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Logical framework for development and discrimination of existing alternative conceptual models of saturated groundwater flow beneath the Pajarito Plateau

Velimir V Vesselinov

Why we need conceptual models

The major reason that we need to develop conceptual models is to be able to surmise possible directions and properties of the groundwater flow. Alternative conceptual models represent alternative directions and properties of groundwater flow.

For example, the head differences between existing observation points (laterally between wells and vertically between well screens) define explicitly neither the direction of the hydraulic gradient nor the direction of groundwater flow. This statement is true even for the simple case of a continuous groundwater flow system. If the groundwater flow system is discontinuous (e.g. there are impermeable layers between the locations of head observation) the interpretation that head differences between observation points represent direction of the hydraulic gradient and/or the direction of groundwater flow is even more erroneous.

Further, the geochemical data are more appropriate than the head data to surmise groundwater flow directions but in many cases their independent interpretation can be inconclusive.

Therefore, the directions and properties of groundwater flow can be surmised only by coupling all the observed data (hydraulic heads, geochemistry, etc) with qualitative knowledge about the system (areas of aquifer recharge/discharge, type of medium heterogeneity, etc) in the process of conceptual model development.

A posteriori, the alternative conceptual models can be tested numerically by invoking their implementation into alternative numerical models. However, care should be used when numerical models are used to test alternative conceptual models or directly surmise the directions and properties of groundwater flow. This is due to the fact that some of the simplifications and underlying assumptions in the numerical model might be impacting the conceptual model implementation and, therefore, the validity of the obtained conclusions.

Here we propose to establish a general logical framework for the conceptual model development. The aim is that all the premises (data, knowledge, theory) used to derive each of elements within each alternative conceptual model are clearly outlined. For example, this is the way it is initially done in the Hydrogeologic Workplan [*Nylander, et al.*, 1998]. As a result, it will be clear what new data and knowledge about the regional aquifer system can impact the conclusions.

Principles of the logical framework for conceptual model development:

- Alternative conceptual models will be based on the observed quantitative data, qualitative knowledge about the system and the physics.

- Alternative conceptual models represent differences in the possible mechanisms of groundwater recharge, discharge and flow. Alternative conceptual models represent differences in the possible directions and properties of the groundwater flow.
- Even if there is a large range of uncertainty in the available data and knowledge about the system, alternative conceptual models can be hypothesized with a given level of certainty (or uncertainty).
- Alternative conceptual models can be ranked based on their probability. The probability will be surmised based on how well they match the observed quantitative data, qualitative knowledge about the system and the physics.
- In addition, the probability can be surmised based on the required complexity in the groundwater system for the conceptual model to be possible. If alternative conceptual models equally well describe the observed quantitative data and qualitative knowledge about the system, the simplest conceptual model (requiring least complexity in the system) is the most probable, i.e. the parsimony principle [*Carrera and Neuman*, 1986a; 1986b; 1986c].
- Alternative conceptual models will be additionally ranked by the hazard associated with contaminant movement along the surmised groundwater flowpaths. The more hazardous conceptual models should be ranked higher than less hazardous ones.
- Old conceptual models do not get ranked higher than the new ones just because they have been applied and tested for a longer period of time.
- Conclusions made in any previous publications by various researchers working on the basin will be used with special care; if needed, reassessment and reanalysis of the underlying premises will be performed. Most importantly, the terminology used to conclusively summarize all the studies has to be unified.
- The alternative conceptual models will be identified clearly and the differences emphasized.
- Premises for each conceptual model and the logical (deductive) connections of the derived conclusions will be clearly outlined.
- There should be no attempts to merge conceptual models that are inconsistent with each other in one conceptual model with high uncertainty bounds. This will induce vagueness in the conceptual model description. This will not clearly emphasize the different flow (and contaminant) directions associated with the alternative conceptual models.

Summary of alternative conceptual models of groundwater flow

CONCEPTUAL MODEL #1: Initial conceptual model

The initial conceptual model of groundwater flow in the regional aquifer under the Pajarito Plateau is outlined in the Hydrogeologic Workplan [*Nylander, et al.*, 1998]. It is based on the hydrogeological work conducted by LANL and other organizations before 1998 in the studied region. The original workplan includes detailed discussion on the premises for each of the proposed conceptual model elements [pages 2-17 – 2-26]. Here is a brief summary of this conceptual model as outlined in the original report [pages 2-26 – 2-30]:

Direction of groundwater flow:

- The slope of the top of the regional aquifer suggests that the flow of groundwater is generally towards the east or southeast, and towards the Rio Grande.

Recharge:

- Relatively small volumes of water move beneath mesa tops under natural conditions, due to low rainfall, high evaporation, and efficient water use by vegetation. Atmospheric evaporation may extend within mesas, further inhibiting downward flow.

- The amount of mesa top recharge along the western portion of Laboratory is uncertain. Higher rainfall, increased vegetative cover, and increased welding and jointing of the tuff might lead to different recharge rates than those observed in better studied portions of the Laboratory.

- Mesa top recharge can be locally significant under disturbed surface conditions. Such change occurs when the soil is compacted, when the vegetation is disturbed, or when more water is artificially added to the hydrologic system by features such as blacktop, lagoons, or effluent disposal.

- Alluvial groundwater is a source of recharge to underlying intermediate perched zones, usually by unsaturated flow. In wetter canyon bottoms, alluvial groundwater may also contribute recharge to the regional aquifer.

