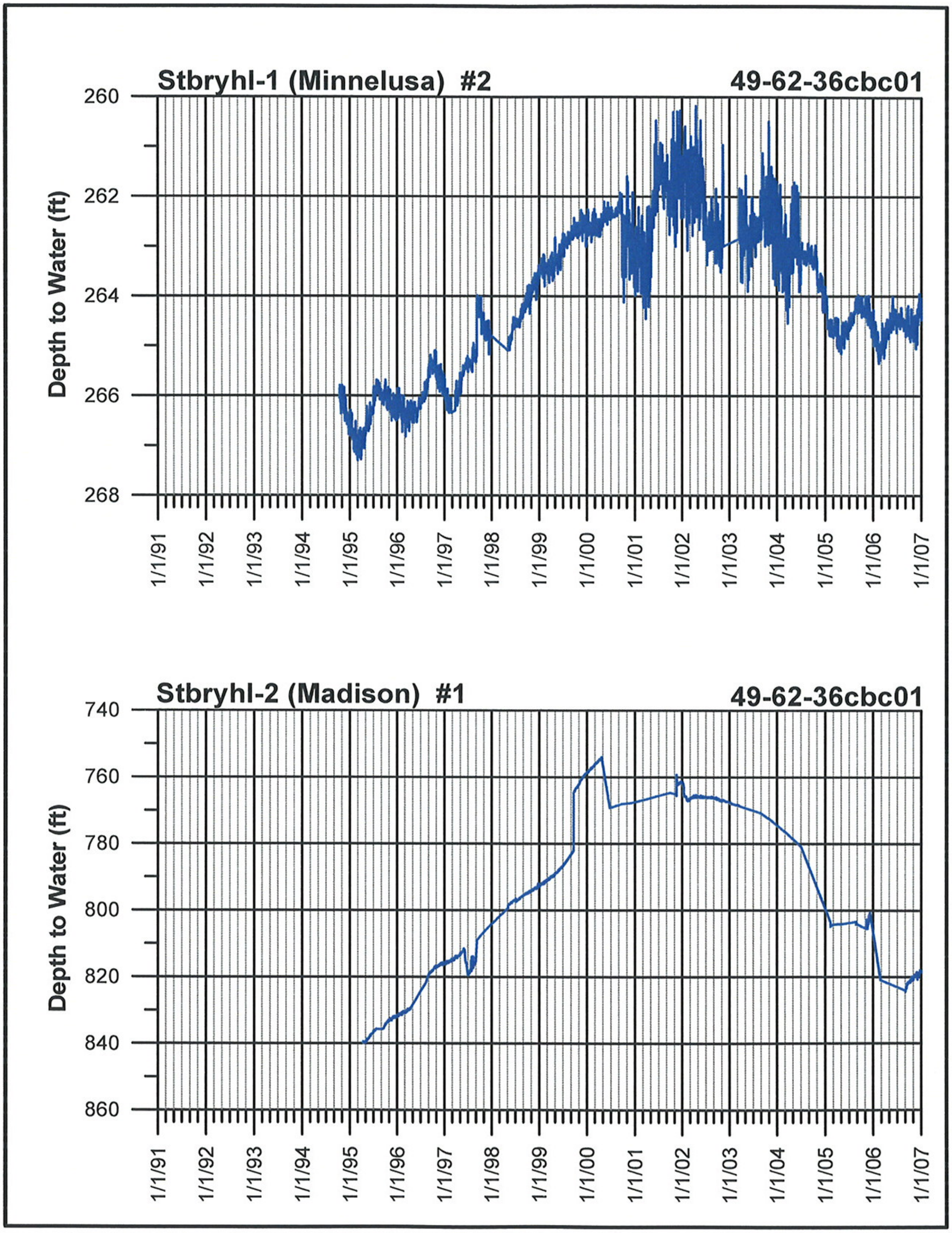
Figure 5-53
Minnelusa-Madison hydrographs at T49N, R62W, Section 36



5.9.5 Madison-Fort Union Hydrographs Compared

Figures 5-54a and 5-54b show hydrographs from the Madison aquifer monitoring wells compared to those from the Fort Union aquifer. The same set of Madison aquifer hydrographs is shown on both figures for comparison to the Fort Union aquifer hydrographs. The Fort Union aquifer hydrographs are arranged by the lines of section shown on Figure 5-46.

