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An alternative conceptual model of groundwater flow and transport in saturated zone beneath the Pajarito Plateau

Velimir V Vesselinov

INTRODUCTION

Presented here is a conceptual model of the regional aquifer beneath the LANL site that incorporates elements from earlier works by others [*Cushman*, 1965; *Griggs and Hem*, 1964; *Keating, et al.*, 2000; *Keating, et al.*, 2001; *Keating, et al.*, 1999; *Koch and Rogers*, 2003; *Koch, et al.*, 2004; *McLin*, 1996; , 2005a; 2005b; *Purtymun*, 1995; *Purtymun and Johansen*, 1974; *Theis and Conover*, 1962; *Vesselinov and Keating*, 2002]. The text below is an attempt to provide a comprehensive conceptualization of the regional groundwater-flow system and related uncertainties based on the available data and observations.

The saturated zone beneath the Pajarito Plateau is a complex aquifer system with hydrodynamic and hydrogeologic properties varying in three-dimensional space and time. The elements of the water balance, properties of the flow medium, and hydrodynamics of the system are discussed below. It is important to note that the site-scale aquifer beneath the Pajarito Plateau is a just a sub-portion of the basin-scale aquifer associated with the Española basin. The site-scale aquifer has dynamic hydraulic connection with the basin-scale aquifer. That is why some of the characteristics of the Española basin aquifer implicating the site-scale aquifer are discussed below as well.

RECHARGE

The most comprehensive study of the aquifer recharge from precipitation, perennial and temporal surface water along the canyons, and human-induced surface water discharges in the vicinity of LANL is conducted by Kwicklis et al. [*Kwicklis, et al.*, 2005]. The study area includes the western slopes of the Sierra de los Valles above LANL and the Pajarito Plateau; the area extends up to the Rio Grande to the east. The recharge is estimated for hydraulic conditions circa 1999 (before the Cerro Grande fire but incorporates the human-induced recharge post 1940's). Spatial distribution of recharge has a complex structure influenced by various factors (spatial distribution of precipitation, surface runoff, geology, vegetation, etc.). 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 estimated which will be addressed in future studies. 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. 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. The local recharge is from natural and artificial (human-induced) sources and can be defined as 'focused' because it is concentrated along canyons. 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.

DISCHARGE

In natural, pre-development conditions, part of the Pajarito aquifer recharge is captured by the regional discharge system for the Española basin which is the Rio Grande. However, spatial distribution of discharge along the river is unknown. Properties of hydraulic connection between the surface and subsurface waters are also unknown. Limited field test data and literature data for similar sites along the Rio Grande suggest that connection should be imperfect, i.e. impeded by low permeable zones associated with alluvial aquifer stretching along the Rio Grande (these low permeable zones are expected not only within the alluvial aquifer but also at the contact between the alluvial and regional aquifer; the low permeable zones can cause localized confinement of the water both in the alluvial and regional aquifers).

Stream flow data provide information on how much water the river has potentially gained from the regional aquifer in the vicinity of Pajarito Plateau in pre-development conditions, which is about 490 kg/s (annually averaged; 12,500 (acre ft)/year) [*Keating, et al.*, 1999]. The flux estimate is associated with uncertainty which can be considered to be higher than the uncertainty in the total recharge estimate referenced in the previous paragraph. The flux estimate includes spring discharges and spring-induced surface flow. The total annually averaged volume of aquifer discharge at springs in the vicinity of Rio Grande is on the order of 60 kg/s and is also uncertain [*Purtymun*, 1995]; springs rates have been relatively persistent without substantial annual variation. Springs occur along areas with lower ground-surface elevation, and based on the groundwater flow structure and hydrogeochemical data, the spring water can be expected to originate predominantly from the shallow portions of the aquifer.

