RGDSS Memorandum
Final

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Cc:		
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Subject:	RGDSS Hydrogeology Review: Southeast Model Boundary Grid, Layering, and Ground Water Inflow	
Date:	October 20, 2015	

Table of Contents

1 Introduction 2

2 Background: Previous RGDSS Work 5

3 SE Boundary Model Grid Review and Recommendations 9

3.1 Geology at the SE Boundary 11

3.2 Recommended Model Grid Changes at the SE Boundary 12

4 Hydrogeologic Conceptualization of the SE Model Boundary 16

4.1 Layer 1 conceptualization and ground water inflow estimates 16

4.2 Layers 2, 3, 4 conceptualization and ground water inflow estimates 19

4.2.1 Factors affecting the hydrogeology 20

5 Hydrogeologic Review of the Culebra Graben and San Pedro Mesa 27

5.1 Culebra Graben and the Culebra Creek Water Gap at San Luis 28

5.1.1 Layers 2, 3, 4 Characteristics in the Culebra Graben and San Pedro Mesa 35

5.2 Southern End of the Culebra Graben 36

6 Conclusions and Recommendations 39

7 References 43

1 Introduction

As part of the calibration and improvement process for the RGDSS San Luis Valley basin-wide ground water model, the State asked HRS to review the boundary ground water inflow to the model in Costilla County, approximately from Blanca Peak on the north, to the CO / NM boundary on the south (for the purposes of this report, called the “SE boundary”) (see Figure 1). Model calibration efforts, discussions with the PRT in Phase 6 of the RGDSS, and newly available geologic and hydrogeologic data, have indicated that review of and possibly changes to certain characteristics of the model boundary in certain areas, including ground water inflow estimates, layering, and the position of the model grid cells at the boundary, are appropriate for improvement in representing the hydrogeology of this area, and in improvement of model calibration.

This review has included the following:

- Review of the hydrogeologic conceptualization along the SE model boundary, including:
  - Review of the SE model boundary grid and recommended adjustments.
  - Review of alluvial (Layer 1) ground water inflow and recommended adjustments.
  - Review of model layering and boundary ground water inflow in the deeper layers (Layers 2, 3, 4) and recommended improvements.

- Review of the hydrogeology of the Culebra Graben and San Pedro Mesa, with emphasis on the layering, characteristics, and ground water flow suggested by the observed geologic structure and hydrogeology. This included:
  - Review of hydrogeology at the Culebra Creek “water gap” at San Luis.
  - Review of the hydrogeology at the south end of the Culebra Graben, south of San Luis as it pertains to the flow at the model boundary.

- Review of the hydrogeologic conceptualization of the SW model boundary near Rito Hondo and Cove Lake areas in Conejos County. Both of these areas, which are located near the southwestern model boundary in Conejos County, were reviewed and discussed with State personnel and PRT members. We do not recommend making any changes to the model grid in those areas at this time.

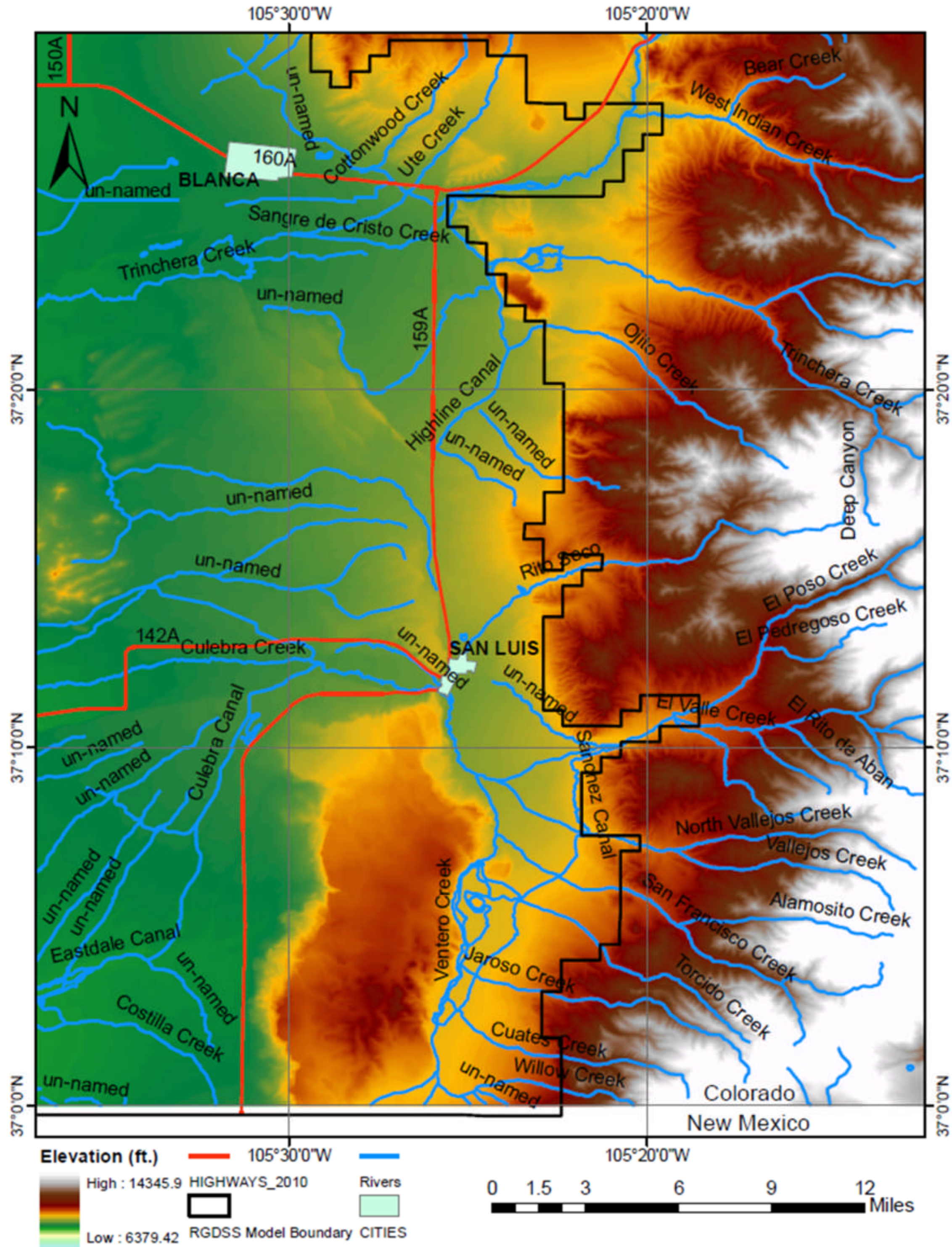


Figure 1: General location of the RGDSS southeast model boundary (black line) prior to recommendations described herein.

2 Background: Previous RGDSS Work

There have been efforts previously in the RGDSS to estimate ground water inflow at the SE boundary of the RGDSS model. The most recent of these efforts was documented in a memorandum by HRS in 2004, which was the result of Phase 3 peer review efforts on inflows and ground water storage in various areas of the San Luis Valley (SLV) by the State, HRS, and other PRT members.[1]

In the SE boundary area, generally defined as Mt. Blanca on the north and the CO / NM state line on the south, the 2004 conceptual model of the hydrogeology at the RGDSS model boundary was somewhat generalized, due to the lack of detailed geologic mapping available at that time. Since that time, there have been several detailed geologic quadrangle maps and technical papers published by the U.S. Geological Survey, the Colorado Geological Survey, and others that have enabled a more detailed review of the layering and structural characteristics that affect the hydrogeology at and near the SE boundary. From the HRS July 17, 2004, memorandum (p. 21-22), the hydrogeologic concept and the estimates of SE boundary inflow were described as follows.

- There is an estimated 12,000 ac-ft/yr ground water inflow along the southeast model boundary extending from the southern end of Mt. Blanca south to the State line. K estimates were based on RGDSS tests at P4 and P6 to the extent those tests were applicable to the materials in the aquifer layers.
- Ground water gradients were based on RGDSS revised water level mapping (Task 32, Hydrogeologic Database Refresh).
- Ground water inflow is dominated by layer 3 (estimated at 5,000 ac-ft/yr) and layer 4 (estimated at 6,200 ac-ft/yr).

[1] HRS Water Consultants, Inc., July 17, 2004, RGDSS Ground Water, Task 4 – Ground Water Boundary Flow and Storage Change, 53p.

Table 7 from the HRS July 17, 2004 memorandum, showing the estimates of formations, layer thickness, aquifer characteristics, and boundary inflow by layer, is reproduced as Table 1 of this report, below.

Table 1: Reproduction of Table 7 from HRS Water Consultants, Inc., July 17, 2004, RGDSS Ground Water, Task 4 – Ground Water Boundary Flow and Storage Change, p. 22.

Table 7
SLV Southeastern model boundary estimated GW inflow

(Mt. Blanca on north, State Line on south)

Layer	Formation(s)	Estimated Thickness (ft)	Estimated K (ft/day)	Estimated Gradient (ft/ft)	Length of contact along model boundary (miles)	Estimated Ground Water Inflow (ac-ft/yr)
1	Quaternary Alluvium	50	50	0.005	0.8	400
2	Clay layers & sand interbeds	20	5	0.002	28	200
3	Santa Fe deposits: sand & clay (Servilleta not present at model boundary)	200	10	0.002	28	5,000
4	lower Santa Fe (clay-rich)	300	5	0.002	28	3,700
	Conejos weathered tuff, clay, sand (transitional with Santa Fe above)	1000	1	0.002	28	2,500
5	(not present)	---	---	---	---	---
					Best estimate of Ground Water Inflow	11,800
	*- Inflow estimates rounded to nearest 100 ac-ft/yr					
	Note, Conejos Fm. may be thicker in some areas at SE boundary, but is predominantly clay. It is therefore judged to contribute no significant amount of ground water inflow.					

A graphical depiction of the general hydrogeologic conceptual model of the SE boundary circa 2004 is shown in Figure 2.