All of the hydrographs on Figures 5-54a and 5-54b have a vertical scale that can show 250 feet of groundwater level fluctuation. The range of 250 feet is large enough to include all but one or two of the Fort Union aquifer hydrographs that exceed 250 feet in fluctuation. In the latter cases, the vertical scale is adjusted so that the entire range of fluctuation for that specific hydrograph is shown. Otherwise, setting the range of the vertical axis on all of the hydrographs to 250 feet provides a one-to-one comparison between groundwater level fluctuations in the Fort Union aquifer and those in the Madison aquifer. The results of this comparison were presented previously in the discussion of the differences shown between the Fort Union aquifer and Madison aquifer characteristics in the opening part of this section of this report. As can be seen by a casual inspection of Figures 5-54a and 5-54b, the Fort Union aquifer hydrographs display a great deal more groundwater fluctuation than those for the Madison aquifer, for the various reasons previously discussed.

5.10 Production Well Hydrographs

An additional source of information about the long-term performance of the Fort Union, Lance/Fox Hills and Madison aquifers is static water level and pumping water level information collected by the City of Gillette over the years from the City's production wells. That information includes partial records of pumping rates. The City's records are presented as hydrographs of the Fort Union aquifer production wells starting with Figure 5-55.

Figure 5-54a
Comparison of Madison and Fort Union aquifer hydrographs

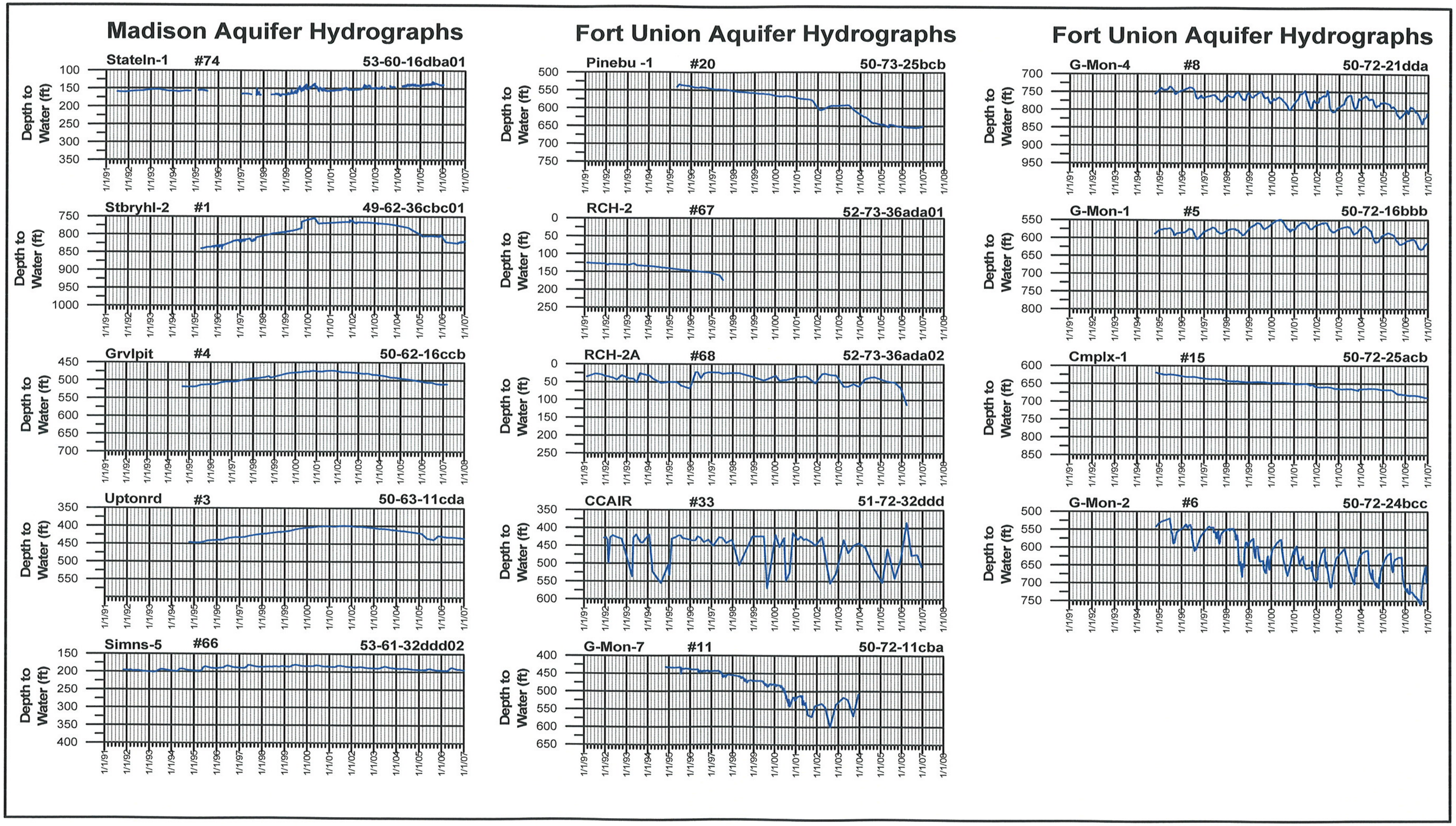


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Figure 5-54b
Comparison of Madison and Fort Union aquifer hydrographs