Except for the spring discharges, it is unknown what portion of the groundwater gained by the river comes from western (Pajarito Plateau/Sierra de Los Valles), eastern (Pojoaque/Sangre de Cristo), and northern (Española) areas of the regional aquifer. The Española basin is asymmetric and has highly heterogeneous properties that do not support an assumption that the eastern and western margins of the basin have equal contribution to the river gain. Consequently, the divide separating groundwaters derived from eastern and western margins cannot be expected to be a straight vertical plane located exactly below the river. The topography (elevation) of the basin suggests that eastern margin of the basin (Sangre de Cristo) can be expected to contribute more recharge than the western margin (Jemez). However, if the flux estimates are accurate, the comparison of the discharge to the river (490 kg/s) and the recharge from the western margin (336 kg/s) proposes that the eastern margin potentially contributes much less (less than 1/4 of the river discharge along the stretch in the vicinity of the Pajarito Plateau) [*Kwicklis, et al.*, 2005]. This observation suggests that the potentially higher Sangre-de-Cristo recharge could be diverted into other portions of the Española basin and/or into neighboring basins to the east. Additionally or alternatively, some of the recharge accumulated along the western margin could be flowing to the south-southeast of the Pajarito Plateau through the deep portions of the regional aquifer. This deep southbound groundwater flow could be discharging into the Rio Grande downstream from the gage stations and/or into the Albuquerque basin to the south. Additional support for this conceptualization comes from a study by Phillips et al. [*Phillips, et al.*, 2004; *Phillips, et al.*, 2003]. Their analysis of hydrologic and geochemical data along the Upper and Middle Rio Grande basins concludes that very limited amount of deep circulation water is discharged at the Rio Grande within the Española basin. Third option is that the recharge from the western margin (336 kg/s) is overestimated and/or the discharge to the river (490 kg/s) is underestimated (which can be expected considering the high uncertainty in these estimates).

After groundwater pumping started in 1946, a portion of the discharge of the Pajarito aquifer occurs at water-supply wellfields: Los Alamos, Guaje, Pajarito, Otowi and Buckman. The total annually averaged pumping rate varies from 20 to up to 400 kg/s, and there is a consistent temporal trend of pumping rate increase (Figure 1). The pumped water can be produced by depleting aquifer storage, diminishing natural discharge to the river and springs, and inducing surface-water recharge. The data suggest that the system has not reached steady-state yet, but according to some studies the aquifer is close to steady-state (equilibrium). When the system reaches or gets closer to steady-state, the storage component will diminish and the pumped groundwater will be entirely supplied by the aquifer recharge. Recent stream flow data suggest that the section of the Rio Grande close the wellfields has changed from a gaining into a losing stream in the summer months when the pumping at the wellfields is most intensive. This demonstrates that the wellfields have already captured a substantial portion of the accessible natural discharge to the river and now they are inducing additional aquifer recharge from the river. Water pumped at the Buckman wellfield potentially originates from the west (the Pajarito Plateau), the Rio Grande, the east (encompassing infiltration recharge along the Sangre de Cristo range and induced recharge from the Pojoaque River) [*Vesselinov and Keating*, 2002]. Theis & Conover [*Theis and Conover*, 1962] suggested that the Los Alamos wellfield might be capturing waters with eastern origin as well.

It is important to note that the pumping rates vary on a temporal scale smaller that the annually averaged representation in Figure 1. The wells on the Plateau pump only for about 35 % of the time each year and there is a seasonal trend (most of the pumping is concentrated from May to July). There is partial head recovery between pumping periods observed at the water-supply and observation wells [*Koch and Rogers*, 2003; *Koch, et al.*, 2004]. As a result, of recovery, the impact of pumping on aquifer storage is delayed and reduced because a portion of the groundwater removed from storage in the pumping period is partially recovered by the natural aquifer recharge in the non-pumping period. The recovery also causes increased and faster impact of the pumping on the natural aquifer discharge to the river and springs. Alternative regime of continuous pumping without recovery will delay the recovery of the storage losses by the natural aquifer recharge until the pumping is completely ceased. This is the case for the Los Alamos wellfield which has already ceased pumping and the pre-development heads are almost completely recovered. Therefore, most of the water pumped by the wellfield through the years has been already provided by the natural discharge to the river. The head recovery due to variability and cessation of the pumping can also have important impact on the groundwater transport velocities in the vicinity of the wellfields.

STRUCTURE OF SATURARTED ZONE

The top of the saturated zone is predominantly phreatic and located about 300-400 m below the ground surface at the Pajarito Plateau. The thickness of unsaturated zone increases to the west of the Plateau and decreases toward the east close to the Rio Grande. The water table is observed for the most part in the Puye Formation. The total thickness of the regional aquifer is unknown. It can be assumed that at a minimum the aquifer encompasses the total thickness of the Basin fill. The Precambrian basement below might not have important impact on the groundwater flow in the shallower portion of the aquifer where we focus our study. If we ignore the basement, the total aquifer thickness varies approximately from 300 m at the basin edges to 2000 m in the central portions of the basin.