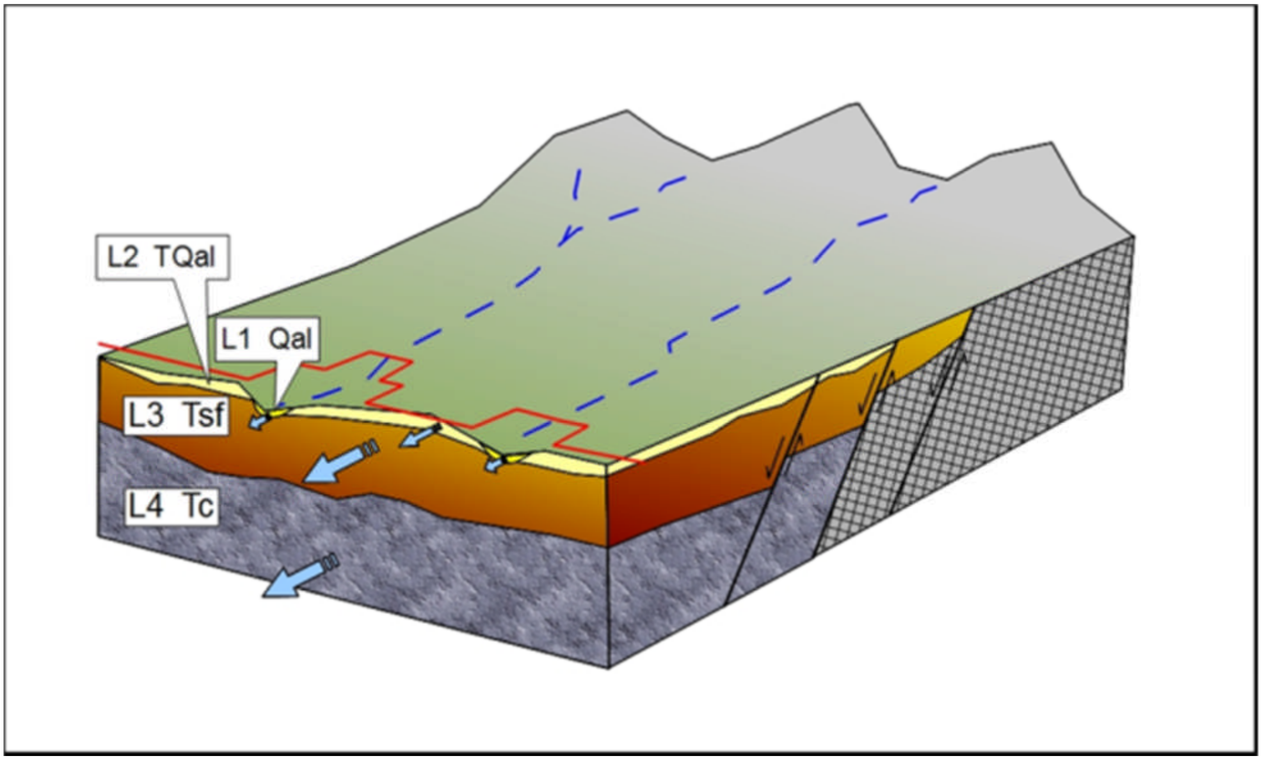


Figure 2: General hydrogeologic conceptualization of model layering and ground water inflow at the SE model boundary, circa 2004. The red line is illustrative, and generally depicts the model boundary.

In summary, the 2004 hydrogeologic conceptualization of ground water inflow at the SE model boundary implemented in the RGDSS Phase 3 modeling was as follows:

- Hydraulic conductivity: based on RGDSS P4 and P6 pumping tests (shallow confined, lower "Alamosa equivalent" [QTa] and upper Santa Fe formation [Tsf]).
- Gradients: based on RGDSS valley-wide water table mapping (initial estimates in Task 7; revised in Task 32).
- Normal faulting: present in the Culebra Graben area, but overall, the conceptual model was one of stratigraphic continuity across the model boundary. Inflow of ground water to the active model domain was estimated to be dominated by stratigraphic continuity at and near the model boundary, not by faulting-related discontinuity.

- Deep percolation of water in recharge areas outside (east of) the model boundary, and ground water inflow to the model was estimated to be constrained only by the Darcy's Law inputs: cross-sectional area, hydraulic conductivity, and hydraulic gradient. There were no estimates of limitations by other potential factors.

- Layer 1 inflow was generalized to occur along the entirety of the 28-mile long SE model boundary.

- Conejos Formation volcanic and volcaniclastic rocks were interpreted to exist in significant thickness (1,000 feet on average) along the SE model boundary.

- Ground water outflow was estimated to occur to the south, out of the model domain, from the Culebra (i.e. Sanchez) Graben area south of San Luis in the sedimentary layers interpreted to exist in that area.

The location of the model grid at the SE boundary, as it existed prior to the recommendations in this memo and as it was conceptualized in RGDSS Phase 3, primarily was based on two factors:

- Coincidence with major faults that were (at that time) mapped along the eastern edge of the Culebra Graben.

- Extension of the model boundary sufficiently far upgradient (east) in creek valleys to make sure any wells or surface diversions that needed to be included, were in fact included in the model.

3 SE Boundary Model Grid Review and Recommendations

As part of this review of the SE boundary hydrogeology, HRS was asked to review the model grid in Costilla County, approximately from Blanca Peak on the north to the CO / NM boundary on the south. This review has included a re-assessment of the hydrogeology for the model grid cells at the model boundary in this area and has incorporated newly available data, research, and information as noted in section 3.1.

Layer 1 in the SE boundary area consists primarily of Quaternary alluvium (in stream valleys) and colluvial soils (in upland areas). Upon review, we have concluded that three segments of the SE boundary require revision of the model grid, see Section 3.2 below. These segments coincide with Culebra Creek, Rito Seco, and Vallejos Creek (see Figure 3). These model boundary changes will result in converting a few model cells to inactive cells within the drainages for each of these three creeks, and converting two cells at Vallejos Creek to active cells. The purpose of the recommended model grid changes at the model boundary is to better reflect the location of major faults at the boundary between the Culebra Graben inside the active model domain and the foothills of the Culebra mountain range outside (east) of the active model domain. These recommended changes also eliminate areas of unnecessary detail from the RGDSS ground water model domain where there are no wells or diversions that need to be represented to accurately model impacts from well pumping.

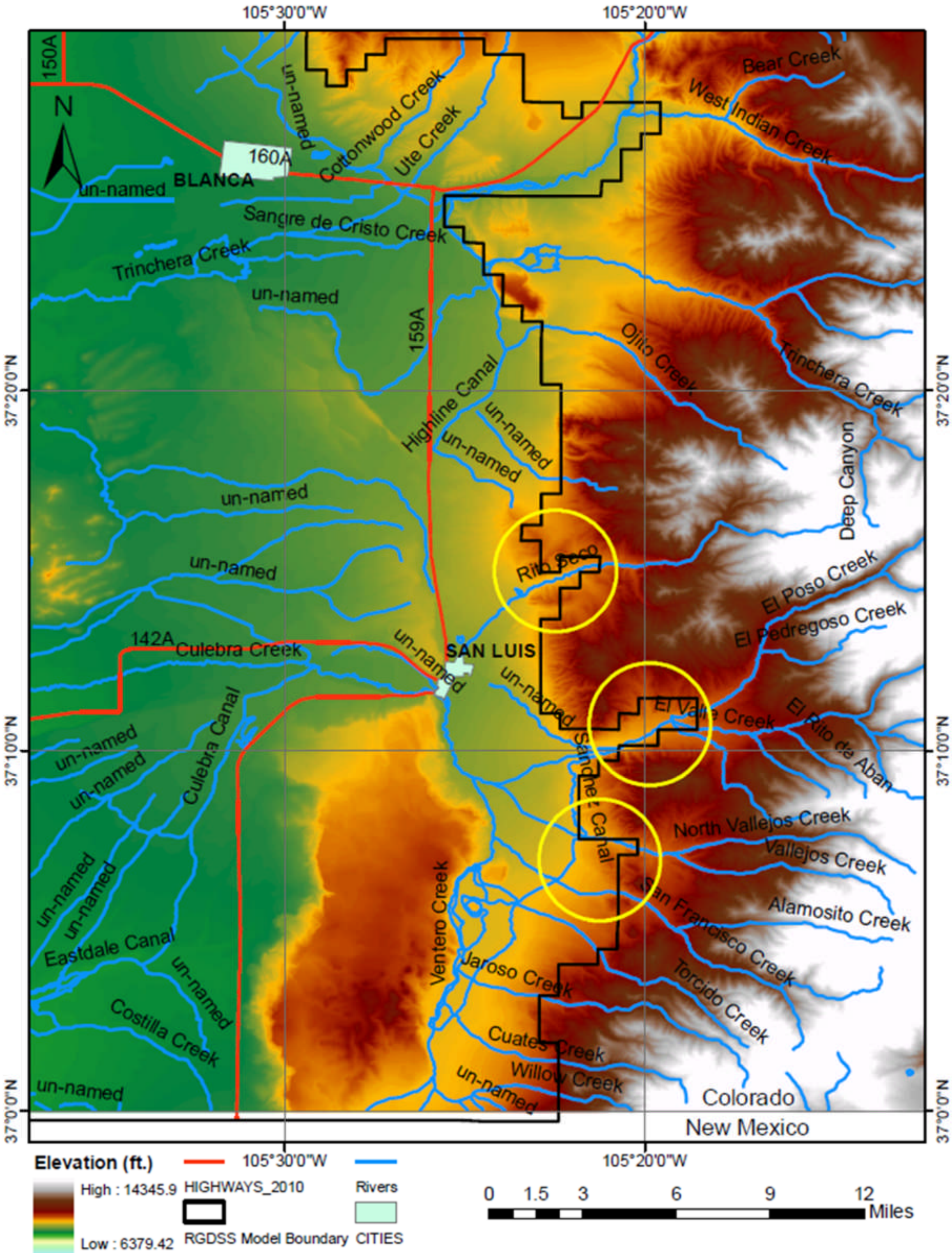


Figure 3: SE boundary showing (from N to S, circled in yellow) Rito Seco, Culebra Creek, Vallejos Creek.

3.1 Geology at the SE Boundary

The conversion of model cells from active to inactive, in certain areas that extend upstream in these creek valleys as shown in Figure 3, will not affect the geologic definition of Layer 1 (Quaternary alluvial deposits) in the ground water model. The ground water inflows can be estimated equally well at the recommended locations. This is due to the continuity of the water-saturated alluvial deposits upstream and downstream of the model boundary in these three creek valleys.

Away from the stream valleys, in the upland hill slope areas along the SE model boundary, Holocene colluvial sediments are common. Our review has shown that the upland colluvium typically is thin – most commonly from zero to less than 10 feet thick – and in most upland areas is not water saturated. Saturated Quaternary alluvial deposits generally are only found within the creek beds. Because this alluvium is confined to a few creek channel locations, spatial resolution of ground water inflow in the SE boundary area can be improved by representing Layer 1 inflow at these creek valleys.

The majority of the Southeast model boundary region, below the near-surface alluvium and colluvium (i.e. Layer 1) is underlain by the Santa Fe Formation (abbreviated Tsf) beneath the creeks as well as beneath the upland areas along this boundary. The Santa Fe formation is represented in deeper model layers in Costilla County as well as other areas in the RGDSS model. The geology of model layers 2, 3, and 4 will be improved by implementing the recommended model cell changes at Culebra Creek, Rito Seco, and Vallejos Creek. This is because the recommended changes will place the model boundary closer to the most recent mapped location of the Sangre de Cristo fault zone. Model Layer 5 exists only in the deeper portions of the Closed Basin to the north, and as far as is known does not exist in the Culebra Graben area along the Southeast model boundary.

As a result of our review of the hydrogeology along the SE boundary, we have developed a set of relatively minor changes to the model grid. These recommended changes are at the Rito Seco, Culebra Creek, and Vallejos Creek. Major creeks further north along the SE model boundary, including Ute Creek, Sangre de Cristo Creek, Trinchera Creek, and Ojito Creek, also were reviewed as part of this effort. We do not recommend making any changes to the model grid at those creeks.