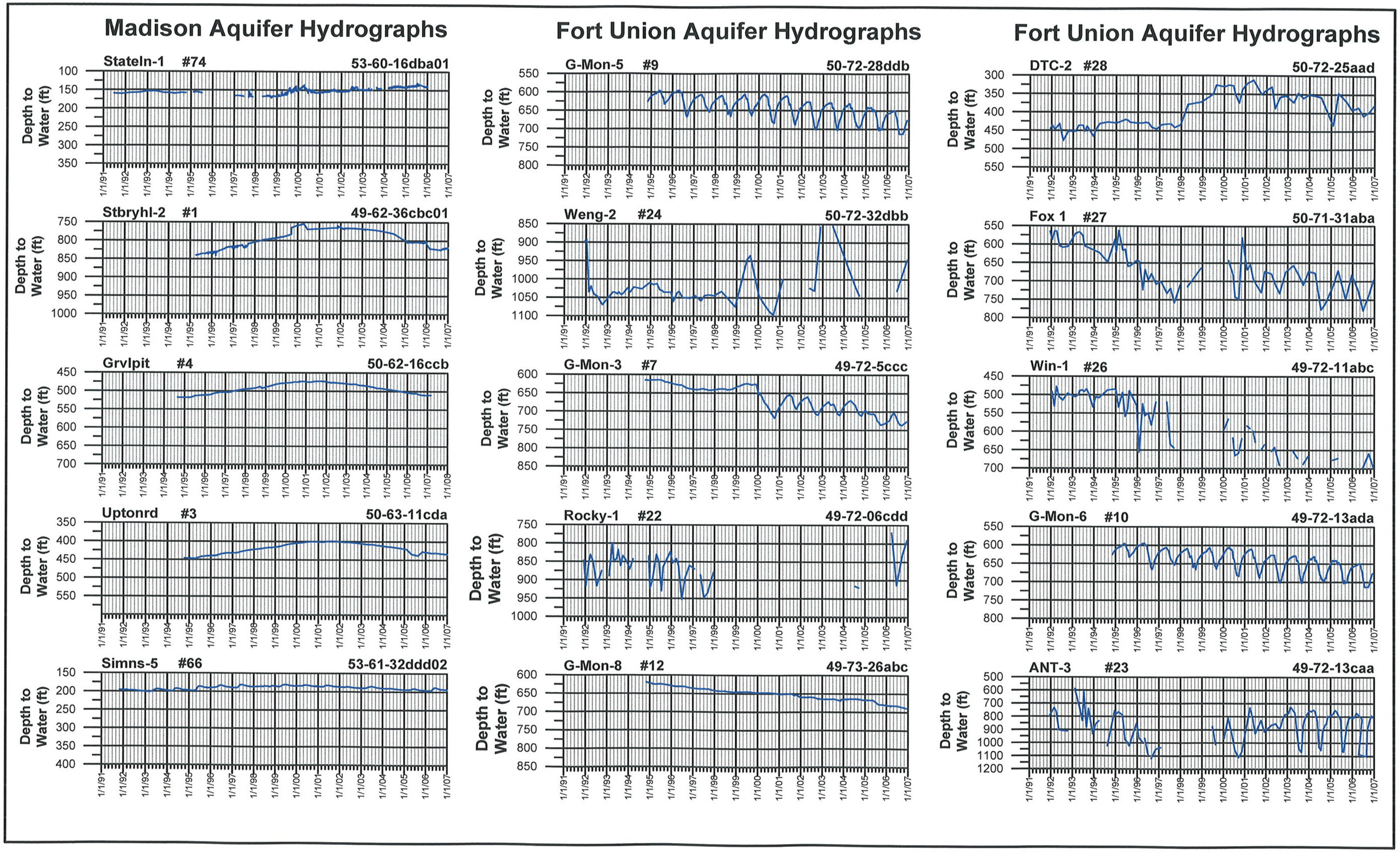


Figure 5-55
Hydrograph of Fort Union production well S-9

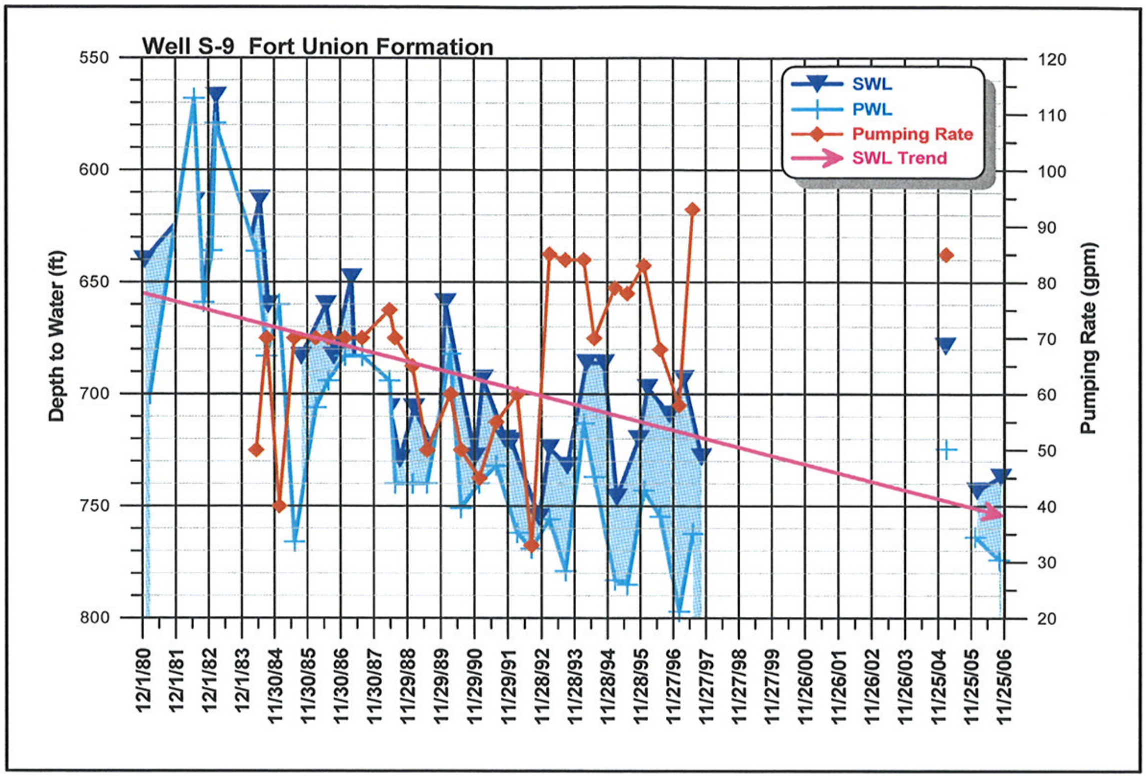


Figure 5-56