The aquifer is comprised of several sedimentary and volcanic hydrostratigraphic units. The sedimentary units predominantly comprise layers of varying thickness, lateral extent, and permeability. Relatively continuous horizontal zones of probably high permeability and low storativity are associated with coarse-grain materials of the Totavi Lentil (in the area between the LANL and the Rio Grande) and the Pumicious Puye. Lateral continuity of low- and high-permeability layers within the rest of sedimentary units cannot be mapped by the existing widely spaced boreholes. Therefore, the lateral continuity is unknown but it cannot be extended at the scale of the Pajarito Plateau. However, stacked and spatially offset low-permeability layers with even limited spatial extent can produce large-scale low vertical permeability zone. This zone can cause confining of the deeper portions of the aquifer. Horizontal large-scale low-permeability layers might be also associated with the contacts between hydrostratigraphic units (e.g. beneath Tb4 basalt flows, soil horizons with higher clay content have been observed). This type of heterogeneity suggests that the medium is strongly anisotropic at larger scales, with high permeability along the layering and low permeability perpendicular to the layering. The unaltered basalts have relatively high permeability, low porosity and low storativity, and the groundwater flow occurs primarily through open fractures. Clay-filled fractures of the altered basalts and low matrix permeability deem these volcanic units to be aquitards. There are sedimentary units between the basalt flows (interflow units) that are clay rich and have low permeability; they can additionally contribute to the regional confining of the deeper portions of the aquifer. The Pajarito Fault zone also may have an important impact on the groundwater flow and recharge distribution. Existing limited hydraulic head data suggest that the fault might be a barrier to groundwater flowing from west to east. This can cause some of the mountain block recharge to be diverted to the south and to the north rather than flowing to the west, toward the Pajarito Plateau. There might be other faults parallel to and east of the Pajarito Fault zone that might be impacting groundwater flow as well but there are no field data for their hydrogeological significance.

The groundwater flow medium as described above can be defined as a complex multi-aquifer-aquitard system. Equivalently, it can be defined as a single large-scale aquifer comprised by multiple small-scale layers/units with aquifer and aquitard properties. The small-scale 'aquifers' and 'aquitards' are associated with high and low permeability layers/units, respectively. As described above, the small-scale 'aquifers' and 'aquitards' have complex spatial distribution within the saturated zone and heterogeneous properties. This conceptual model also suggests some level of compartmentalization within the saturated zone.

For our description of hydrogeologic conditions under the Pajarito Plateau, it is important to emphasize the existence of two zones in the regional aquifer, shallow and deep, that are characterized by very distinctive hydrodynamic behavior based on the available field data. The shallow zone of the aquifer is under predominantly phreatic conditions, with relatively small thickness, having a good hydraulic connection with the unsaturated/perched zones above the regional water table. The shallow zone is a conduit of the local focused recharge occurring beneath the Pajarito Plateau and discharging under natural conditions at the river and the springs (even disregarding the expected uncertainty in the flux estimates, note the consistency between the total rate of local recharge, ~67 kg/s, and the total rate of the springs, ~60 kg/s). The deep zone is of relatively greater thickness and varies from unconfined to confined, generally from east to west. The deep zone is hydraulically connected to the area of mountain-block recharge to the west (Sierra de Los Valles/Pajarito Fault zone) which is also the area where the confined pressures originate. In natural conditions, the discharge of the deep zone waters into the river and springs can be expected to be limited due to the confinement.

To the west (Sierra de Los Valles/Pajarito Fault zone), where most of the recharge occurs, the saturated zone is phreatic with high water-table elevations (higher than the heads to the east). In this area, the deep and shallow aquifer zones must be hydraulically connected and both unconfined. This is required to allow the recharge and active confinement of the deep aquifer zones to the east. This mechanism is also allowed by the existing geologic structures (the Pajarito Fault zone, fracture systems and rocks (the Tschicoma Formation) associated with the Jemez Volcanic Field). To the east of Pajarito Fault zone, the shallow zone continues to be under phreatic conditions and is additionally recharged by local infiltration through the unsaturated zone beneath the Pajarito Plateau. In natural conditions, the local recharge is transported laterally in the shallow phreatic zone towards discharge areas to the east (Rio Grande, springs). However, the deep aquifer zone should be transitioning from unconfined to weakly-confined and to confined along the flowpath to the east of recharge zone. The deep hydraulic heads are distinctive (higher, due to the confinement, or lower, due to the pumping) from the water table elevation in the shallow zone. Close to the Rio Grande, the deep wells of Los Alamos and Buckman wellfields also become artesian (flowing with confined hydraulic heads higher than the ground surface).