3.2 Recommended Model Grid Changes at the SE Boundary

The recommended active model boundary changes are shown in Figures 4, 5, and 6. Solid red lines represent the recommended new active model boundaries where all model cells to the left (west) of these lines are retained and all model cells to the right (east) of these red lines are omitted. Model cells have been converted to inactive cells at each of the three creeks. Additionally, two model cells have been converted to active cells at Vallejos Creek in order to better delineate the alluvial sediments and creek channel at this location, and to give better continuity with the underlying geologic structure. The specific model boundary row / column changes are listed below.

Rito Seco: Model cells converted to inactive cells: 161_110 to 161_111, 162_110

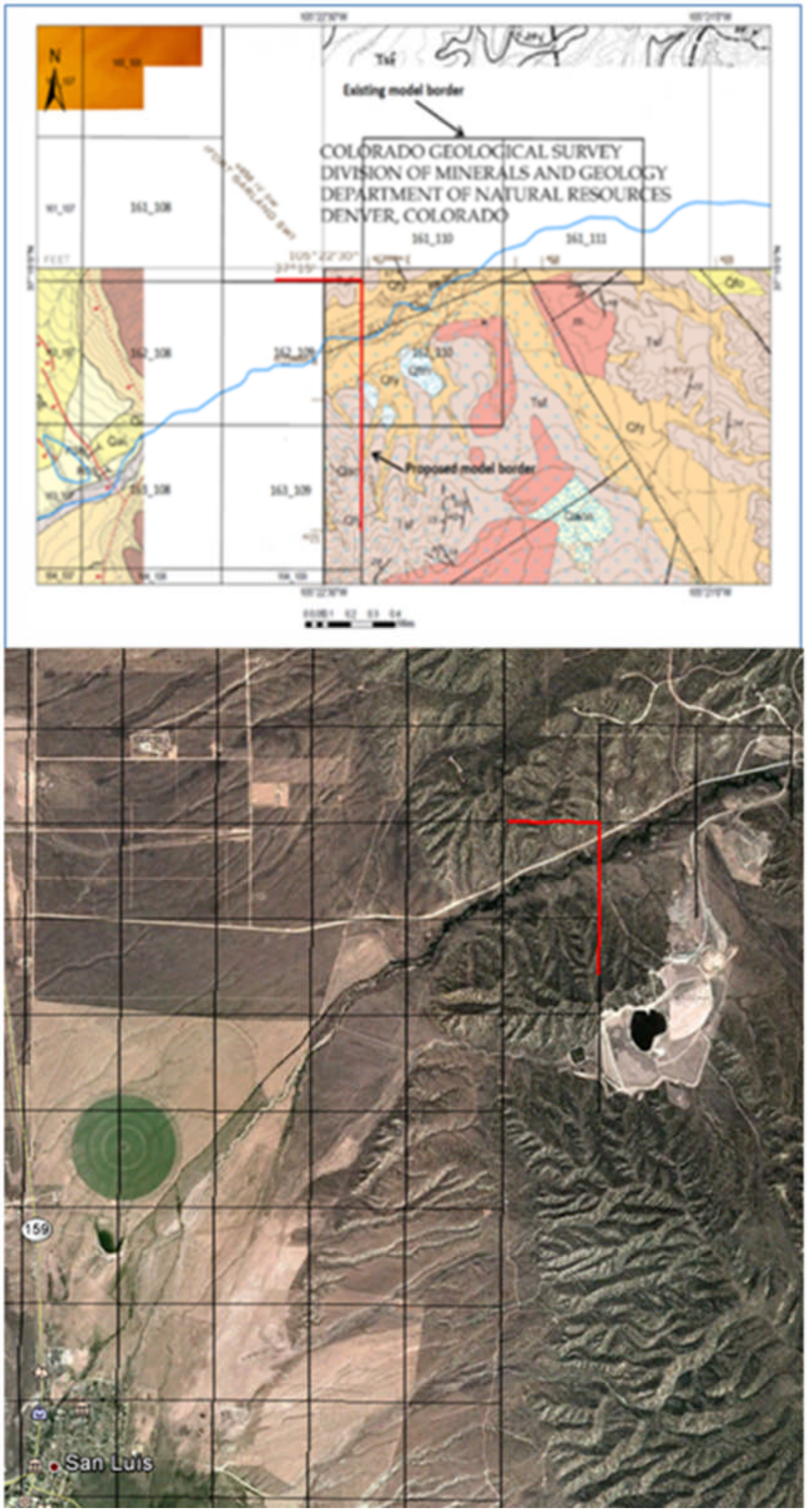
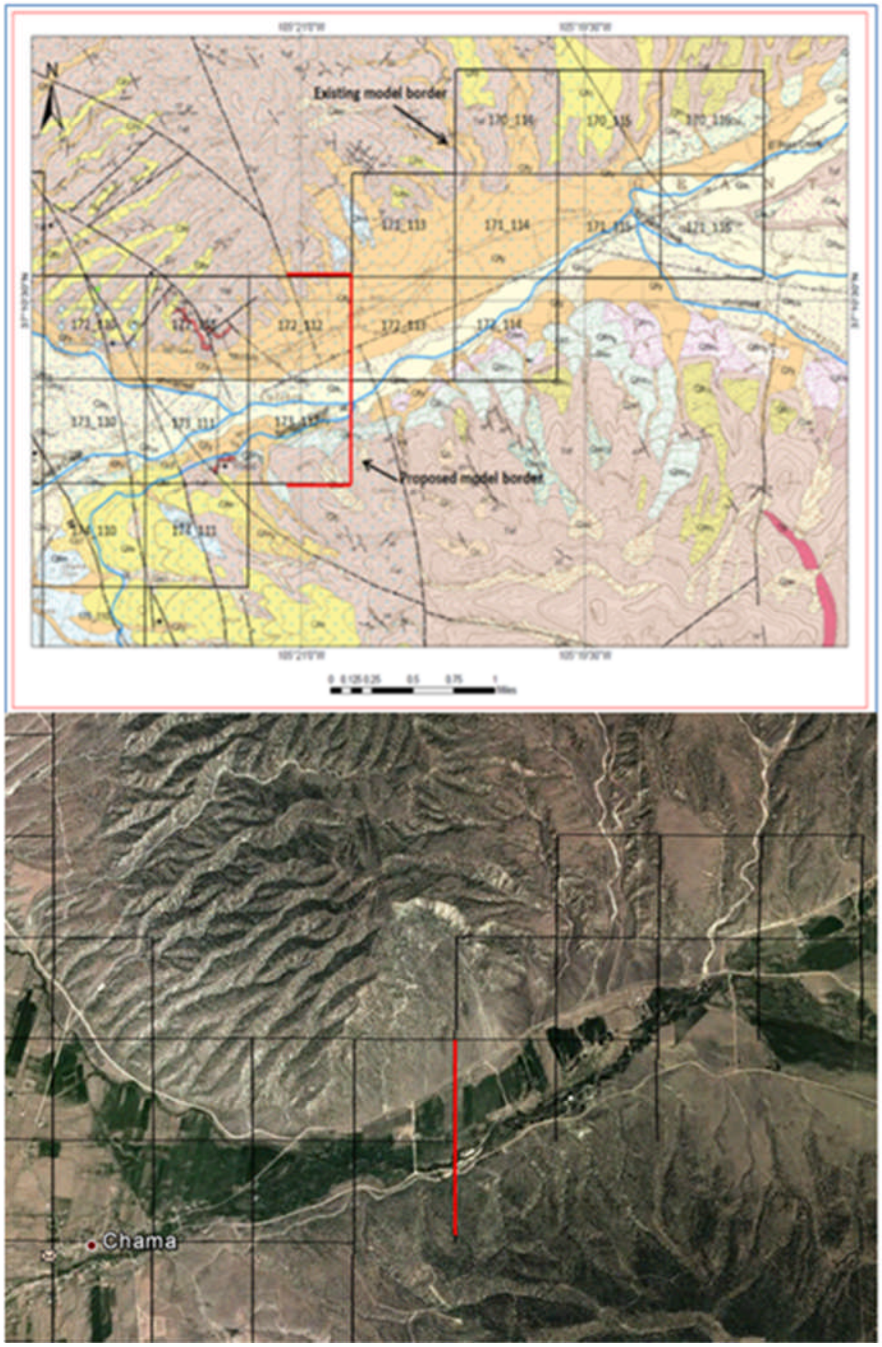


Figure 4: Recommended grid changes at Rito Seco.



<u>Culebra Creek</u>: Model cells converted to inactive cells: 170_114 to 170_116, 171_113 to 171_116, 172_113 to 172_114.

Figure 5: Recommended grid changes at Culebra Creek.

Vallejos Creek: Model cells converted to inactive cells: 179_113. Model cells converted to active cells: 178_111 to 178_112.

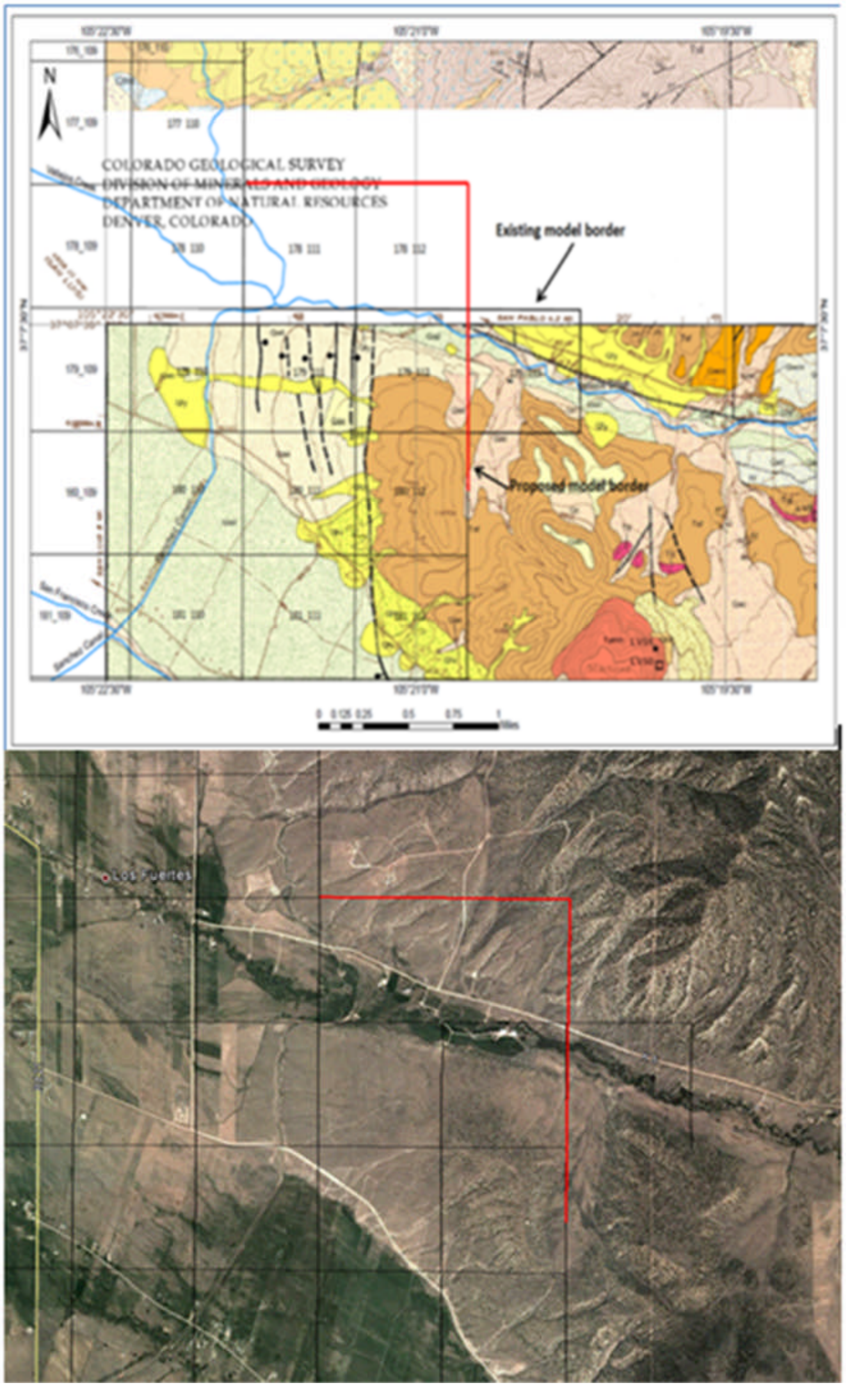


Figure 6: Recommended grid changes at Vallejos Creek.