Hydrograph of Fort Union production well S-10

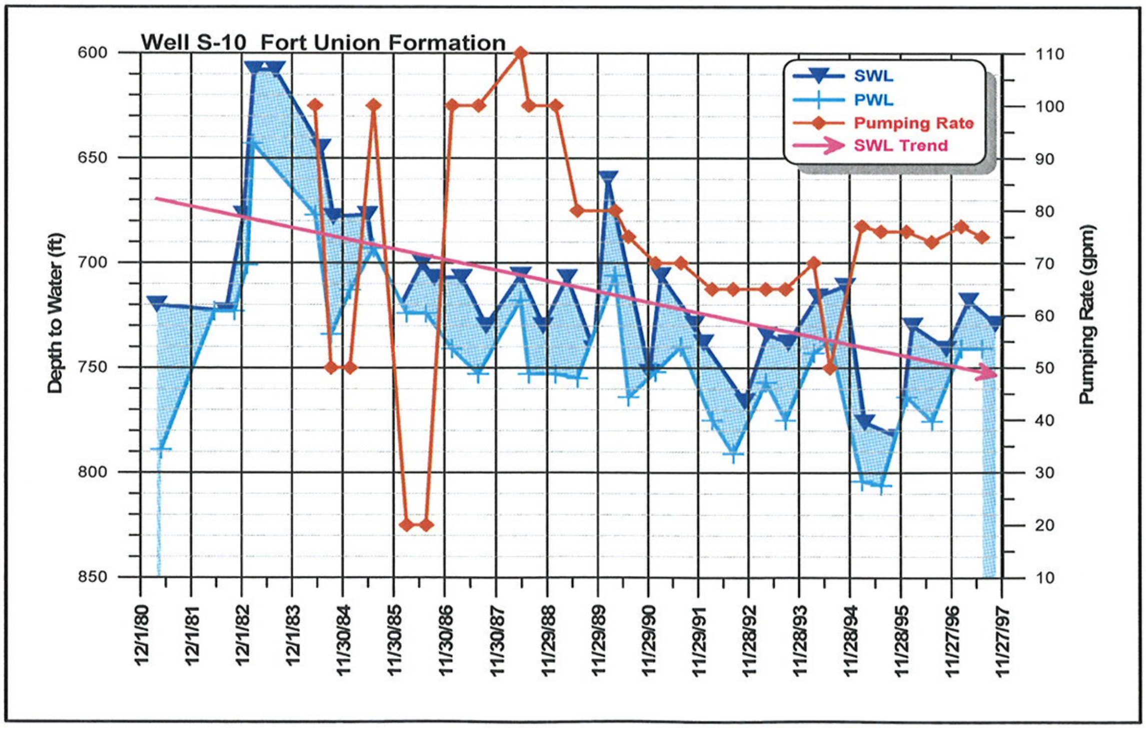


Figure 5-57
Hydrograph of Fort Union production well S-12