- Intermediate perched zone and alluvial groundwater may be minor sources of recharge to the regional aquifer relative to the amount of public water supply pumping from the regional aquifer. The hydraulic connection between the regional aquifer and the land surface is not strong at most locations.

- Regional aquifer groundwater within the eastern portion of the Pajarito Plateau (generally along the Rio Grande) is of different recharge origin than under the central part of the Plateau.

- Sources of recharge to the regional aquifer are uncertain. Geochemical data show that the Valles Caldera is not the source of major recharge, contrary to statements in earlier Laboratory reports. Major recharge may occur by southerly flow along the late Miocene trough described initially by Purtymun [*Purtymun*, 1984], infiltration along the flanks of the Jemez Mountains, or possibly via percolation beneath canyon bottoms.

Contaminant dilution:

- If present, Laboratory-derived contaminants in the regional aquifer are likely to vary in concentration. The contaminant concentrations are probably below maximum contaminant levels (MCLs) for drinking water because; (1) regional aquifer underflow dilutes contaminant concentrations in recharge; and (2) contaminant concentrations in alluvial and intermediate perched zone groundwater are expected to decrease with depth due to dilution and geochemical attenuation along vertical migration pathways.

The initial conceptual model is slightly modified in the first annual status report for the FY98 [*Nylander, et al.*, 1999] [pages 19-30]. In the report, each of the initial conceptual model elements and its premises are reexamined in detail in lieu of newly collected data. Here is a brief summary of the important changes pertaining to the regional aquifer:

- <u>Flow Directions</u>: It is emphasized that water supply pumping affects flow directions in the aquifer near supply wells. The variation of these effects with depth and distance is not known at present. This influence on flow directions could have an important impact on contaminant movement in the regional aquifer.

- <u>Sources of recharge:</u>

    - Alluvial groundwater in specific wetter canyon bottoms is a source of recharge for the regional aquifer based on new observations.

    - Based on observed strong downward vertical hydraulic gradient on the western edge of the Laboratory and preliminary numerical modeling, it is concluded that the area along the flank of the Jemez Mountains is a recharge area with the recharge originating in the Jemez Mountains.

    - Along the western edge of the Laboratory, deep perched groundwater may be a major source of recharge to the regional aquifer. The volume of on-site regional aquifer recharge from stream bottom infiltration of natural streamflow into alluvial groundwater is small relative to the amount of public water supply pumping from the regional aquifer. When considered also with potential infiltration of effluent discharge streams, however, the annual volume of on-site regional recharge from stream bottom infiltration may be significant.

- <u>Contaminant dilution</u>: In this section, it is added that vertical gradients in the upper portion of the regional aquifer affect dilution of contaminant concentrations in the recharge sources, i.e. upward gradients influence mixing of the recharging water with resident aquifer water while downward gradients inhibit this mixing.

- <u>Heterogeneity of the hydraulic properties of the regional aquifer:</u> Vertically, hydraulic properties vary greatly between geologic units thereby contributing to varying water yield. Laterally, the regional aquifer commonly exhibits confined characteristics near the Rio Grande but appears to be unconfined in other parts of the Pajarito Plateau. Water level declines due to pumping vary across the Plateau, usually ranging from 0.6 to 3 feet per year. Water levels have declined the least in wells that penetrate a thick zone of permeable sediments that transect the central part of the Plateau.

CONCEPTUAL MODEL #2: Since FY99

A new alternative conceptual model is proposed in the annual status report for the FY99. It is further improved and modified in the following annual status and milestone reports without substantial changes [*Keating, et al.*, 2001; *Keating, et al.*, 1998; *Keating, et al.*, 1999; *Nylander, et al.*, 2001; *Nylander, et al.*, 2000; *Nylander, et al.*, 2002]. Here is a brief summary as it is outlined in the last annual status report for the FY02 [*Nylander, et al.*, 2003] (pages 3-1 – 3-3):

- <u>Hydrostratigraphy:</u> The regional aquifer beneath the Pajarito Plateau occurs in rocks of the Puye Formation, the Cerros del Rio basalts, the Tschicoma Formation, and the Santa Fe Group.

- Flow medium properties: The hydraulic conductivity of aquifer rocks is heterogeneous and averages approximately 140 m/yr.

- Hydrodynamics: The aquifer is unconfined in the west and confined or partially confined in some locations near the Rio Grande.

- Flow directions: At the western edge of the plateau, the water table is located approximately 300–400 m bgs. The hydraulic gradient in the western portion of the aquifer is generally downward. Groundwater flow is east/southeast, toward the Rio Grande. The hydraulic gradient in the eastern portion of the aquifer near the Rio Grande is generally upward. Groundwater velocities vary spatially with a typical value of 10 m/yr. Local deviations in flow direction occur because of lithologic heterogeneities and water supply pumping.

- Discharge: The Rio Grande is the main discharge area for the regional aquifer. The radiocarbon ages of water from deep wells beneath the Pajarito Plateau range from about 1000 to 6000 yr, although tritium activity indicates that a portion of the water is less than 50 yr old. Groundwater chemistry in many wells near the Rio Grande (high total dissolved solids [TDSs], high concentrations of naturally occurring solutes such as arsenic, boron, uranium, and fluoride, and depleted stable isotope values) is different from that beneath the Pajarito Plateau and from the eastern Española basin, suggesting that old water (about 30,000 yr) discharges near the river. Water flowing east-southeast from beneath the Pajarito Plateau mixes with this older water as it approaches the Rio Grande.