4 Hydrogeologic Conceptualization of the SE Model Boundary

Model calibration efforts, discussions with the PRT in Phase 6 of the RGDSS, and newly available geologic and hydrogeologic data, have indicated that review of and possibly changes to certain characteristics of the model boundary in certain areas, including ground water inflow estimates, layering, and the position of the model grid cells at the boundary, are appropriate and may improve model calibration.

4.1 Layer 1 conceptualization and ground water inflow estimates

As discussed previously, Layer 1 in the SE boundary area which consists primarily of Quaternary alluvium in the stream valleys, and colluvial soils and alluvial fan sediments in upland areas. Holocene alluvial fan deposits and other colluvial sediments are found on the upland hill slopes above the creeks, while Quaternary alluvial (Qal) deposits are found within the creek valleys. From a spot-check of well logs, and from aerial imagery, the upland areas mostly are drained, and the colluvium is estimated to be typically 0 to 10 feet thick. No appreciable Layer 1 ground water inflow to the active model area is believed to exist within upland areas and hill slopes upstream of the model boundary. This is due to the lack of any significant thickness of alluvium and colluvium and also because creek beds on hill slopes appear to be ephemeral or dry. Also, in many areas at the SE boundary, thin surface soil is underlain by the Santa Fe Formation (Tsf) at each of the creek locations, and no appreciable Layer 1 deposits appear to exist.

Saturated alluvium does exist in the majority of the creek valleys, as demonstrated from the well logs we reviewed. Several creeks that enter the SE boundary appear perennially to have ground water moving through the Layer 1 alluvium into the active model domain. These creeks include Ute Creek, Sangre de Cristo Creek, Trinchera Creek, Ojito Creek, Culebra Creek, Rito Seco, and

Vallejos Creek. The magnitude of groundwater inflow from these creeks was evaluated from the saturated portion of Quaternary alluvial sediments in the subsurface (Qal) acting as underflow into the model (See references 3 through 10 in the reference list at the back of this report). This ground water underflow is recommended to be assigned to Layer 1 of the model as boundary ground water inflow at the appropriate creek valley locations.

The saturated thickness of the alluvial sediments within the creek beds is estimated to extend from the water table down to the base of the Qal / Tsf (i.e. Layer 1 – Layer 2) contact, as interpreted from well logs.

Darcy's Law was used as the means of estimating ground water underflow to the model at each creek. The general form of Darcy's Law is first presented and explained in more detail as follows (Celia and Pinder, 2006). Darcy's Law expresses the volume of ground water moving through a porous medium such as streambed sediment, based on the cross-sectional area of flow (A), the average estimated hydraulic conductivity (K), and the hydraulic gradient (-dh/dl).

$$Q = -KA\frac{dh}{dl}$$

Hydraulic conductivity was estimated based on material types described on driller's logs from water wells in the stream valleys. These logs were from the Colorado Division of Water Resources well permit database (See reference 1). The majority of sediments from the creeks as listed in the logs are described as sands, gravels, and boulders. A hydraulic conductivity value of 100 ft/day for a medium sorted, medium grained sand was judged to be representative of the majority of the alluvial sediments (Celia and Pinder, 2006).

The hydraulic gradient was derived from the hydraulic head between pairs of wells adjacent to the model border, where available. Well elevations and stream elevations were based on the geographic coordinates of such features from a digital elevation model (D.E.M.) used in ArcGIS maps for this analysis. If a pair of wells was not available at model boundary cells, then the hydraulic gradient was approximated to be equal to that of the hydraulic grade line of the creek immediately upstream of the model boundary.

The cross-sectional area was calculated by multiplying the saturated thickness of the creek bed by the estimated width of saturated alluvium in the creek channel. The saturated thickness for all creek beds was estimated to be the portion of the water-saturated alluvium above bedrock, which is generally the Santa Fe Formation in this area (Tsf; Layer 2). The width of the saturated alluvium was determined from geologic maps and also from aerial imagery from Google Earth, bounded by the visible vegetation adjacent to creeks. Figure 7 shows a sample image of the saturated alluvium width at Sangre de Cristo Creek.

Figure 7: Example of saturated alluvium width estimate (Sangre de Cristo Creek adjacent to Highway 160 east of Ft. Garland.

The cross-sectional area of the creek flood plains varies depending on the creek valley width and saturated alluvial thickness. A summary of the estimated Layer 1 inflow associated with the saturated alluvium of each creek is shown in Table 2. The inflow has been expressed in Acre-ft/year.

Table 2: Summary of alluvial (L1) ground water inflow estimates at SE model boundary for seven streams entering the model. (note: these estimates also are summarized in Table 3 along with the deeper layer inflow estimates).

Permit #	X	Y	Elevation (ft.)	Creek	Depth to Qal / Tsf Contact (ft.)	Water Level (ft.)	Hydraulic Head (ft.)	Saturated Thickness (ft.)	Well Distance (ft.)	Hydraulic Gradient	Alluvium Width (ft.)	Alluvium Desciption	K estimate (ft/day)	Saturated Area (ft^2)	Inflow, Q (Acre• ft/year)	RGDSS Row_Column
76965-A	-105.425	37.450	8059	Ute	20	10	8049.0	10.0	949	0.005	300	sand, gravel, boulders	100	3,000	10	129_106
186911	-105.427	37.448	8062		15	17.7	8044.3					clay, sand, gravel, boulders				
47434-F	-105.406	37.428		Sangre de Cristo	60			60		0.010	850	clay, sand, gravel, boulders	80	51,000	340	138_103
48400-F	-105.417	37.423	7924			Flowing										
98834	-105.406	37.391	7960	Trinchera	85	2	7958	83		0.014	275		100	22,825	270	142_105
65254-F	-105.407	37.390	7945									silty sand, gravels, clay				
62952-F	-105.370	37.363	8218	Ojito	77	12	8206	65	-	0.02	200	Sand, sandy & clay, sand & gravel	100	13,000	220	146_108
195696	-105.357	37.253	8460	Rito Seco	60	?			4971	0.019	200	Silt, sand & gravel, clay, gravel	100	9,000	140	162_109
237961	-105.372	37.246	8370		55	10		45								
38864-M					57	24		33								
73532-A	-105.336	37.173	8404	Culebra	67	49	8355	20	-	0.013	400	Sand & gravel, clay, gravel	120	8,000	100	173_112
110890	-	-	-		-	8										
216775	-105.334	37.121	8523	Vallejos	50	27	8496	23	-	0.012	150	Sand, gravel, clay	120	3,450	40	179_113
														Total	1,120	

4.2 Layers 2, 3, 4 conceptualization and ground water inflow estimates

Since approximately 2004, there has been a significant increase in the availability and detail of data relating to the hydrogeology of the Southeast area of the RGDSS model, including the SE boundary, the Culebra Graben, and San Pedro Mesa. Recent work includes new 7 ½ - minute geologic maps, technical papers on the geology and structure of the area, fault characterization at mountain fronts in the Rio Grande Rift (of which this study area is a part), oil and gas test drilling (one well) and geophysical studies. All of these have been considered in this review. References reviewed for this task are listed in the Reference List at the back of this report.

Based on this review, there are several factors that have led to the need for revision of the earlier conceptualization of Layers 2, 3, and 4 along the SE boundary and in the Culebra Graben, the major geologic structural trough that exists generally between the basin-margin faulting that delineates the SE model boundary and San Pedro Mesa and its northern extension (north of San Luis and the Culebra Creek water gap) San Pedro Questa. The revised conceptualization leads to recommendations for revisions to layer thickness, layer and boundary-inflow hydraulic conductivity values. These parameter revisions, in turn, lead to revised estimates of boundary ground water inflow.

4.2.1 Factors affecting the hydrogeology

Much of the recent geologic and geophysical work in the Culebra Graben area has resulted in a much more complex concept of the role of faulting, both synrift (i.e. occurring during rifting) and pre-rift during earlier mountain-building episodes. Based on material types in and adjacent to the fault zones, and the apparent effect of the faulting on water levels, the faulting has a significant effect on the boundary hydrogeology. Figure 8 is an illustration showing the more complex layering and faulting that is known to exist in this area based on recent mapping.

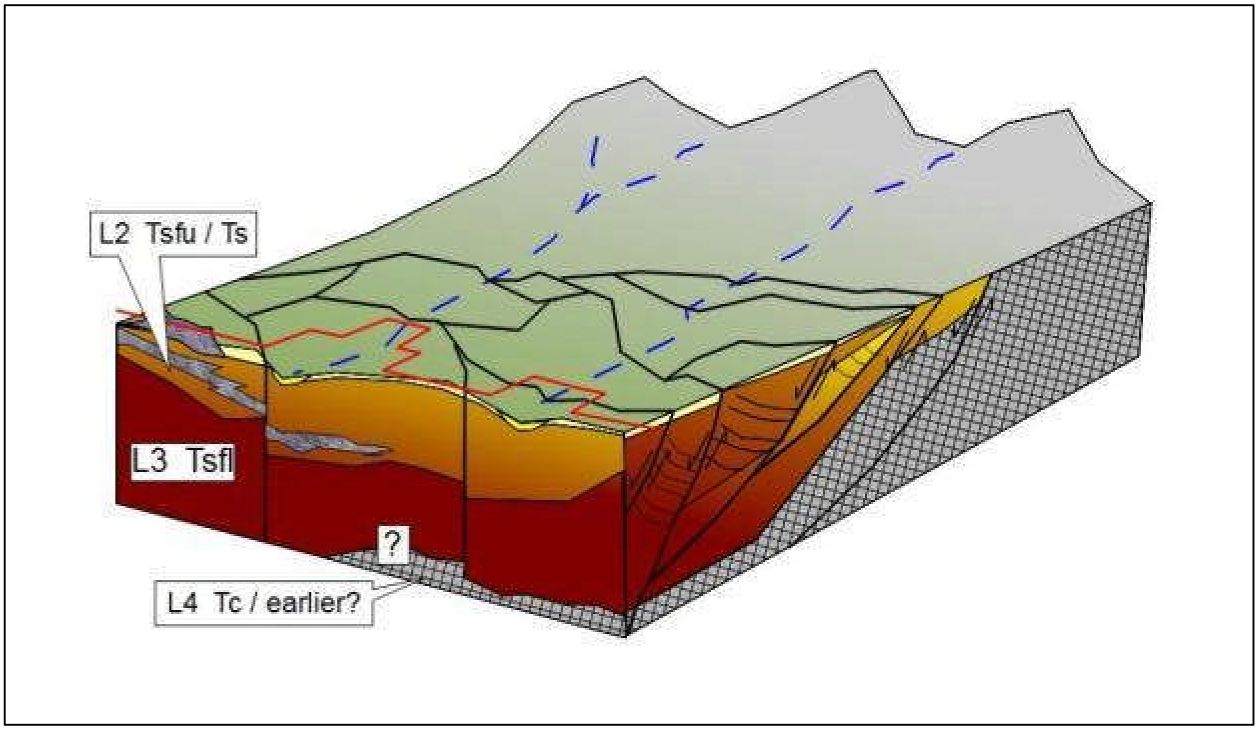


Figure 8: Revised conceptualization illustrating the general geologic framework at the SE model boundary. (Compare to Figure 2, earlier conceptualization.)