Field tests suggest that the deeper portion of the aquifer appear to be leaky-confined during pumping (e.g. [*Cushman*, 1965; *McLin*, 2005a; 2005b; *Purtymun, et al.*, 1990; *Theis and Conover*, 1962]). This implies that the major deep water-producing units are confined, but during pumping they capture additional water. This additional water can be coming from (1) aquifer storage within low permeability/high storativity above zones above, below or within the production zones (leakage), (2) seepage from 'aquifers' above and below the production zones (including the shallow phreatic zone). Another mechanism that can mimic 'leakage effect' is the three-dimensional structure of the flow. The pump tests were interpreted assuming two-dimensional flow system and, therefore, the 'leakage' effects are probably overestimated due to the disregard of the flow three-dimensionality.

The presence of confined groundwater at depth requires existence of a confining zone. As discussed above, there are various hydrostratigraphic units that can provide this large-scale confinement. In the zone between the shallow phreatic and the deep confined zones, the groundwater can be also expected to gradually transition with depth from unconfined to weakly-confined and to confined hydrodynamic behavior (although, there are no field observations for the hydrodynamic properties of the transitioning zone).

There are no explicit field data defining spatial geometry of the shallow phreatic and the deep confined zones. The lateral extent and thickness of the zone separating the phreatic and the confined zones of the aquifer is also unknown. However, the separation (confining) zone should be horizontally large enough to propagate the high pressures accumulated in the recharge areas, and sufficiently low-permeable to preserve the confinement at depth. The thickness of the aquifer above the zone of confinement can be deduced by the depth of the water supply screens below the water table. The water-supply wells are confined but we do not know exactly at what depth the confined hydrostratigraphic units are present. The screen length of the water-supply wells on the Pajarito Plateau is in the range of 200 to 500 m, and the screen depths beneath the water table are on the order of 50-70 m. If we assume that a confined hydrostratigraphic unit occurs at the very top of the screen (which is confirmed by the limited hydrogeological information we have about some of the wells), the thickness of both the phreatic and transitioning (confining) zones is on the order of 50-70 m in the region of the Pajarito wellfields. The thickness should be decreasing to the east (closer to the river).

Large-scale confinement of the deep zone does not preclude leakage from the deep to shallow zones due to the higher pressures at depth in pre-development conditions and leakage from the shallow to the deep zones due to pumping in post-development conditions. This mechanism also allows the water-supply wells to capture some of the local recharge on the Pajarito Plateau. The field test data also suggest that the confining zone is heterogeneous, i.e. different portions of the aquifer are characterized with different leakage coefficients. Therefore it can be expected that the leakage might be occurring predominantly through spatially-limited areas beneath the Pajarito Plateau.

It is important to note that the intensive pumping at depth might be also causing the hydraulic disconnection of the saturated zone. For example, the perched zone observed in the vicinity of PM-3 could be (or could have been) a part of the regional phreatic zone.

The active connection between the confined deep zone of the aquifer and the areas of recharge is confirmed by relatively rapid recovery of the artesian conditions after pumping has been ceased in the Los Alamos wellfield. Therefore, the deep portion of the aquifer does not contain stagnant pressurized paleowater disconnected from modern recharge. Furthermore, this recovery mechanism is possible if and only if the deep portion of the aquifer is confined.

Existing flowing deep wells close to the Rio Grande can be caused only by the confinement. The other possibility of an unconfined aquifer with upward flow component close to the discharge boundary (Rio Grande) cannot cause these 'confinement' effects due to geometry of the flow system: substantial distances to recharge and discharge zones, relatively small aquifer thickness, and well screens extending over substantial portion of the aquifer thickness. Furthermore, the 'unconfined' scenario for the deep portion of the aquifer does contradict the observed recovery of flowing conditions after the pumping has been ceased.