- Recharge: The largest component of recharge occurs as underflow of groundwater from the Sierra de los Valles, west of the Pajarito Plateau. Recharge also occurs from leakage from mesas, from alluvial groundwater in canyon bottoms on the Pajarito Plateau, and from intermediate perched groundwater. Local recharge on the Pajarito Plateau is important because it provides pathways for contaminants that originate from effluent discharges.

The major difference between this and previous conceptual model comes from the fact that the Rio Grande is defined as a discharge zone for the deep portions of the regional aquifer through upward groundwater flow. Further, the upward groundwater is defined to be one of the major causes for the observed flowing wells in the vicinity of the Rio Grande. In the previous conceptual model these wells are identified as artesian wells and the flowing is due to regional confinement of the deep aquifer system.

CONCEPTUAL MODEL #3

A new alternative conceptual model is proposed as a result of the work on this synthesis report. It has many common elements with the conceptual models explained above. However, there are important differences. The new conceptual model emphasizes the three-dimensionality in the structure and properties of groundwater flow beneath Pajarito Plateau. The model accentuates the differences between directions and properties of groundwater flow in the shallow, phreatic, and the deep, predominantly confined, zones of the aquifer.

Conceptual model components (elements):

Origin of the water at the White Rock springs:

- At the moment, the lowest discharge points for any deep groundwater beneath the Plateau are the water-supply wellfield, the Cochiti Lake and the Albuquerque basin. The spring elevations are much higher. Here 'deep' groundwater is defined as water residing in the deep portions of the aquifer where the elevations are generally lower than the water stage elevations along the Rio Grande. The discharge elevations of the White Rock springs are close to or slightly higher than the water stage elevations along the Rio Grande in their vicinity.

- Therefore, at the moment, all the water discharged at the springs has to have a shallow origin (phreatic zone of the regional aquifer, perched zones, local hydrogeological structures, etc.). <u>There should not be any 'deep' water component.</u> Here, the 'deep' water component is defined as groundwater coming to the springs along upward flowpaths from the deep zones of the aquifer.

- Before the pumping started the lowest discharge points for any deep water beneath the Plateau were the Cochiti Lake and the Albuquerque basin. The spring elevations were much higher again. <u>There should not have been any 'deep' water component in pre-development conditions as well.</u>

- There are no explicit measurements, but to the best of our knowledge the intensive pumping under the Plateau and at the Buckman wellfield has no impact on the spring rates. <u>Therefore again, we can conclude that the 'deep' water component in the spring waters was negligible in pre-development conditions.</u>

- In fact, we have observed subsidence of the ground surface in the area around Buckman wellfield which demonstrates the substantial cone of depression formed due to the pumping. The area of subsidence includes the spring locations. If the springs and the water-supply wells were draining the same portions of the aquifer, the springs would have ceased to exist a long time ago because of pressure drops due to the pumping. <u>Therefore the water-supply wells and the springs discharge different portions of the regional aquifer which are characterized with certain hydraulic separation</u>. (It should be also noted that the observed subsidence should in fact negligibly increase the springs discharge rates due to decline on their discharge elevations.)

- Another possible alternative is that the spring water is <u>predominantly</u> from 'perched' layers within the unsaturated zone. This alternative is improbable due to relatively small annual variation of the spring rates. If the springs were taping predominantly 'perched' waters their rates will be highly variable on a seasonal basis (some of the spring form perennial streams). Further in some cases; the 'perched' zones that were identified as spring sources could be mistakenly identified as a 'phreatic' zone of the regional aquifer. <u>Therefore even if there is a 'perched' water component in the spring water it is not dominant and much smaller compared to the 'phreatic' water component</u>. (This does not preclude for contamination of the springs through the 'perched' zone flowpaths; this only states that in the spring water balance, 'perched' water is a minor component.)

- <u>Therefore the most probable conceptual model is that the spring water is predominantly from the shallow phreatic zone of the regional aquifer. There is no 'deep' water component and a negligible 'perched' water component in the spring water. There is hydraulic separation between the zones discharged by the springs and the water-supply wells. The contamination of the springs along deep flowpaths is highly unlikely.</u>

Upward flow from the deep aquifer zones into the Rio Grande (and its alluvial aquifer):

- There are no data explicitly suggesting the existence of upward groundwater flow into the Rio Grande. Previously it was suggested the deep flow is demonstrated by the old water observed near the Rio Grande and the observed upward vertical head differences.

  The observed upward vertical head differences define neither the direction of the hydraulic gradient nor the direction of groundwater flow (see above).

  Analyses emphasizing the existence of both old and young waters in the vicinity of the Rio Grande and concluding that the Rio Grande is a regional discharge and mixing zone for both deep and shallow regional groundwater are inconclusive. These analyses have ignored the spatial location of the samples (shallow vs. deep portion of the aquifer), hydrodynamic properties (confined/unconfined) of the sampled hydrostratigraphic units, and the flow directions within these units (potential recharge and discharge zones). These analyses have also ignored the impact of medium heterogeneity; in general, the groundwater in the low permeability units should be much older than that in the high permeability units. These analyses have also ignored the possibility that 'old' waters can be associated with different mechanism of flow rather than the proposed deep flowpath from the Jemez Mountains (downward flow) to the Rio Grande (upward flow). For example, a deep flow under the Rio Grande of groundwater with Sangre de Cristo origin may exist, as proposed by Fraser Goff [*Goff*, 1991]. The old water can also originate from groundwater flow with Jemez origin which merges into the Rio Grande along southern-southeastern, predominantly horizontal flowpaths (without upward groundwater flow component).