The recent geologic mapping has led to an understanding that many of the faults along the SE boundary, and also outside the model boundary to the east, have resulted in formation of relatively isolated, imbricate fault blocks[2]. The presence and types of faulting related to the Rio Grande Rift and also to earlier mountain building has caused lower Santa Fe (Tsf) materials to be much shallower than had been thought previously. This suggests lower hydraulic conductivity for Layers 2, 3, and 4 than the previous conceptualization using results of RGDSS aquifer tests P4 and P6, which were in sediments of the upper Santa Fe and possibly younger Alamosa Fm. sediments. This is supported by records of water wells in the foothills areas outside (east) of the SE boundary. Most water wells inferred to be screened in the Santa Fe sediments in that area report low yields: averaging 10 gpm or less.

[2] Imbricate: complex zones of faults where many of the planes of fault movement are concave upward, and meet and form a single detachment surface at depth.

Complex faulting at, and in the vicinity of, the SE boundary also appears to have a strong influence on the water table gradient at the model boundary. A spot-check of water levels in wells located across the SE boundary, and across mapped faults that are outside the model boundary, often indicate elevation differences that are larger than would be expected of Darcian flow gradients in porous sediments. This leads us to conclude that horizontal hydraulic conductivity (Kh) of model layers 2, 3, and 4 across the faults in most cases is significantly reduced from the Kh of the layer materials themselves, thereby causing “steps” or dislocations in the water table across the faults. This serves to reduce the rate at which ground water may flow into the active model area at the SE boundary, as compared to the 2004 hydrogeologic conceptual model (see Figure 2). It also leads to a re-estimation of the boundary inflow characteristics: we estimate that the Kh transverse to the SE model boundary that controls ground water inflow is generally on the order of one-tenth the Kh of the model layers (see Table 3).

Table 3

Layer	Formations	Representative Saturated Aquifer Thickness (ft)	Estimated Formation Hydraulic Conductivity (ft/day)	Estimated Hydraulic Conductivity Transverse to Faulting near Boundary (ft/day)	Estimated Representative Gradient at Boundary (ft/ft)	Length of contact at model boundary (feet)	Saturated Cross-Sectional Area (ft^2)	Estimated Ground Water Inflow (ac-ft/yr) *
SLV Southeastern Model Boundary Estimated Ground Water Inflow								
Revised:	June, 2015							
1	Quaternary Alluvium							
	Ute Creek	10	100	Not applicable	0.005	300	3,000	10
	Sangre de Cristo Creek	60	80	"	0.01	850	51,000	340
	Trinchera Creek	83	100	"	0.014	275	22,825	270
	Ojito Creek	65	100	"	0.02	200	13,000	220
	Rito Seco	45	100	"	0.019	200	9,000	140
	Culebra Creek	20	120	"	0.013	400	8,000	100
	Vallejos Creek	23	120	"	0.012	150	3,450	40
					Total Inflow: Layer 1			1,120
2	Santa Fe (upper Sand/gravel facies with silt & clay interbeds)	200	20	2	0.002	147,840		1,000
3	Santa Fe (lower) mudstone & sandstone (interbeds of Servilleta volcanic rocks not present or are drained at the model boundary)	200	5	0.5	0.002	147,840		200
4	Santa Fe (lower) mudstone, sandstone, conglomerate (some interbeds of volcanic rocks exist; may or may not be present at model boundary)	1000	0.1 to 1.0	0.01	0.002	147,840		0
5	Model Layer 5 is not present in this area.	---	---	---	---	---		---
					Total Inflow: Layers 2 - 4			1,200
					Total Estimated GW Inflow: all layers			2,320
	*- Layer 1 inflow estimates rounded to nearest 10 ac-ft/y. Layers 2, 3, 4 Inflow estimates rounded to nearest 100 ac-ft/yr							

There are several previous studies in the San Luis Valley, in other areas in the Rio Grande Rift, and elsewhere, that support the concept of reduced Kh under certain conditions from upgradient to downgradient across faults.

- Huntley (1976): In his Ph.D. thesis, Dr. David Huntley observed higher water levels upgradient of normal faults in fan deposits of Alamosa Fm. age and younger in the Closed Basin. Dr. Huntley discussed several possible reasons for this, and rejected several potential reasons. One of the more probable reasons is the presence of “fault gouge”, a clay-rich material formed from the sediments that are subject to grinding action due to movement along the plane(s) of fault movement.

- HRS Water Consultants, Inc. (1991): As part of a hydrogeologic study of the Baca Graben area (eastern part of the Closed Basin) in preparation for the trial of AWDI’s nontributary claim, HRS noted several locations in young (Quaternary?) alluvial fans near the Sangre de Cristo mountain front where water table was elevated significantly upgradient of a fault scarp, as compared to downgradient of the fault scarp (HRS, 1991, testimony in AWDI trial).

- San Marco project (1980) and RGDSS, (2012): Test drilling and pumping tests done in the Costilla Plain near Mesita in the late 1970's showed significant reduction in well production, and a "step" dislocation of the water table in Santa Fe and Alamosa fm. sediments and Servilleta volcanic rocks associated with the Mesita Fault. This also is seen further north, near Highway 142 in the Costilla Plain (RGDSS, Mesita Fault hydrogeologic review, 2012).

- Benson, R., (1997?): In his Ph.D. dissertation, Dr. Rob Benson (now of Adams State University) noted the presence of clay-rich fault gouge material he called "fault clay" associated with fault detachment surfaces in Santa Fe and also in crystalline rocks associated with the San Luis gold deposit in the Rito Seco area a few miles NE of the town of San Luis.

- Wilson, J.L, and H. Guan (2004): In a study of mountain-block hydrology and mountain-front recharge in arid environments in the SW United States, these authors noted that faults can act as conduits or as barriers to ground water movement, depending on the type of faulting and the material types in the faulted formations:

> "Brittle-rock faults may become a saturated flow hydraulic conduit in a direction parallel to the fault plane, while acting as a hydraulic barrier when perpendicular to the fault. Faults in poorly lithified sediments, including non-welded tuffs, usually develop deformation bands with significantly reduced permeabilities." - (Wilson & Guan, p. 16.)

- Benson, A., (2004): In a study of the hydrogeology of Taos County, including the Sunshine Valley in northern New Mexico, adjacent to this study area on the south, this author mapped partial isolation of water table elevations within fault blocks in Santa Fe sediments and Servilleta formation volcanic rocks.

- RGDSS (2000): The 72-hour test of an irrigation well (Permit no. 22152-RF) adjacent to RGDSS piezometer no. 4 (HRS, 2000), located in the east-central Costilla Plain, showed that the presence of a nearby fault acted as a reduced permeability aquifer boundary, in upper Santa Fe and possibly also younger sediments of Alamosa Fm age.

Thus, based on our observations and on the similarity with nearby areas noted to contain fault-gouge reduction in Kh, we recommend revision of the SE model boundary to include the characteristics and estimated inflows as shown in Table 3 as a starting point for improving the model calibration in the SE boundary / Culebra Graben area.

Another factor in the ground water recharge in the vicinity of the SE boundary is the fact that the majority of the recharge area outside (east of) the SE boundary is Santa Fe Fm. or older crystalline rock. In addition, most of this area is quite hilly, and is relatively deeply dissected by the ephemeral streams causing erosion. These factors, together, suggest that the majority of the water sourced in the area east of the SE boundary enters the model as surface inflow (i.e. rim inflow) or as ground water in Layer 1 (Quaternary alluvium in stream valleys) and to a lesser degree in Layer 2 (upper Santa Fe sand and gravel facies: see Table 3). The deeper layers, Layers 3 and 4, probably receive, and transmit to the active model area, a relatively small percentage of the available water. The hilly topography suggests that most ground water is recharged and discharged in relatively shallow, local recharge – discharge “cells” (Toth, 1963) and that deeper ground water recharge – discharge cells, such as are known to be present in the very flat topography of the Closed Basin of the SLV, constitute a much smaller part of the ground water budget at the SE boundary.

Based on this hydrogeologic review, we conclude as follows:

- A much smaller volume of water enters the SE boundary of the RGDSS model as ground water than was estimated in the 2004 conceptual model (about 2,320 ac-ft/y, as compared to 11,800 ac-ft/y in 2004; see Table 3 and Table 1, respectively).

- Approximately 48% (1,120 ac-ft/y) enters the model as ground water in Layer 1, through the alluvium associated with the perennial and intermittent streams in the area (see Table 3).
- Approximately 52% (1,200 ac-ft/y) enters the SE boundary as ground water in Layers 2, 3, and 4. Of this amount, only about 200 ac-ft/y is estimated for Layer 3 inflow, and, to the nearest 100 ac-ft/y, 0 ac-ft/y inflow is attributed to Layer 4 as ground water inflow.

5 Hydrogeologic Review of the Culebra Graben and San Pedro Mesa

The Culebra Creek valley (Culebra Graben; also called the Sanchez Graben) and San Pedro Mesa and its northern extension (San Pedro Questa) are fault-bounded blocks of sedimentary and volcanic formations that have been moved upward (the mesa; called a horst) and downdropped (the Culebra valley; called a graben) relative to the formations that surround these features. The faulting, and the resulting layer thicknesses and characteristics, determine many of the hydrogeologic characteristics in these areas. Figure 9 shows the general structural relationships between San Pedro Mesa, the Culebra Graben, and the faults that bound these structures.