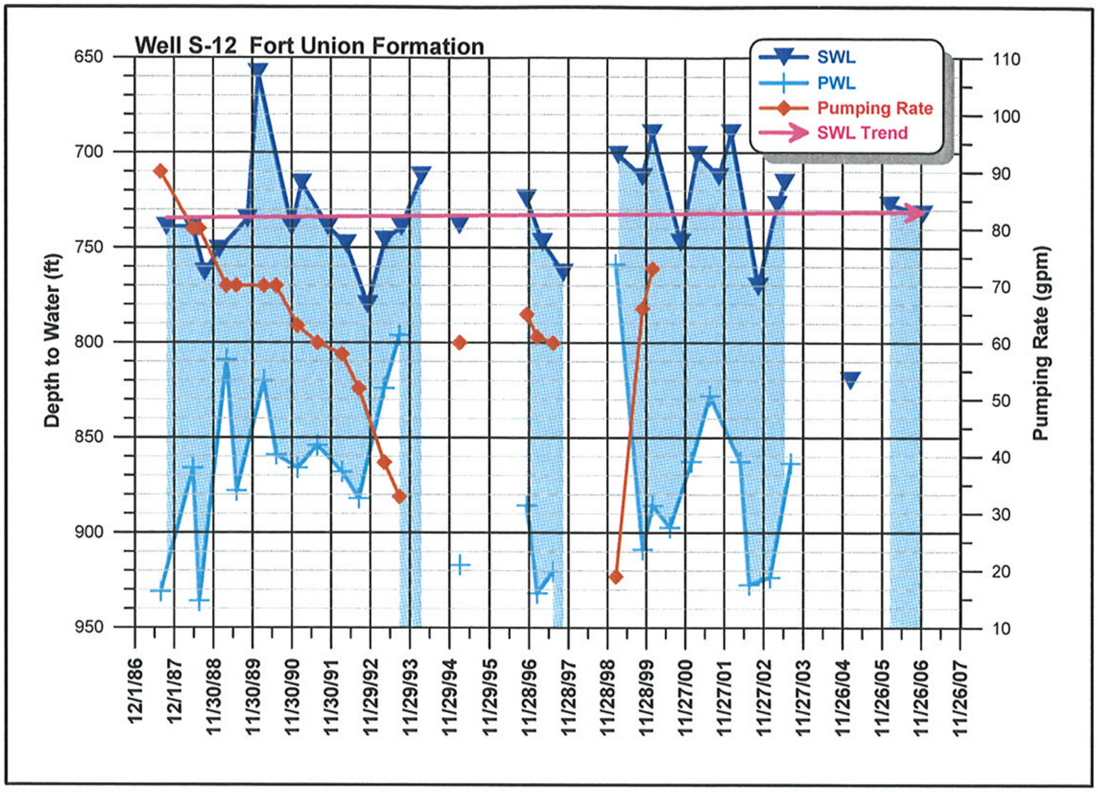


Figure 5-58
Hydrograph of Fort Union production well S-17

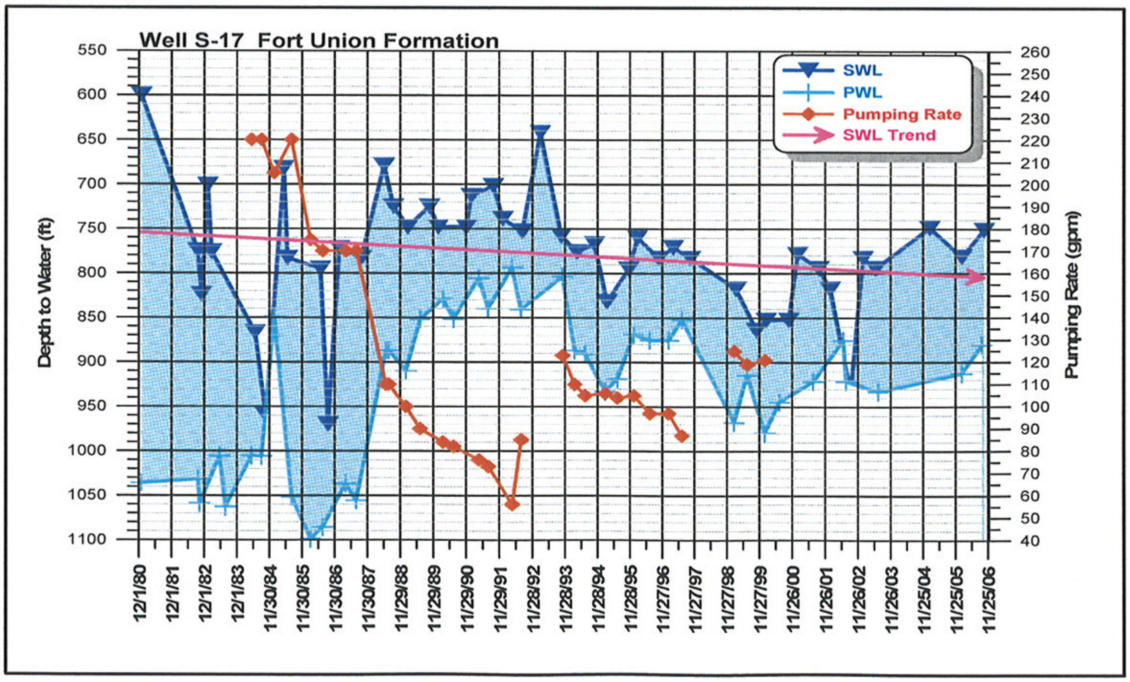


Figure 5-59