- Theoretically, the upward flow can exist if and only if there is regional hydrogeological structure providing resistance for the flow to the south in the Cochiti Lake and/or the Albuquerque basin. Such a structure can be a low permeability zone or no-flow boundary obstructing completely the flow to the south. Another alternative is to have hydraulic-pressure buildup in the Albuquerque basin which prevents more water to be discharged from the Espanola basin.

- There are not any hydrogeological evidences that such a dominant and spatially extensive obstructive structure does exist. There is no hydraulic-pressure buildup in the Albuquerque basin; exactly the opposite it is true; the hydraulic pressures in the Albuquerque basin are much lower than the hydraulic pressures in the Espanola basin.

- The study of Fred Phillips [*Phillips, et al.*, 2004; *Phillips, et al.*, 2003] concludes that minor, if any, old ('deep') water flows into the Rio Grande within the Espanola basin and probably most of the deep Espanola basin water flows directly into the Albuquerque basin.

- The Albuquerque basin study by the USGS [*Plummer, et al.*, 2004; *Sanford, et al.*, 2004] (their model domain includes portions of the Espanola basin model) also concludes that there is southerly-bound deep groundwater flow from the Jemez Mountains (and the Sangre de Cristo Mountains) into the Albuquerque basin, and the flow is not obstructed by any hydrogeological structures.

- Further the Albuquerque basin study by the USGS [*Plummer, et al.*, 2004; *Sanford, et al.*, 2004] demonstrates that the deep portion of the Albuquerque basin is filled with groundwater recharged predominantly in the Jemez Mountains.

- Therefore the groundwater from the Espanola basin should be flowing without substantial resistance into the Albuquerque basin.

- Even if there is resistance for the flow to the south and substantial upward flow does exist in the vicinity of the Rio Grande, the discharge zone will form seepage faces along both sides of the river which will be observable on the ground surface (marshes, wet zones, springs; regarding springs see the discussion above). Such manifestations on the ground surface do not exit.

- Therefore the most probable conclusion is that the upward flow from the deep aquifer zones into the Rio Grande (and its alluvial aquifer) does not exist. Old groundwater with Jemez Mountains origin can be flowing into the Rio Grande along southern-southeastern predominantly horizontal flowpaths.

- It has been suggested that the existing consistency in the rates along the boundary between the Espanola and Albuquerque basins predicted by all the Espanola and Albuquerque basin models demonstrates the existence of the upward flow into the Rio Grande. This conclusion is made since all the Espanola basin models (USGS, LANL) 'predicted' that such an upward flow exists. This argument however is somewhat circular.

  In all the Espanola basin models (USGS, [*Hearne*, 1985; *McAda and Wasiolek*, 1988], LANL[*Keating, et al.*, 2005; *Keating, et al.*, 2003; *Vesselinov and Keating*, 2002]) the upward flow is an intrinsic assumption in the conceptual and/or numerical model development.

  All of the Espanola basin models developed so far are imposing obstruction for the groundwater flow to the south through the type of boundary conditions and the shape of lateral model boundaries. If there is no obstruction for the flow to the south, the same outflow rates can be still achieved using a different set of model parameters. However this will result in a different groundwater flow network within the Espanola basin, which will not comprise substantial upward discharge of deep groundwater into the Rio Grande (as the current models do).

  All the Espanola basin models developed so far force an upward flow towards the Rio Grande by the type of boundary conditions imposed on the top of the model domain and by the assumption of confined flow in the model. The top of the model is defined as a constant-flow boundary (predominantly with a zero rate, i.e. a no-flow boundary) everywhere accept at the river where a constant-head boundary is imposed. This model configuration also provokes an upward flow towards the river. If the top of the model is a 'material' boundary (i.e. follows the change in the water-table even if the flow is still assumed to be 'confined') and the river is represented by a generalized boundary condition of a third kind (which takes into account the imperfect hydraulic connection between the regional aquifer and the rivers), the model imposed requirements for an upward flow will not be as severe.

  Pumping tests at the alluvial aquifer along the Rio Grande have consistently demonstrated the imperfect hydraulic connection between the ground and surface waters. Therefore, the regional aquifer is not perfectly connected to the river as well. Imperfect hydraulic connections between the ground and surface waters are commonly observed in the hydrogeological literature and practice. These studies demonstrated that the rivers should be generally defined as a generalized boundary condition of a third kind.

  Also note that various studies of the Albuquerque basin by the USGS produced inconsistent flux estimates for the amount of water coming from the Espanola basin. The flux estimates vary over a wide range.