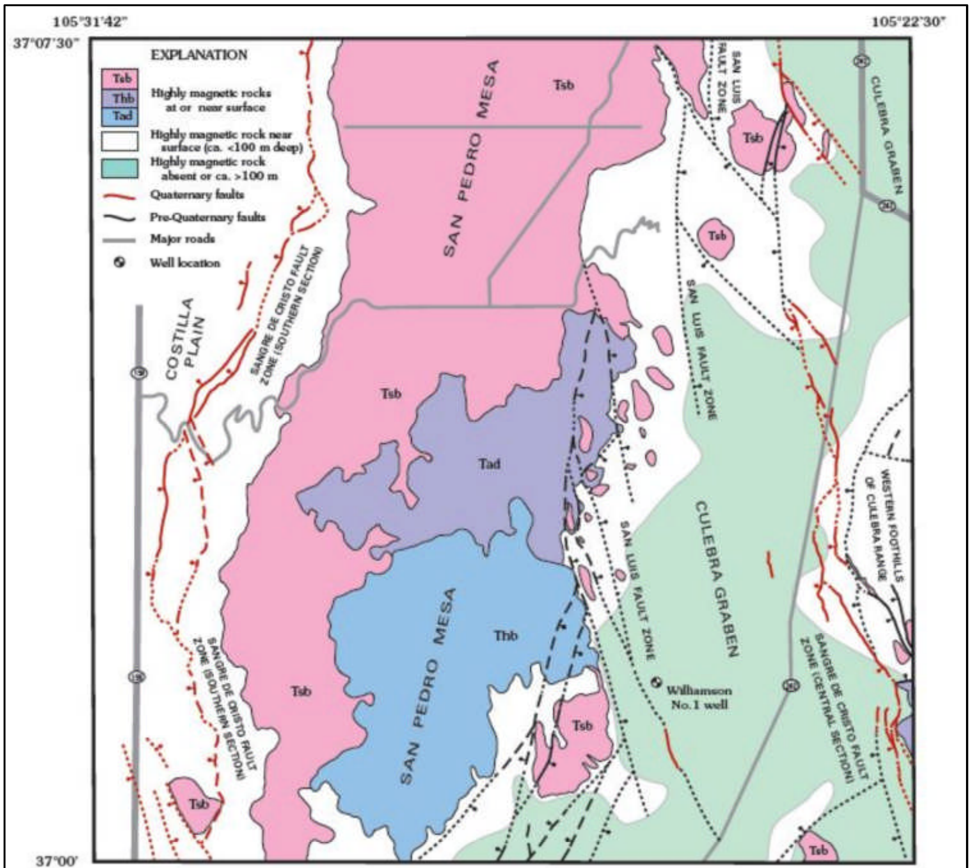


Figure 1. Simplified map showing relative depth to magnetic rocks east of San Pedro Mesa as determined from high-resolution aeromagnetic data of Bankey and others (2006). Area east of San Pedro Mesa has relatively deep magnetic rocks owing to downdropping of the Servilleta Basalt (unit Tsb) in the Culebra graben, which is compartmentalized by NNW-SSE-trending splays of the San Luis and Sangre de Cristo fault zones. On San Pedro Mesa, Early Proterozoic and Paleozoic rocks that are possibly rooted and pre-Servilleta volcanic rocks (units Thb and Tad) suggest the area was a Neogene structural high in addition to being a Pliocene-Pleistocene horst.

Figure 9: Excerpt from Thompson et al, 2007, Preliminary Geologic Map of Sanchez Reservoir Quadrangle and Eastern Part of the Garcia Quadrangle. USGS OFR 2007-1074.

5.1 Culebra Graben and the Culebra Creek Water Gap at San Luis

Culebra Creek and Rito Seco merge near the town of San Luis, Colorado in an area near the water gap formed by erosion through San Pedro Mesa. These creeks, and several smaller tributaries, dominate the movement of surface water in the Culebra Graben, formed by a series of normal faults that are part of the Central Sangre De Cristo Fault Zone. (Drenth et. al, 2008). The Servilleta Fm volcanic rocks and a sandy siltstone / mudstone facies of the Santa Fe Formation are exposed on the top and sides of the horst block (San Pedro Mesa and San Pedro Questa) and also to the east in the Culebra Graben at the base of the Culebra Mountains (Drenth et. al, 2008). Quaternary colluvial sediments and alluvial fan sediments fill the valley floor (Culebra Graben) in addition to alluvial sediments from creeks flowing into the San Luis Valley (Drenth et. al, 2008).

A series of well logs from water wells in this area indicate that the Quaternary alluvium (Qal) thickens significantly from east to west across the graben. In particular, wells located upstream toward the Culebra Mountains adjacent to the model boundary indicate a total alluvium thickness of 67 feet in Culebra Creek and 47 feet in Rito Seco. Most of the completed wells within the valley near San Luis are relatively shallow: most are on the order of a total depth of only 60 feet. However, one deep well located in the center of the valley near the town of San Luis indicated an alluvium thickness of 300 feet. Additional wells downstream (west / southwest) one to two miles from the water gap indicate alluvium depths of at least 200 feet. Figure 10 is a generalized cross section that shows the westward thickening of the alluvium, and the other structural and stratigraphic relationships as they relate to model layers 1 through 4 in the San Pedro Mesa and Culebra Graben area. Figure 11 shows the location of this cross section.

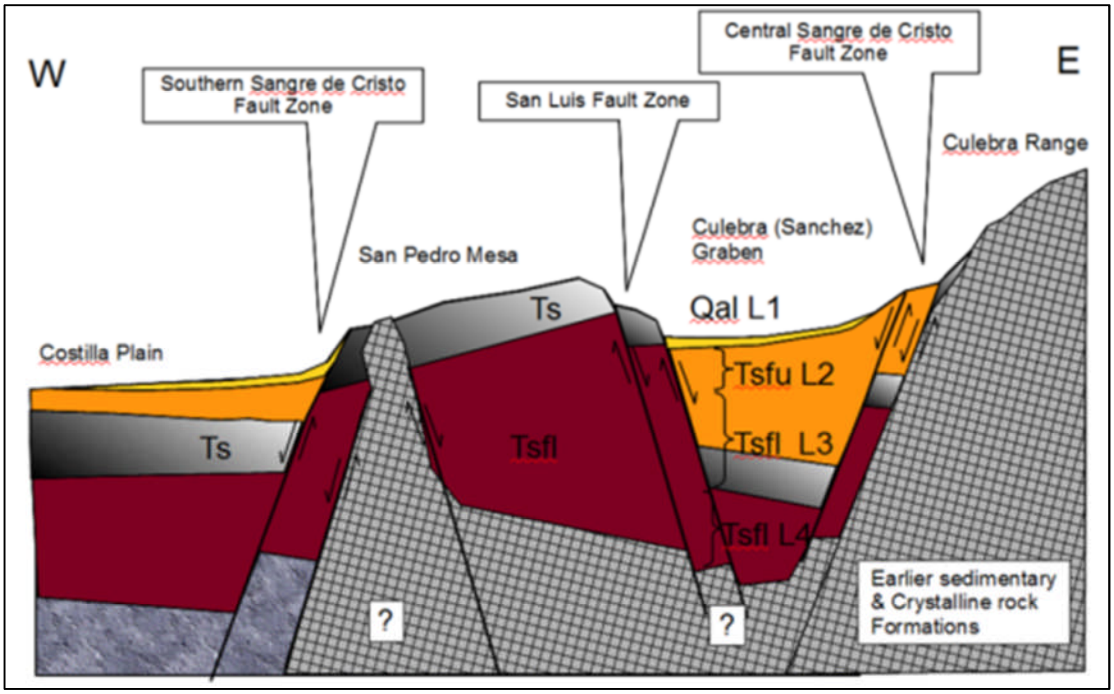


Figure 10: Generalized geologic cross section through San Pedro Mesa and Culebra (Sanchez) Graben. Not to scale.

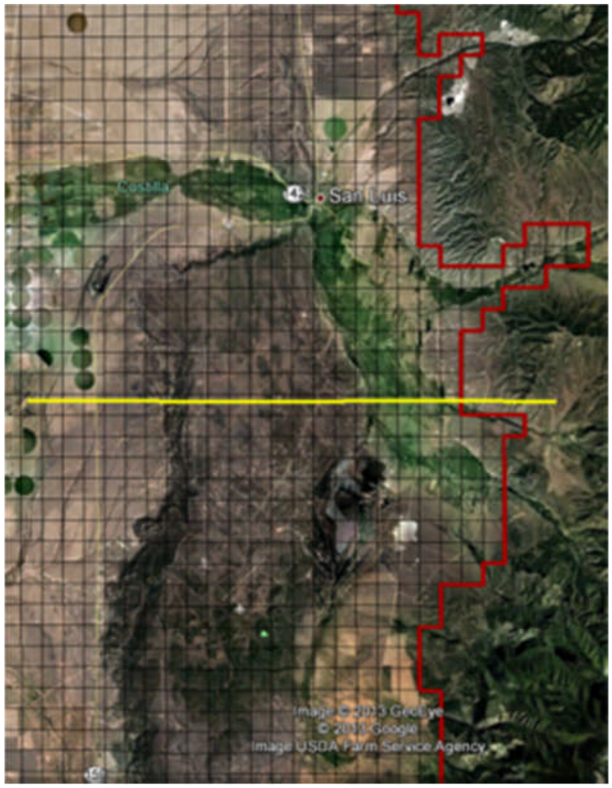


Figure 11: Location of the geologic cross section shown in Figure 5.

An estimate for the ground water underflow through the water gap within the Quaternary alluvium (Qal) was evaluated using a Darcy's Law analysis (see Table 4). The hydrogeologic parameter values, including estimated Kh, were estimated from the grain size descriptions and specific capacity information presented on geologic maps and from driller's reports from water wells from the Colorado Division of Water Resources well permit database.

The relatively large areal extent of the valley floor of the Culebra Graben indicates a broad spectrum of grain sizes ranging from clays to boulders. This is reflected in the driller's logs. However, the majority of sediments described in the logs are described as sands and gravels. Due to the relatively large area, a representative hydraulic conductivity was chosen to account for both coarse grained and fine grained sediments. A poorly sorted, medium grained sand Kh value of 80 ft/day was chosen to be representative of the majority of these materials (Celia and Pinder, 2006).

The hydraulic gradient was evaluated between pairs of wells near Culebra Creek at the water gap (see Table 4). A total of three pairs of wells were evaluated for ground water underflow through the water gap. The hydraulic gradient was estimated at 0.01 ft/ft.

The cross-sectional area of the saturated alluvial underflow at the water gap was treated as trapezoidal, and was estimated to have a significant thickness based on the few logs available for this area. The apparent saturated width of alluvium at the water gap was estimated at 2,000 feet, as determined from a combination of geologic maps and aerial imagery from Google Earth. Although the width of the saturated alluvium was relatively large, the water gap is narrowly situated between the horst block of San Pedro Mesa (south) and San Pedro Questa (north). The horst is comprised of the Santa Fe Formation and Servilleta Basalt member of the formation (Drenth. al, 2008).

A truncated V-shaped (trapezoidal) channel is appropriate for the shape of the alluvial paleovalley at this location because Culebra Creek is narrowly bounded on the north and south by the prominent San Pedro horst. The depth to ground water is relatively shallow within wells in the water gap, ranging from 8 feet to 15 feet, averaging to 12 feet. The saturated thickness was estimated by as the difference between the total alluvium depth and depth to ground water: resulting in an estimate of 288 feet. The upper width of the trapezoid (top) was determined to be 2000 ft. and the lower width (base) is estimated to be 1000 ft.