An important demonstration of the separation between the upper and lower portions of the regional aquifer is the independence of the spring rates to the intensive pumping in their vicinity, particularly at the Buckman wellfield. If the aquifer was comprised of relatively uniform medium the substantial drawdowns at of the pressure heads due to the pumping would have substantially decreased or completely ceased the groundwater discharges at the springs. The spring rate independence to the heavy pumping also demonstrates that the substantial (major) portion of the groundwater discharged at the springs comes from the shallow portion of the aquifer while neglectable (minor) portion of the groundwater discharged at the springs comes from the deep portion of the aquifer.

It is important to note that the distribution of the mountain-block recharge between the shallow and deep zones is governed by unknown and potentially complex mechanism depending on many hydrogeologic factors. It can be anticipated that one of these factors would be the hydraulic head distribution in the shallow and deep zones to the east of the recharge zone. For example, intensive pumping the deeper portions can be expected to cause more mountain-block recharge to be captured by the deep aquifer zone. Alternatively, intensive local recharge can decrease the amount of mountain-block recharge transmitted through the shallow aquifer zone.

GROUNDWATER FLOW

The existing groundwater flow has a complex three-dimensional structure which is different from the classical basin-scale flow structure suggested by Toth [*Toth*, 1963] (cf. [*Freeze and Cherry*, 1979]). The shallow phreatic and the deep confined zones potentially have different flow directions and gradients. This is especially true for the central section of the aquifer, where pumping stresses are most focused. For example, the pumping test data demonstrate the limited and delayed impact of the pumping in the deep confined zone on the heads and flow directions in the shallow phreatic zone.

In pre- and post-development conditions, the general flow direction at the water table is from west to east. Large-scale flow directions can be surmised based on the hydraulic head gradient data and the anisotropy of the medium (flow and head-gradient vectors do not coincide in an anisotropic medium). At the water table, horizontal components of the hydraulic head gradient tend to have an easterly/southeasterly direction across the plateau and the gradients range from 0.0026 to 0.162. Generally, gradients are higher to the west and lower to the east.

It is important to note that the phreatic zone can yield contaminant path ways to the springs. In a simplified point of view, the phreatic zone can be also regarded as a regional 'perched' zone. The phreatic zone is predominantly within the Puye Fanglomerate and the Pumicious Puye. These units potentially include spatially continuous high-permeable zones. The structure of the Puye heterogeneities and the limited thickness of the phreatic zone can also potentially diminish the contaminant dilution. It has been already discussed that the groundwater flow in the phreatic zone is mostly impacted by the local recharge (which also transports the potential contaminants to the saturation zone) and is not that much impacted by the pumping in the deep portions of the aquifer.

There is not enough data to characterize pre- and post-development flow directions in the deeper portions of the aquifer. However, as discussed above the discharge of the deep zone waters into the Rio Grande is limited due to the observed confinement, and as a result the deep flow should be predominantly oriented to the south-southeast.

Along multi-screen wells, hydraulic heads tend to decrease with depth and the vertical component of the head gradient ranges from 0 (neutral) to 0.245 (downward). In general, the measured vertical components are greater than the horizontal components of the hydraulic gradients. Nevertheless, the flow vectors can be expected to predominantly coincide with the direction of the layering due to high anisotropy of the medium (10-1000 times higher large-scale permeability along the layering). The observed magnitude of vertical components of the hydraulic gradients is caused by many factors. The major factors are high medium heterogeneity 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.

We should note that the well screens used to measure the vertical head distribution target zones in the aquifer associated with relatively higher permeability and separated by zones with relatively lower permeability. In this sense, the head measurements could be much more representative for the local medium heterogeneity rather than the regional three-dimensional structure of the flow. The measured substantial head differences between adjacent high-permeability layers and the difficulty in tracing these layers laterally demonstrate strong small-scale heterogeneity of the aquifer both laterally and vertically (or certain level of compartmentalization as discussed above). The small-scale hydraulic head differences in a vertical direction are controlled by small-scale heterogeneity features that might not be important for the large-scale characterization of the medium properties and flow directions, but potentially extremely important for pathway analysis of potential contaminant transport.

CONCLUSION

This conceptual model has important implications related to:

- Impact of the Pajarito pumping on the groundwater recharge/discharge.