Confinement and subsidence:

- Subsidence of the land surface has been observed in the area around the Buckman wellfield.
- The land subsidence is undoubtedly due to the groundwater pumping.
- This type of subsidence according to Terzaghi's theory can be formed if and only if the pumped hydrostratigraphic units are confined (it is impossible for land subsidence to occur if the units are unconfined). It is also possible if and only if there are unconsolidated layers within the confined aquifer subject of pumping. The groundwater leakance (due to the pumping) that causes the subsidence can originate from the unconsolidated layers within a confined aquifer only. The subsidence cannot be caused by leakance from the confining, overlying and underlying, aquitards.
- These conditions define a typical 'confined aquifer-aquitard system' which is defined by a confined aquifer zone including low permeable/high storativity layers (aquitards/aquicludes; typically unconsolidated clays) that provide the leakance. The leakance is caused by slow water release from unconsolidated layers within the confined zone. It is also possible to have additional leakance caused by dewatering of the confining, overlying and underlying, aquitards ('leaky aquifer' mechanism). However the leakance from the overlying and underlying aquitards cannot cause the subsidence. Therefore the internal (within confined aquifer-aquitard system) leakance must exist.
- In the predevelopment conditions, the leakance out of the aquifer through the confining aquitards should be small enough (less than available recharge) to keep confining conditions in the confined aquifer-aquitard system for thousands of years since the system and the overlying rocks have been deposited. Equivalently, in post development conditions, the leakance into the confined aquifer-aquitard system through the confining aquitards can be expected to be equally small.
- Therefore, the aquifer pumped by the Buckman wellfield is confined including unconsolidated interlayers (confined aquifer-aquitard system). The springs are obviously disconnected from this confined system.

Cause for the flowing wells:

- Flowing wells have been observed in the vicinity of the Rio Grande.
- Some of the wells were used for water supply. The flowing conditions have recovered after the intensive pumping over the years has ceased.
- The mechanism for flowing wells in unconfined aquifers described by Freeze and Cherry ([*Freeze and Cherry*, 1979]; page 199, Figure 6.5.b) is valid only when the well is initially drilled. The flowing is a result of upward flow close to a discharge boundary. However, based on physics, after the well is drilled and when the groundwater flow system reaches a new steady-state condition, the well will cease to flow.

- Therefore, the recovery of flowing conditions after the pumping is ceased is theoretically impossible under unconfined conditions.

- Therefore, the aquifer pumped by the flowing (artesian) wells (e.g. the Los Alamos wellfield) is confined as well.

- The suggestion that the flowing wells are a result of potential upward flow close to a potential discharge boundary (in this case the Rio Grande) is inaccurate.

- The flowing wells should be called artesian.

Confined zone(s) in the Santa Fe Group

- The subsidence around Buckman continuously extends towards the Los Alamos wellfield (and locations of other deep artesian wells in the vicinity as well).

- Based on this and other hydrogeological considerations (screen depth, etc), the Buckman and Los Alamos wellfields are most probably pumping the same confined aquifer-aquitard system in the Santa Fe Group.

- Based on the layering of the Santa Fe Group, the most probable source of recharge for the confined aquifer-aquitard system in pre-development conditions is located to the east, in the Sangre de Cristo Mountain.

- This recharge mechanism for the Los Alamos wellfield was also suggested earlier by Fraser Goff [*Goff*, 1991].

Upward flow from the deep aquifer zones into the Rio Grande and its alluvial aquifer (continued):

- The very existence of a confined zone at depth prevents the existence of substantial upward flow of the deep water into the Rio Grande (and its alluvial aquifer).

Aquifer definitions: confined, leaky confined, semi-confined, unconfined, phreatic

- We must establish a more precise set of terminology for our current analysis and in the presentation of previous studies of the Espanola basin in order to avoid vagueness. One of the important reasons for miscommunication and difficulties to establish a general conceptual framework comes from the inconsistent use of terminology and/or inconclusive conclusions. Previous studies of the Espanola basin should be adjusted to use consistent terminology. For example, as I emphasize below 'leakance' can occur or appear to occur (without actually having 'leakance') in very different hydrodynamic settings, and all of these very different type of aquifers might be imprecisely called 'leaky'.

- Typically all the confined aquifers are NOT perfectly isolated by the overlying and underlying aquitards. The flow through the aquitards is called leakance, and the aquifers are generally defined as being leaky confined. If the leakance is substantial, it will be represented in the pumping test data as a temporal stabilization of drawdown; the aquifer will be called leaky. If the leakance is insubstantial, it will not be represented in the pumping test data, and the aquifer will be called confined. Regardless of whether the aquifer is 'confined' or 'leaky', there are possibilities for contaminant pathways through the aquitards. It is also important to note that pumping of either confined and leaky-confined aquifers can cause ground-surface subsidence.

- There is another mechanism that allows confined aquifers to appear to be leaky without being ‘leaky’ in the terms described above. This is when the ‘confined’ aquifer includes interlayers (aquitards, aquicludes) that provide the leakance within the pumped zone. This type of aquifer can be defined as a confined aquifer-aquitard system. The water is taken out of the interlayers by two mechanism (1) hydraulic pressure gradients and (2) ‘squeezing’ by the increasing of overburdening pressure (Terzaghi’s theory). The second mechanism is dominant. Pumping of this type of aquifer can cause substantial subsidence. This type of aquifer should NOT be called leaky confined. If substantial additional leakance through the overlying and underlying aquitards occurs, the aquifer should be called a leaky confined aquifer-aquitard system. However, typically the rate of leakance from interlayers can dominate the flow from the overlying and underlying aquitards and the two leakance mechanisms might be difficult to discriminate using pumping test data only.

- If a confined aquifer obtains a substantial amount of water from ‘leakance’, the pumping test estimate of specific storage can be very high, in the range for ‘unconfined’ aquifers.