Table 4 tabulates records of water wells in the vicinity (within about one mile either upstream or downstream) of the Culebra Creek water gap at San Luis. As shown in Table 4, there is a range of well depths and saturated thickness values. Although well records in the San Luis / Culebra Graben area east of the water gap show alluvial thicknesses up to approximately 300 feet, it is unlikely that an alluvial saturated thickness exceeding 150 to 200 feet exists at the water gap, due to the presence of Santa Fe formation sediments that have been thrown upward by faulting along the east edge of San Pedro Mesa. For purposes of underflow calculation, we have used an estimate of 200 feet saturated thickness in the alluvium in the water gap. A more accurate approximation would require installation of a test hole, logged by a hydrogeologist, in the water gap.

Based on the estimated representative aquifer parameter values for the alluvium through the water gap, the estimated alluvial ground water underflow through the Culebra Creek water gap is estimated to be approximately 600 ac-ft/y (about 0.8 cfs). This estimated underflow is less than 10% of the surface water discharge in Culebra Creek through the water gap (based on WY 2015 wintertime base flow of 10 to 20 cfs; and not accounting for any surface flow through ditches that also traverse the water gap. This illustrates that only a small percentage of the total inflow of water to the SE boundary is manifested as ground water underflow, due to the reduction in Kh across the Sangre de Cristo fault zone near the model boundary, and across the Culebra Creek water gap at San Luis. We believe it also supports the hypothesis that the basin margin faults, including the faults along the SE boundary as well as the fault zone at the Culebra Creek water gap between the Culebra Graben and San Pedro Mesa, tend to restrict the lateral movement of ground water through the deeper layers at the fault locations. From this, we conclude that the ground water underflow moving through the Culebra Creek water gap as Layer 1 ground water underflow represents the majority of the ground water outflow from the Culebra Graben from all model layers.

This hypothesis is also supported by the fact that water tables are high in the topographically lower areas of the Culebra Graben (i.e. near the town of San Luis), and artesian head is documented as being relatively common in this area. This indicates upward movement of ground water from deeper layers to shallower layers in the San Luis / water gap area. Downgradient of the water gap, flowing wells do not occur according to the available water levels and well records, and water table gradients generally have a downward component.

Table 4

Wells in vicinity of Culebra Creek Water Gap at San Luis, CO									
Permit No.	Total Depth	Static Water Level	Pumping Water Level	Pumping Rate (gpm)	Specific Capacity (gpm/ft)	Estimated T* (ft^2/d)	Saturated Thickness (ft)	Estimated Kh (ft/d)	Comments
19564-FR	270	130	180	1000	20	4,000	140	29	Sand, gravel, clay interbedded
21590-F	300	60	110	1000	20	4,000	240	17	sand & gravel; clay; fractured granite below 70'
27694	57	1	NR	30	4.3	900	56	16	Alluvium: sand, gravel, clay short test: 1/2 hour
21708	83	10	70	350	5.8	1,200	73	16	mostly gravel
21446	30	8	23	100	6.7	1,300	22	59	sand and gravel. Low rate test; Kh not estimated.
R-14304	180	20	90	1125	16.1	3,200	160	20	No lithologic log.
23234	90	63	96.5	230	6.9	1,400	27	52	No lithologic log.
21446	30	8	23	100	6.7	1,300	22	59	sand and gravel
246266	200	12	NR	20	---	---	---	---	Sand. Kh not estimated.
27944	60	6	56	5	---	---	---	---	gravel, sand, sandy clay, boulders. Low rate test; Kh not estimated
244156-A	60	8	NR	15	---	---	---	---	sand and gravel. Low rate test; Kh not estimated.
23693	200	NR	NR	NR	---	---	---	---	Sand and gravel; 185-200' clay. Kh not estimated.
						Median	65	24	
* - Jacob linearization, as described in Driscoll, F., Groundwater and Wells, p. 1021, for unconfined aquifers.									

Table 5

Culebra Creek Water Gap Estimated Alluvial Ground Water Underflow					
Estimated Saturated Thickness (ft)	Median Kh (ft/d)	Estimated Gradient (ft/ft	Water Gap Width (ft)	Saturated Cross-sectional Area (ft^2)	Estimated Alluvial Underflow (ac-ft/y)
200	24	0.01	1980	396,000	800

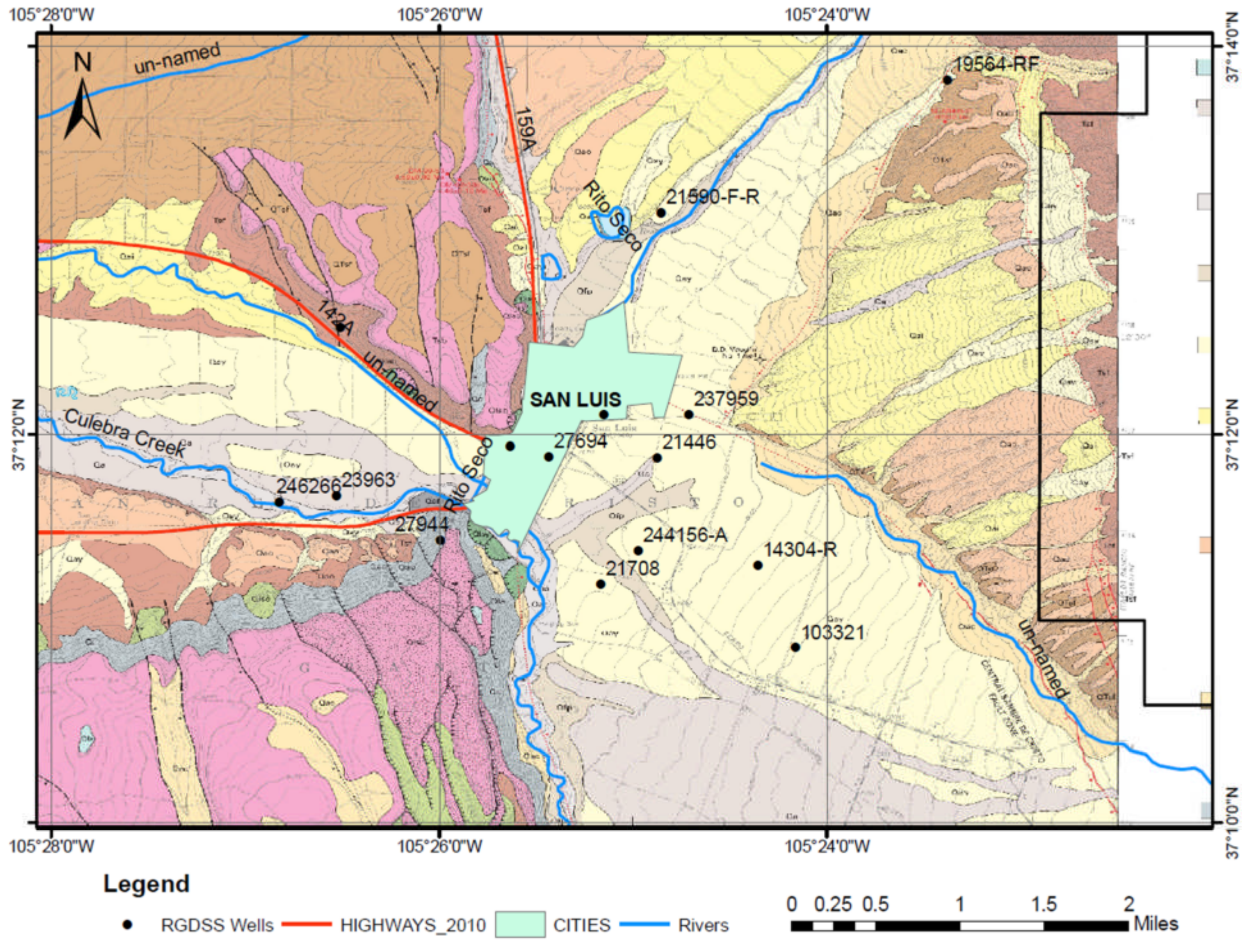


Figure 12: Wells in vicinity of Culebra Creek Water Gap at San Luis, CO.

5.1.1 Layers 2, 3, 4 Characteristics in the Culebra Graben and San Pedro Mesa

Based on review of published geophysical studies, logs from two oil and gas test wells (Williamsen no. 1, near the south end of the Culebra Graben, and the Vaughn no. 1, a few miles NE of San Luis), and the few deep water wells that exist in the area, the estimated layer thicknesses and hydraulic characteristics of the deeper model layers are estimated to be as shown in Table 3. In general, the deeper layers may thicken considerably near the center and southern portions of the Culebra Graben, but the hydraulic conductivity of these deep lower Santa Fe, and possibly also Conejos Fm. sedimentary and volcaniclastic rocks (predominantly mudstone, sandstone, and some conglomerate) is so low that little if any ground water recharge, movement, and discharge is estimated to take place below approximately 1,500 to 2,000 feet depth.

As with the SE model boundary, ground water movement across the faulted boundary between the Culebra Graben and San Pedro Mesa is estimated to be significantly reduced due to the formation of clay-rich fault gouge. In addition, San Pedro Mesa, capped with Servilleta volcanic rocks, may be cored in part by Precambrian crystalline rock, and almost certainly is underlain with lower Santa Fe fm mudstone and sandstone of relatively low Kh. Thus our best current estimate is that the volume of ground water moving laterally in the deeper layers from the Culebra Graben is small - perhaps only a few hundred acre-feet per year - as compared to larger volumes estimated to move upward and discharge to Layer 1 sediments and the surface streams that discharge through the Culebra Creek water gap at San Luis.

5.2 Southern End of the Culebra Graben

As shown on Figure 13, the Culebra Graben and San Pedro Mesa geologic structures terminate just south of the CO – NM state line. South of the southern end of the Culebra Creek watershed, shown as a red dotted line on Figure 13, the geology is dominated by very old crystalline rocks of Precambrian age that outcrop in this area, as part of the mountain uplift in that part of the southern Sangre de Cristo range. These rocks are inferred to be of very low hydraulic conductivity. Costilla Creek has eroded through the Servilleta Fm and part of the Santa Fe Fm.

This is a significant structural change from the deep sedimentary and volcanic rock filled trough of the Culebra Graben. The deep structure of the Culebra Graben, and its southern terminus, is seen on Figure 14, which is an interpretation of the thickness of Santa Fe formation rocks from U.S. Geological Survey recent geophysical surveys in this area (Drenth et al, 2008). Figure 14 also shows the truncation of the Santa Fe sediments within approximately 1 to 2 miles of the CO – NM border. Based on these geologic and geophysical maps, we conclude it is appropriate to represent ground water flow as effectively zero at the state line boundary, in the San Pedro Mesa and Culebra Graben regions.