- Impact of the Pajarito pumping on the potential contaminant transport.
- Flow directions beneath the Pajarito (impacted by pumping, flow structure, local recharge, etc).
- Some of the perched zones might be incorrectly identified and might be part of the regional phreatic zone.
- Potential contaminant path ways to the springs through the phreatic zone of the regional aquifer.

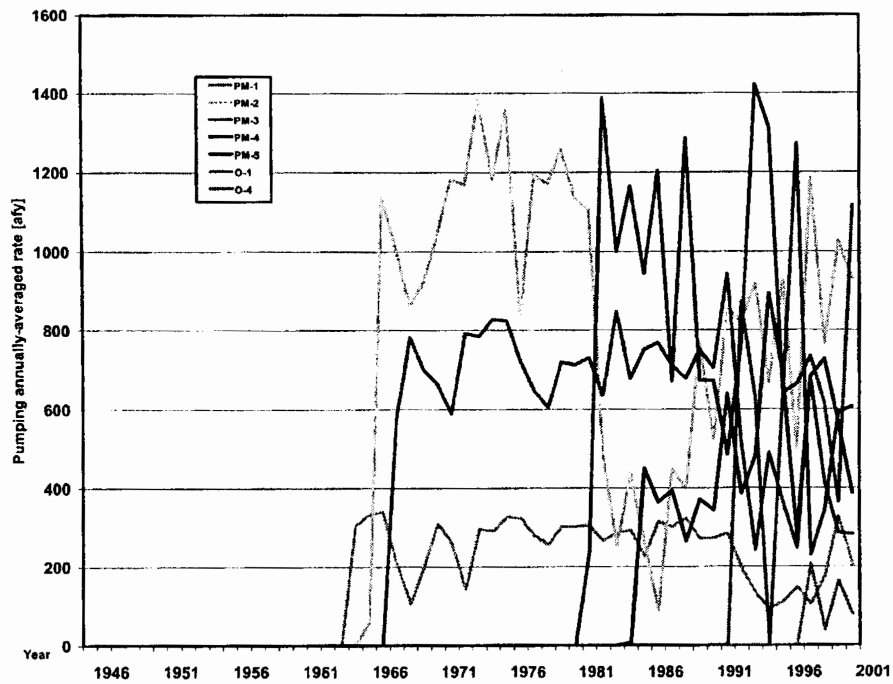

Figure 1: Annually averaged pumping rates [afy] of the wells in vicinity of the Mortandad canyon.

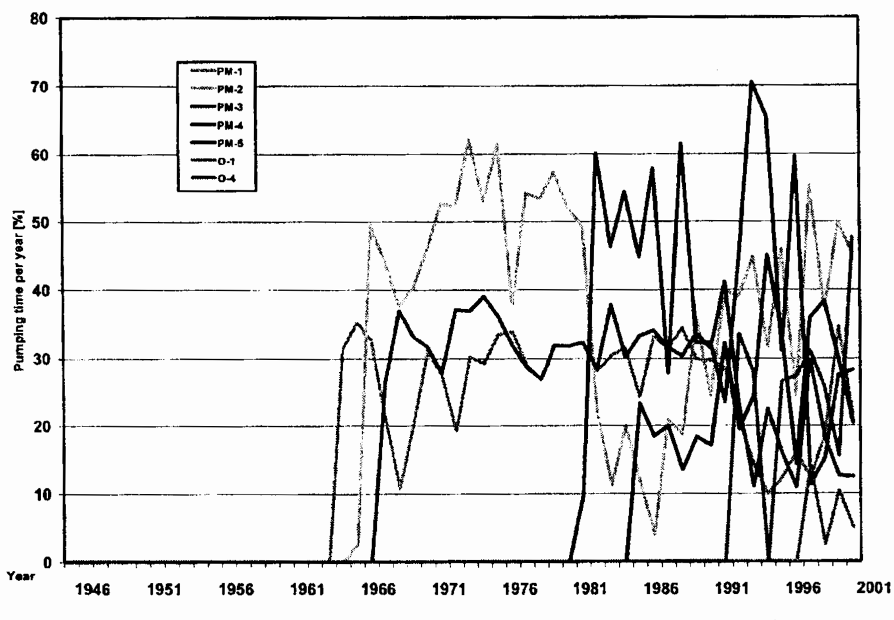

Figure 2: Percent of time the wells in vicinity of the Mortandad canyon were pumping each year. During non-pumping periods, the hydraulic heads at the wells have been recovering.

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