- An aquifer can be also defined incorrectly as ‘leaky confined’ if the so called semi-confined conditions exist. In this case, the pumping is performed in an unconfined highly permeable layer which is overlaid by an unconfined lowly permeable layer. The response of short-time pumping test is similar to a typical leaky confined aquifer (even though the aquifer is not confined at all). However over the longer period of pumping, the water-table changes start to play a more and more dominant role and the aquifer behaves as a typical unconfined aquifer. The temporal stabilization of drawdown between those two regimes, early- and late-time) is caused by the ‘leakance’ between the two unconfined layers (not because of the delayed gravitational drainage of the unsaturated zone due to decline of the water table).

  This mechanism was suggested to exist in the aquifer subject to water-supply pumping by Cushman [*Cushman*, 1965]. However, all the arguments discussed above indicate that the aquifer subject to water-supply pumping is most probably not semi-confined. Theoretically pumping of semi-confined aquifers cannot cause any land subsidence. ‘Semi-confined’ conditions most probably exist close to the recharge boundaries where all the water-bearing zones are more or less unconfined (see below). Therefore, Cushman’s conclusions have to be taken with special care.

- Based on the pumping test data, an aquifer can be also defined incorrectly as ‘leaky confined’ if typical unconfined conditions exist. The typical type curves for unconfined aquifers show temporal stabilization of drawdown. This is a result of the delayed gravitational drainage of the unsaturated zone due to the decline of the water table during the pumping. It can be incorrectly interpreted as ‘leakance’. However, all the arguments discussed above indicate that the aquifer subject to water-supply pumping is most probably not unconfined. Theoretically pumping of unconfined aquifers cannot cause any land subsidence.

- Based on the pumping test data, an aquifer can be also defined incorrectly as ‘leaky confined’ if the three-dimensional cone of depression around the well hits a boundary of recharge (e.g. a ‘fixed head’ or ‘fixed flux’ boundary). The reaching of the recharge boundary will slow the rate of drawdown decline. Once the available recharge is ‘exhausted’ the rate of drawdown decline will increase again. The obtained drawdown curve will resemble 'leaky confined' conditions even though such conditions do not exist.

- <u>All of this demonstrates that special care should be taken in the interpretation of pumping tests suggesting 'leaky confined' or 'unconfined' conditions. The pumping tests can be inconclusive for definition of hydrodynamic conditions. The analysis of hydrodynamic properties of an aquifer should also include interpretation of impact due to long-term pumping records. In general, the hydrodynamic properties of an aquifer should be identified using a conceptual model framework that incorporates all the data and knowledge about the system.</u>

- Intensive pumping of a confined aquifer can cause substantial dewatering and the groundwater flow in close vicinity to the well to be under unconfined conditions (the top of the saturated zone does not extend any more to the bottom of the overlying aquitards). This will not be phreatic conditions since the new 'water-table' below the regional 'water-table' above will not be directly connected to the atmosphere and will not be subject to barometric pressure effects. Hydraulic and pneumatic separation is induced by the overlying aquitard. There will be two 'water-tables' one over the other. The pumping record might still suggest that the well is experiencing confined flow.

- <u>Phreatic zone</u> is the regional water-table zone below the unsaturated zone.

- <u>Perched zone</u> is separated from the regional phreatic zone by the vadose (unsaturated) zone.

- Phreatic zone can be mistakenly identified as a perched zone if there is an unsaturated zone below it due to intensive pumping at depth.

- Phreatic zone can be mistakenly identified as a perched zone if the hydrostratigraphic units below it do not appear to be fully saturated when intersected with a borehole only because of their low permeability properties.

- Identification of some of the perched zones as being 'confined' strongly suggests that these perched zones might be incorrectly identified portions of the regional aquifer system. By definition, perched zones cannot be confined.

- Substantial thickness (more than 100 m) of some of the perched zones also strongly suggests that these perched zones might be incorrectly identified portions of the regional aquifer system. It is difficult to imagine that under such a high hydraulic pressure, the underlying units will not be fully saturated.

- Therefore again the perched zones should be identified using a conceptual model framework which incorporates all the data and knowledge about the system.

Aquifer recharge:

- Spatial distribution of recharge has a complex structure influenced by various factors (spatial distribution of precipitation, surface runoff, geology, vegetation, etc.).

- The most comprehensive study of the spatial distribution of aquifer recharge from precipitation, perennial and ephemeral surface waters, and human-induced surface water discharges in the vicinity of LANL is conducted by Kwicklis et al. [*Kwicklis, et al.*, 2005].

- The area studied by Kwicklis et al. [*Kwicklis, et al.*, 2005] includes the western slopes of the Sierra de los Valles above LANL and the Pajarito Plateau; the area extends to the Rio Grande to the east. It excludes the central portion of the Sierra de los Valles (the caldera). It is unknown what portion if any of the recharge in the caldera flows to the east in the Espanola basin. Potentially most or all of the caldera recharge flows to the west in the Jemez river basin as suggested by Fraser Goff.

- The study of Kwicklis et al. [*Kwicklis, et al.*, 2005] ignores the temporal variations in the recharge. The recharge is estimated for hydraulic conditions circa 1999 (before the Cerro Grande fire, but incorporates the human-induced recharge post 1940's).

