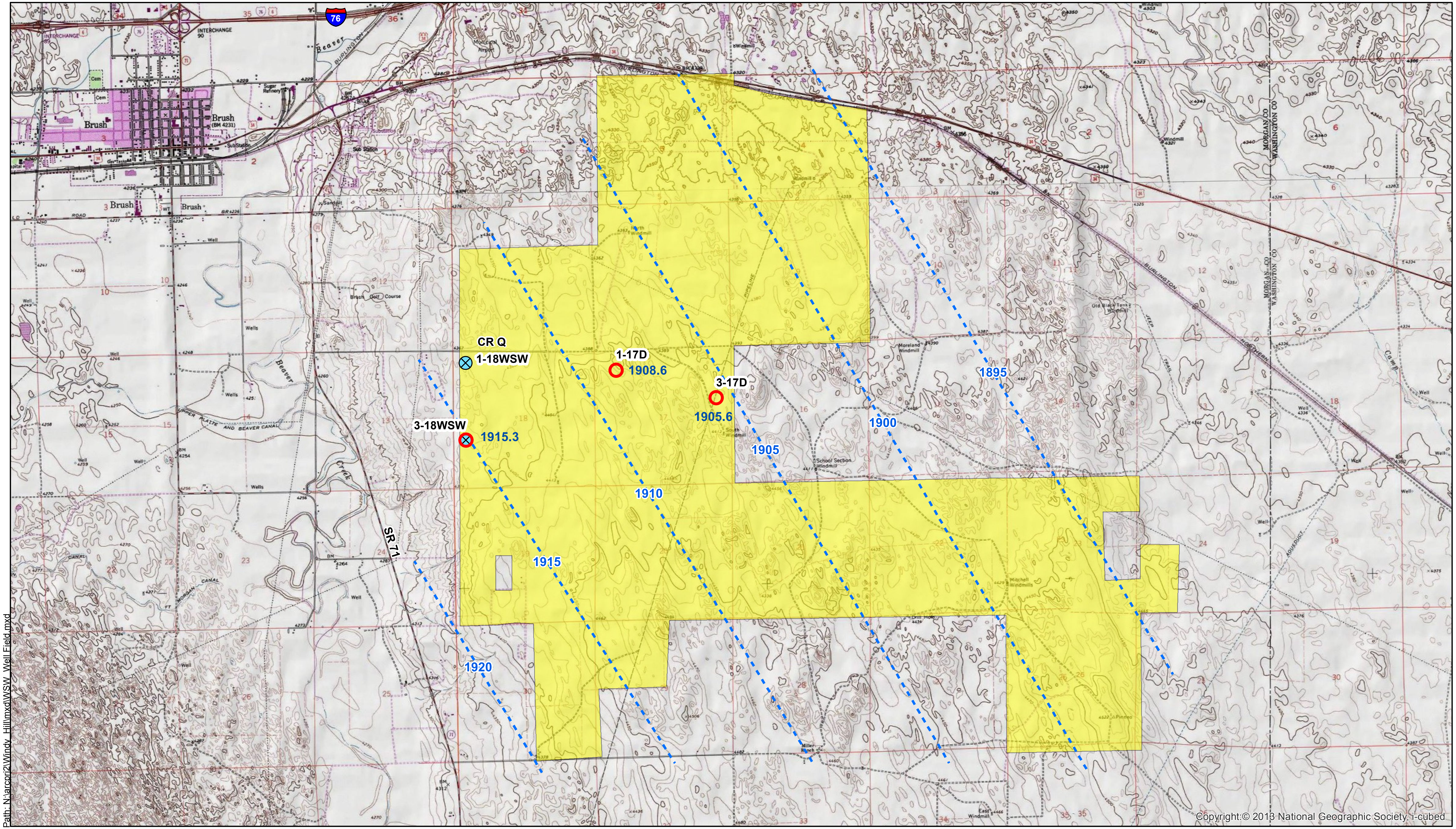
Figure 10

Dakota Sandstone Predevelopment Potentiometric Surface Elevation in Northern Denver Basin

Windy Hill Gas Storage LLC
114-910338



Path: N:\arcgis\Windy_Hill\mxd\WSW_Well Field.mxd

Legend

- Proposed Water Supply Well
- Windy Hill Project Area Boundary
- Potentiometric surface elevation contour (feet msl)
- Well location and measured potentiometric surface
- 1915.3 elevation (feet msl)