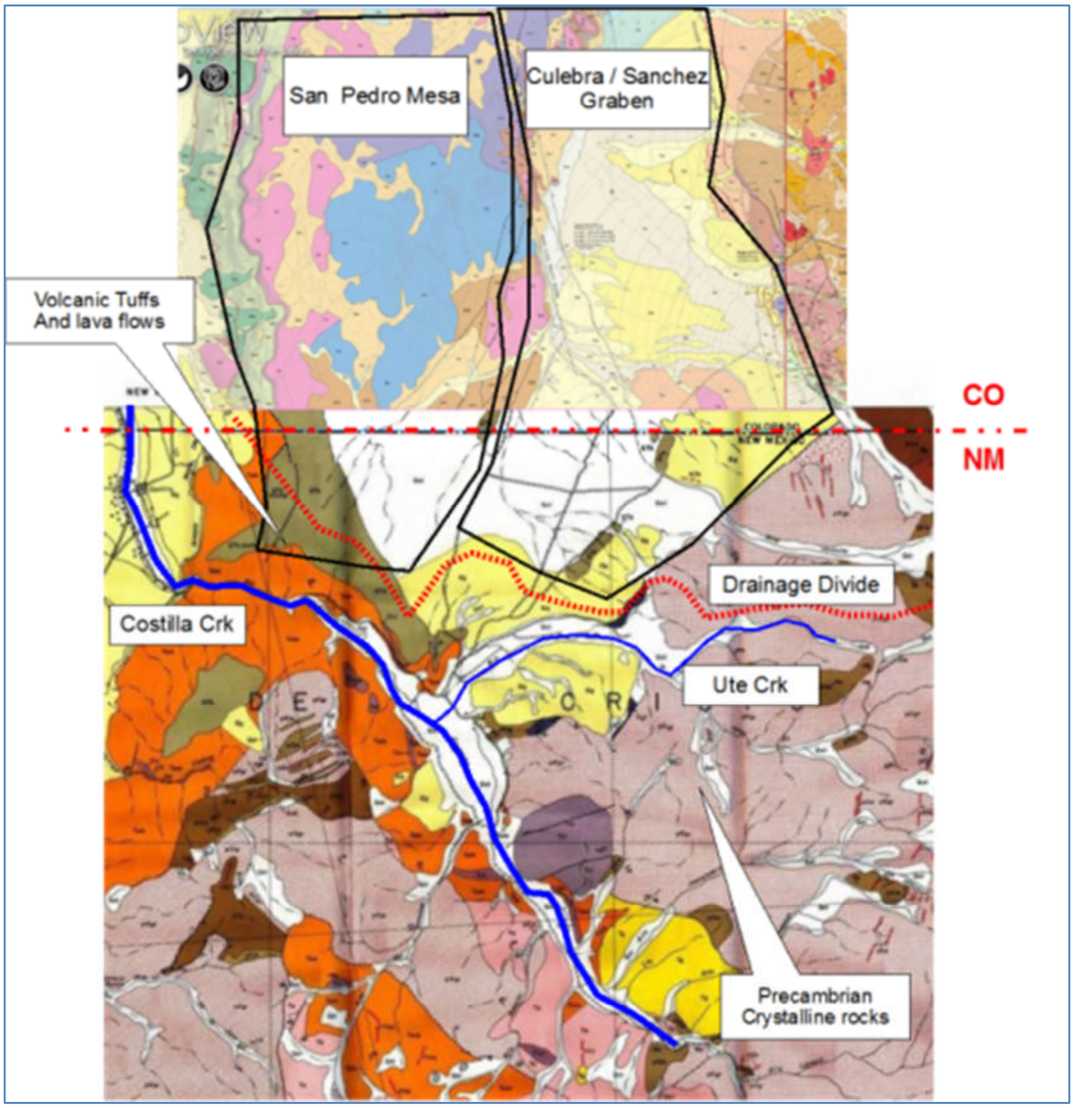


Figure 13: Mosaic of two geologic maps, and selected hydrologic features, in the State line boundary / Costilla Creek region.

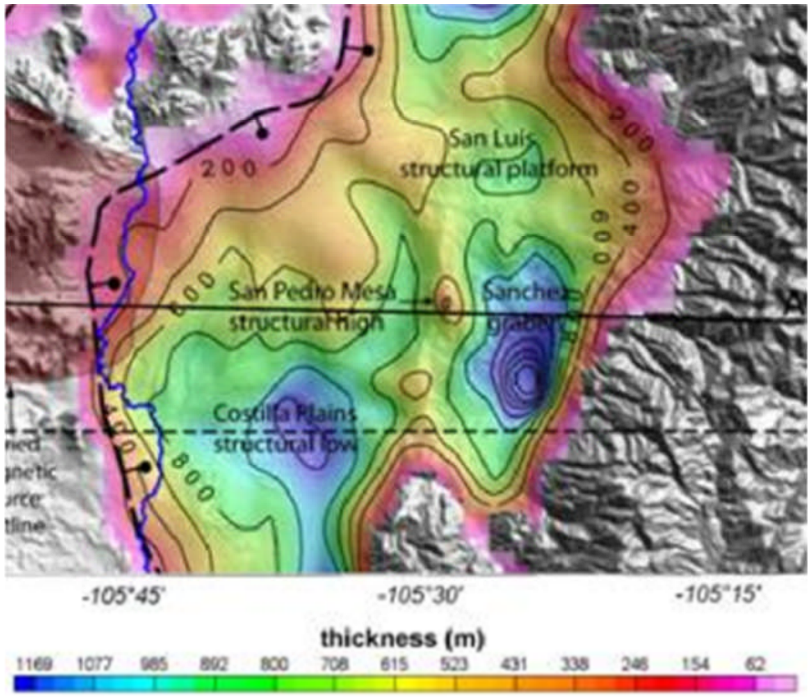


Figure 14: interpreted thickness of sedimentary and volcanic rocks comprising the Santa Fe formation (Drenth et al, 2008, Figure 14).

6 Conclusions and Recommendations

As a result of our review of the hydrogeology along the Costilla County portion of the RGDSS model (SE model boundary), we have developed a set of recommended changes to the model conceptualization along the SE model boundary, the Culebra Graben and San Pedro Mesa, the southern end of the model boundary at the structural truncation of the Culebra Graben, and the ground water outflow from the Culebra Graben at the Culebra Creek water gap. Table 3 and Table 4 of this report contain recommended starting points for the next phase of RGDSS model calibration, including layer thicknesses, layer hydraulic conductivity values (Kh), and layer Kh values at the fault-controlled boundaries along the SE model boundary and the Culebra Graben – San Pedro Mesa contact.

The following conclusions and recommendations summarize all of the conclusions and recommendations discussed in this report.

- As a result of our review of the hydrogeology along the SE boundary we have developed a set of relatively minor changes to the model grid. HRS recommends that the following model cells be converted from active to inactive or inactive to active:
  - Convert the following model cells at Rito Seco from active to inactive: 161_110 to 161_111 and 162_110.
  - Convert the following model cells at Culebra Creek from active to inactive: 170_114 to 170_116, 171_113 to 171_116, 172_113 to 172_114.
  - Convert the following model cells at Vellejos Creek from active to inactive: 179_113 and model cells from inactive to active cells: 178_111 to 178_112.

- The magnitude of groundwater inflow from these creeks was evaluated from the saturated portion of Quaternary alluvial sediments in the subsurface (Qal) acting as underflow into the model. This ground water underflow is recommended to be assigned to Layer 1 of the model as boundary ground water inflow at the appropriate creek valley locations.

- The complex faulting at, and in the vicinity of, the SE model boundary also appears to have a strong influence on the water table gradient at the model boundary. A spot-check of water levels in wells located across the SE boundary, and across mapped faults that are outside the model boundary, often indicate elevation differences that are larger than would be expected of Darcian flow gradients in porous sediments. This leads us to conclude that horizontal hydraulic conductivity (Kh) of model layers 2, 3, and 4 across the faults in most cases is significantly reduced from the Kh of the layer materials themselves, thereby causing “steps” or dislocations in the water table across the faults. This serves to strongly reduce the rate at which ground water may flow into the active model area at the SE boundary. It also leads to a re-estimation of the boundary inflow characteristics: we estimate that the Kh transverse to the SE model boundary that controls ground water inflow is generally on the order of one-tenth the Kh of the model layers (see Table 3).

- Based on this hydrogeologic review, we conclude as follows:

    - A much smaller volume of water enters the SE boundary of the RGDSS model as ground water than was estimated in the 2004 conceptual model (about 2,320 ac-ft/y, as compared to 11,800 ac-ft/y in 2004; see Table 3 and Table 1, respectively).
    - Approximately 48% (1,120 ac-ft/y) enters the model as ground water in Layer 1, through the alluvium associated with the perennial and intermittent streams in the area (see Table 3).
    - Approximately 52% (1,200 ac-ft/y) enters the SE boundary as ground water in Layers 2, 3, and 4. Of this amount, only about 200 ac-ft/y is estimated for Layer

3 inflow, and, to the nearest 100 ac-ft/y, 0 ac-ft/y inflow is attributed to Layer 4 as ground water inflow.

- As with the SE model boundary, ground water movement across the faulted boundary between the Culebra Graben and San Pedro Mesa is estimated to be significantly reduced due to the formation of clay-rich fault gouge. In addition, San Pedro Mesa, capped with Servilleta volcanic rocks, may be cored in part by Precambrian crystalline rock, and almost certainly is underlain with lower Santa Fe fm mudstone and sandstone of relatively low Kh. Thus our best current estimate is that the volume of ground water moving laterally in the deeper layers from the Culebra Graben westward to the Costilla Plain region is small - perhaps only a few hundred acre-feet per year - as compared to larger volumes estimated to move upward and discharge to Layer 1 sediments and the surface streams that then discharge through the Culebra Creek water gap.

- In general, the deeper layers may thicken considerably near the center and southern portions of the Culebra Graben, but the hydraulic conductivity of these deep lower Santa Fe, and possibly also Conejos Fm. sedimentary and volcaniclastic rocks (predominantly mudstone, sandstone, and some conglomerate) is so low that little if any ground water recharge, movement, and discharge is thought to take place below approximately 1,500 to 2,000 feet depth.

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- Based on our observations and on the similarity with nearby areas noted to contain fault-gouge reduction in Kh, we recommend revision of the SE model boundary to include the characteristics and estimated inflows as shown in Table 3 as a starting point for the next phase of improvements to the model calibration in the SE boundary / Culebra Graben area.

- We conclude that the ground water moving through the Culebra water gap as Layer 1 ground water underflow (estimated at 800 ac-ft/y), represents the majority of the ground water outflow from the Culebra Graben from all layers in that area.

- Our best current estimate is that the volume of ground water moving laterally in the deeper layers from the Culebra Graben is small - perhaps only a few hundred acre-feet per year - as compared to larger volumes estimated to move upward and discharge to Layer 1 sediments and the surface streams that discharge through the Culebra Creek water gap

- Based on the new and revised geologic and geophysical maps published since approximately 2004, as discussed in this report, we conclude it is appropriate to represent ground water flow as effectively zero at the state line boundary, in the San Pedro Mesa and Culebra Graben regions.

The conclusions and recommendations discussed in this document are based on the best data currently available. The geology of the subject area is complex, and as new data becomes available, there will be a need for periodic review and reassessment of the hydrogeologic conceptualization of the SE model boundary and ground water inflow in this area.

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