Hydrograph of Fort Union production well S-18

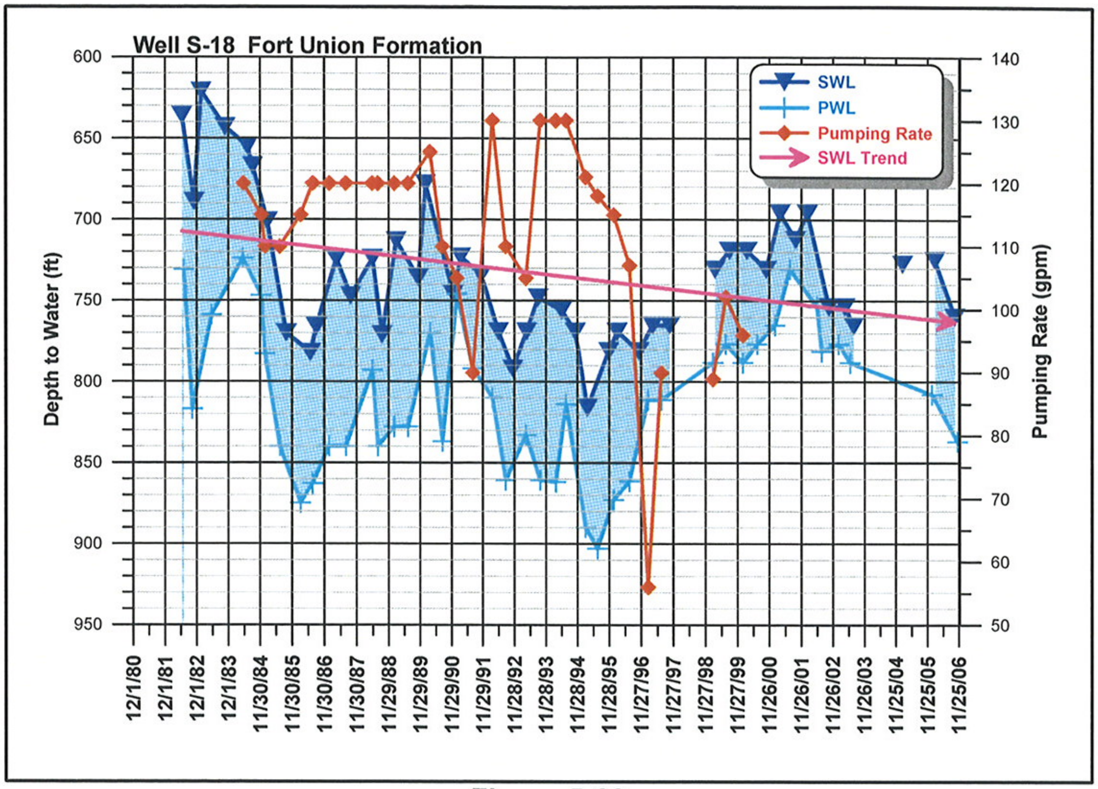


Figure 5-60
Hydrograph of Fort Union production well S-19