N

SCALE IN FEET

0 2,000

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Figure 11

Dakota J-4 Sandstone Potentiometric Surface Elevation in Windy Hill Project Area

Windy Hill Gas Storage LLC

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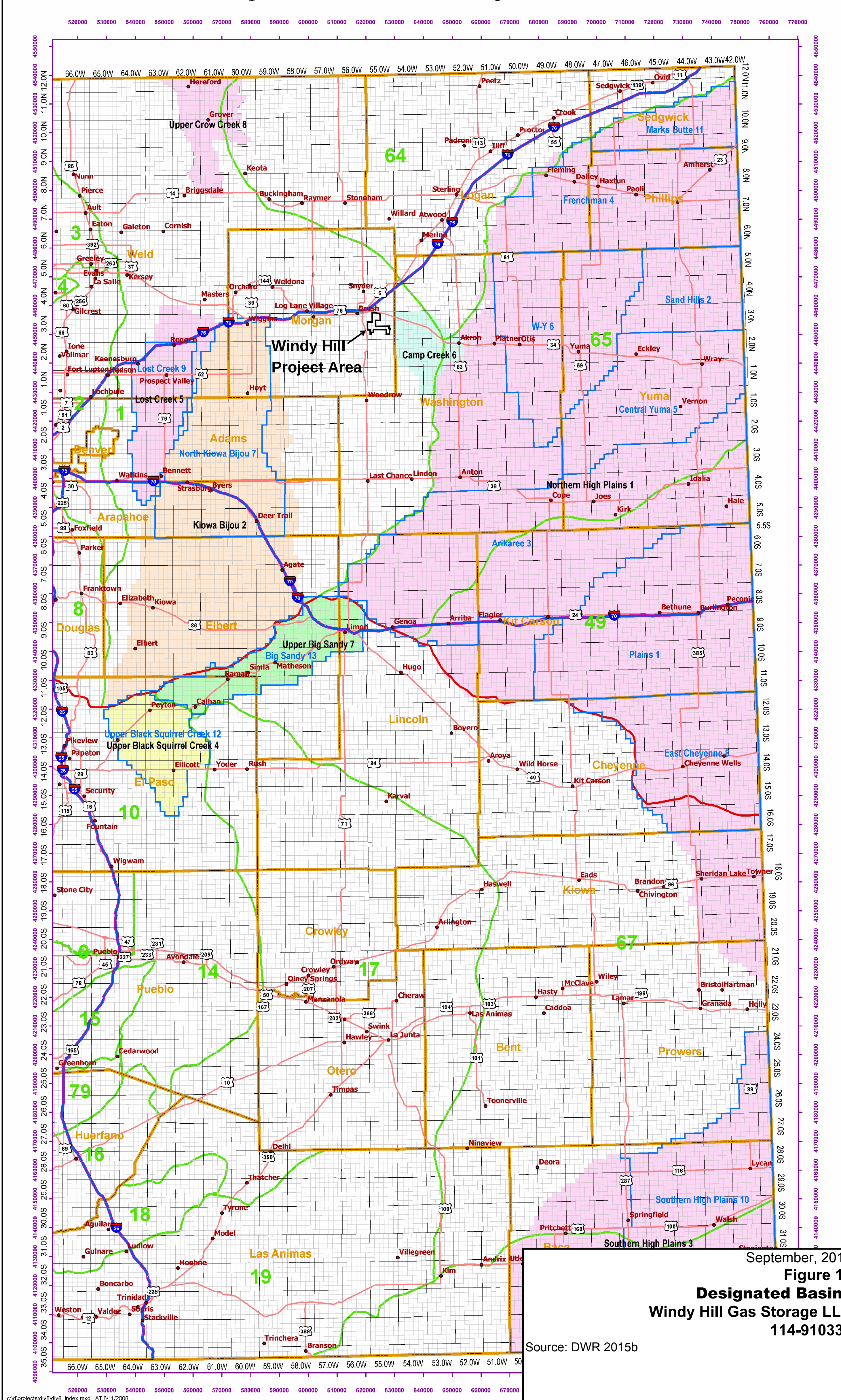
Designated Basins and Management Districts



September, 2015

Figure 12

Designated Basins

Windy Hill Gas Storage LLC

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Source: DWR 2015b