- The total amount of annually averaged recharge to the aquifer is on the order of 336 kg/s (8,600 (acre ft)/year). There is uncertainty associated with this estimate, which will be addressed in future studies by Kwicklis et al. [*Kwicklis, et al.*, 2005]

- The aquifer recharge occurs primarily in the Sierra de los Valles, to the west of and within the Pajarito Fault Zone (about 80% or ~ 270 kg/s), and annually averaged infiltration rates vary from 25 to 500 mm/a. This recharge component can be defined as 'mountain' or 'diffuse' recharge. The mountain aquifer recharge is predominantly from precipitation.

- Additional recharge occurs locally on the Pajarito Plateau accounting for about 20% of the total volume (~ 67 kg/s), and the annually averaged infiltration rates vary from 0 to 25 mm/a. This recharge component can be defined as 'local' recharge. The local recharge is from natural and artificial (human-induced) sources.

- A portion of the local recharge can be defined as 'canyon' or 'focused' because it is focused along canyons. According to the model of Kwicklis et al. [*Kwicklis, et al.*, 2005], the total canyon recharge is approximately 52 kg/s, or more than 3/4 of the local recharge.

- Still according to the model of Kwicklis et al. [*Kwicklis, et al.*, 2005], the total recharge through the mesas between the canyons is not negligible and is on the order of 15 kg/s, or less than 1/4 of the local recharge. This portion of local recharge can be defined as 'mesa' recharge.

- Temporal variation in the human-induced surface water discharges is substantial. Human-induced surface water discharges are a substantial portion of the local aquifer recharge. Some of the human-induced surface water discharges are also a major source for groundwater contamination.

- Temporal variations in the natural recharge also exist (pre-/post- Cerro Grande fire conditions, wet/dry climate cycles, global climate changes).

- Temporal variations in the aquifer recharge are important to consider and analyze.

Mechanism of mountain aquifer recharge:

- Mountain aquifer recharge is predominantly from precipitation.

- Geological features potentially facilitating the aquifer recharge are the Pajarito Fault zone, fracture systems and fractured rocks (the Tschicoma Formation) associated with the Jemez Volcanic Field.

- The existing fault and fracture systems and the lack of dominant lowly permeable layers (no sedimentary rocks) prevent the existence of a confined zone at depth.

- The water infiltrating to the aquifer and the induced elevated hydraulic heads due to recharge are potentially propagating in depth along the faults and fractured rocks.

- The zone of mountain aquifer recharge is potentially the zone where the pressures of the deep confined zones to the east are generated.

- The mountain aquifer recharge is also one of the potential sources of the water in the shallow phreatic zone of the regional aquifer to the east. However, the geochemistry of the shallow phreatic zone will be potentially dominated by the local recharge (see below).

Mechanism of local aquifer recharge:

- Local recharge is from natural (precipitation, perennial and temporal surface waters) and artificial (human-induced surface water discharges) sources.

- Human-induced surface water discharges made up a substantial portion of the local aquifer recharge. Human-induced surface water discharges are also a major source for groundwater contamination.

- There are numerous observations for existence of a regional water-table beneath the Pajarito Plateau.

- The water-table is predominantly observed in the Puye Formation.

- There are numerous observations of lowly permeable layers associated with the Puye Formation that reduce vertical penetration of the water and the hydraulic pressures associated with the local aquifer recharge.

- This allows for formation of an unconfined zone under water-table conditions, i.e. a phreatic zone, within the regional aquifer.

- According to existing theory, when the water associated with the local recharge reaches the water table (theoretically it is much more accurately to say ‘when the water reaches the full-saturation zone, which includes the capillary-fringe zone above the water table’), it will move laterally and will not cause pressure buildups. (The local recharge does not inject itself in the aquifer.)

- In our case (steep water-table) theoretically, the geometry of the water-table defines a contaminant flow path.

- The pressure buildups are possible <u>if and only if</u> there are dominant and spatially extensive hydrogeological features obstructing the lateral groundwater flow in the phreatic zone.

- There is not any hydrogeological evidence that such dominant and spatially extensive structures exist.

Local aquifer recharge and spring rates:

- Kwicklis et al. [*Kwicklis, et al.*, 2005] estimate that the local recharge (canyons/mesas) on the Pajarito Plateau is approximately 67 kg/s.

- Purtymun [*Purtymun*, 1995] estimate that the total annually averaged volume of aquifer discharge at springs in the vicinity of Rio Grande is approximately 60 kg/s.

- Both estimates suggest that there is consistency in the order of magnitude of these values (both estimates are uncertain, and therefore we do not expect more than order-of-magnitude consistency).

Confined zone(s) beneath the Pajarito Plateau

- The pumping test data and other hydrogeologic information (drilling logs, medium heterogeneity, barometric-pressure/tidal effects, etc.) suggest that the deep water-supply wells are taping confined zones beneath the Pajarito Plateau.

- The interpretation of pumping test data suggests also that some of the water comes from leakance caused most probably by flow from interlayers within the confining zones and/or through the confining, overlying/underlying, layers.

- To the best of our knowledge, land subsidence has not been observed on the Pajarito Plateau. However, even without surface manifestation compaction of the confined water-bearing formations due to intensive pumping could exist.

- The existence of shallow phreatic and deep confined zones suggests certain hydraulic separation between them, i.e. a confining zone.

- The thickness of the confining zone is expected to be spatially very variable. It can also be non-existing (hydrogeological windows) at some locations.

- Properties of hydraulic connection between the shallow phreatic zone and the deep confined zone are unknown. It can be expected that the properties are spatially very heterogeneous.