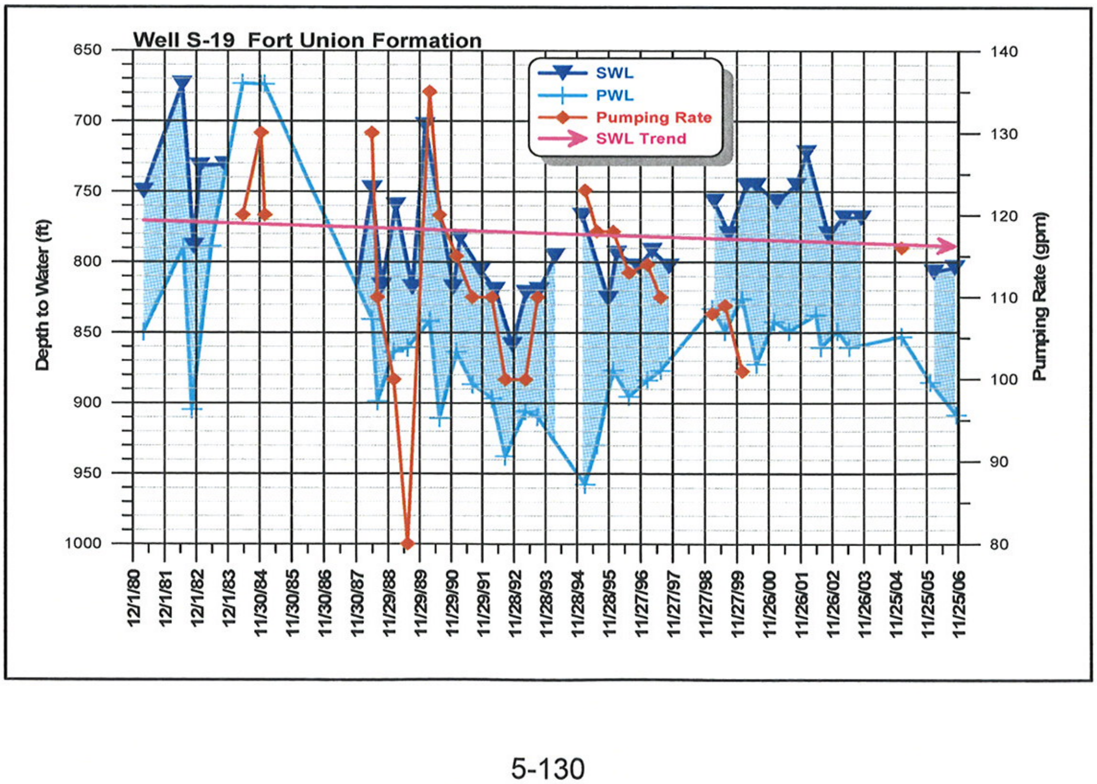


Figure 5-61
Hydrograph of Fort Union production well S-20

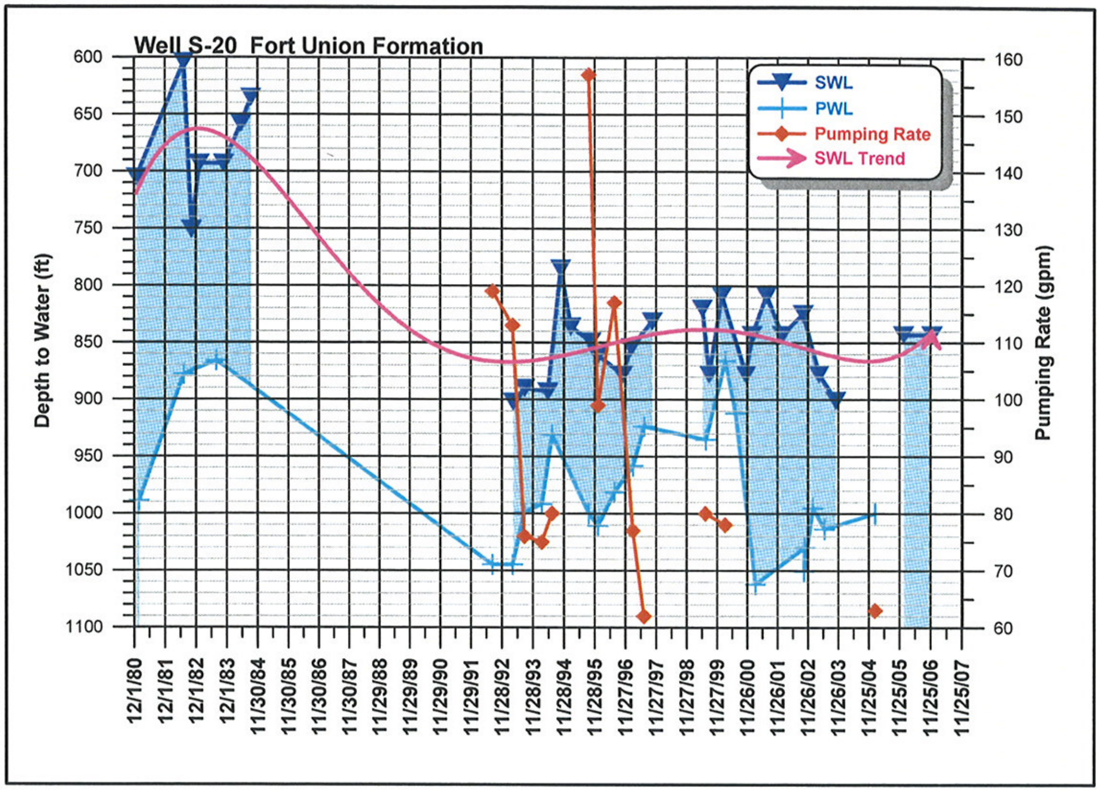


Figure 5-62