- Hydrogeological data and previous analyses suggest that hydraulic separation becomes more prominent spatially from west to east.

- A zone of generation of confining pressures can be traced to the possible recharge areas to the west along the flanks of Jemez Mountains and to the north along the Miocene trough defined by Purtymun.

- In contrast to the predominant discharge of the shallow phreatic zone along the Rio Grande, the deep confined zone should be discharging predominantly to the south (Albuquerque basin, Cochiti Lake; not along the Rio Grande).

- This defines different predominant flow directions for the shallow and deep aquifer zones.

Vertical downward flow beneath the Pajarito Plateau

- Along multi-screen wells, hydraulic heads tend to decrease with depth, and the vertical component of the head gradient ranges from 0 (horizontal) to 0.245 (downward).

- In general, the measured vertical components of the hydraulic gradient are greater than the horizontal components of the hydraulic gradient.

- However, the observed horizontal and vertical head differences define neither the direction of the hydraulic gradient nor the direction of groundwater flow (see above). This statement is for the case of a continuous groundwater flow system. If the groundwater flow system is discontinuous (e.g. there are impermeable layers between the locations of head observation), the interpretation that head differences between observation points represent direction of the hydraulic gradient and/or the direction of groundwater flow is even more erroneous. The observed medium heterogeneity at the scale of the vertical head measurement suggests that the discontinuous (compartmentalized) groundwater flow is much more likely to exist.

- The direction of the flow vectors can be expected to be predominantly dominated by the direction of highest permeability of the medium permeability tensor. This direction should coincide with the direction of the layering due to high anisotropy of the medium (large-scale permeability along the layering is about 10-1000 times higher than the large-scale permeability perpendicular to the layering).

- The observed magnitude of vertical components of the hydraulic gradients is caused by many factors. The major factors are high medium heterogeneity (compartmentalization) and anisotropy, the structure of the groundwater flow system (recharge at high elevation, discharge at low elevation, and resulting sloping water table), and intensive pumping in deeper portions of the aquifer.

- It is important to note that even if the medium is uniform and there is no pumping at depth, the sloping of the water table (as a result, sloping of flowpaths in the vicinity of the water table) is enough to cause the observed decline of hydraulic heads with depth. If the boreholes were slanted perpendicular to the sloping water-table there will be no head differences along the borehole (boreholes will be aligned with the slated equipotential lines). But since the boreholes are vertical, increased pressures with depth are observed that are consistent with the theory.

- As discussed above, the ‘local’ recharge cannot cause the observed vertical head differences. It can be possible if and only if there is pressure buildup due to hydrogeological structure obstructing lateral flow in the phreatic zone. As discussed above, such hydrogeological structures have not been observed.

- <u>Therefore most probably, there is not vertical downward flow beneath the Pajarito Plateau in the predevelopment conditions. In post-development conditions, the water-supply wells can be causing vertical flow in addition to other factors discussed above. Most probably, the ‘local’ recharge does not impact the observed vertical head differences.</u>

Potential fast contaminant flow paths to the White Rock Springs along the phreatic zone of the regional aquifer

- The top of the saturated zone is under water table conditions.
- The long-term monitoring (since 1950's) demonstrates minor changes in the water-table elevations; even more negligible are changes in the magnitude and direction of the "water-table" hydraulic gradients [*Koch and Rogers*, 2003; *Koch, et al.*, 2004].
- Due to natural structure of the groundwater flow, ambient hydraulic gradients in the "water-table" (phreatic) zone are substantial (i.e. slope of the water table is very high); on the order of 0.01 [*Koch and Rogers*, 2003; *Koch, et al.*, 2004].
- In addition, recent pumping tests also confirm that, the groundwater flow in the phreatic zone experiences a limited impact by the pumping of the water supply wells that are tapping deeper portions of the aquifer [*McLin*, 2005a; 2005b].
- Pumping test data also suggest pronounced hydraulic separation between the shallow (phreatic) and deep (pumped) portions of the regional aquifer [*McLin*, 2005a; 2005b].
- Contaminants, originating from the LANL sites, move through the unsaturated zone and reach the regional aquifer at the water table.
- By definition, the water-table is a contaminant flowpath, i.e. the physics requires that the contaminants reaching the water-table will move predominantly along the sloping water table.
- As discussed above, the springs along the White Rock canyon are potentially discharging water predominantly from the phreatic zone.
- As a result, there are potential fast contaminant flow paths along the phreatic zone with advective transport velocities on the order of 500 m/a and travel times from the LANL boundaries to the Rio Grande and the White Rock Springs on the order of decades [*Vesselinov*, 2004].

Conclusions

Conceptual models of the regional aquifer have evolved since the mid 1980's. Recent data and analyses, suggest an alternative conceptual model that includes two hydraulically separated zones. Both zones have different mechanism of recharge and discharge, different hydrodynamic properties of groundwater flow. The shallow zone is predominantly phreatic, recharged predominantly by local (mesa, canyon) recharge over the plateau, and discharges at the springs and the Rio Grande. The deep zone is predominantly confined, recharged predominantly in the mountain area and discharged to the south-southeast along the Rio Grande, the Cochiti Lake and the Albuquerque basin. There is no upward flow from the deep aquifer zones into the Rio Grande (and its alluvial aquifer). Old water originating within Jemez Mountains might be still flowing into the Rio Grande (and its alluvial aquifer system) along southern-southeastern, predominantly horizontal flowpaths.

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