Hydrograph of Fort Union production well S-21

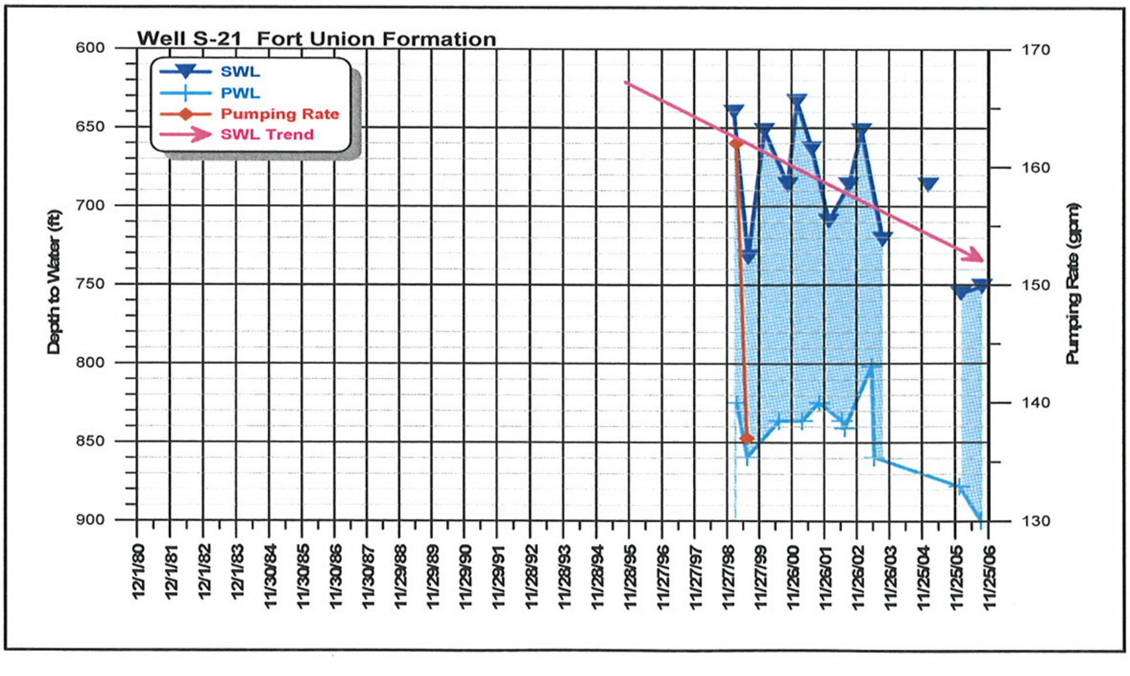


Figure 5-63
Hydrograph of Fort Union production well S-22

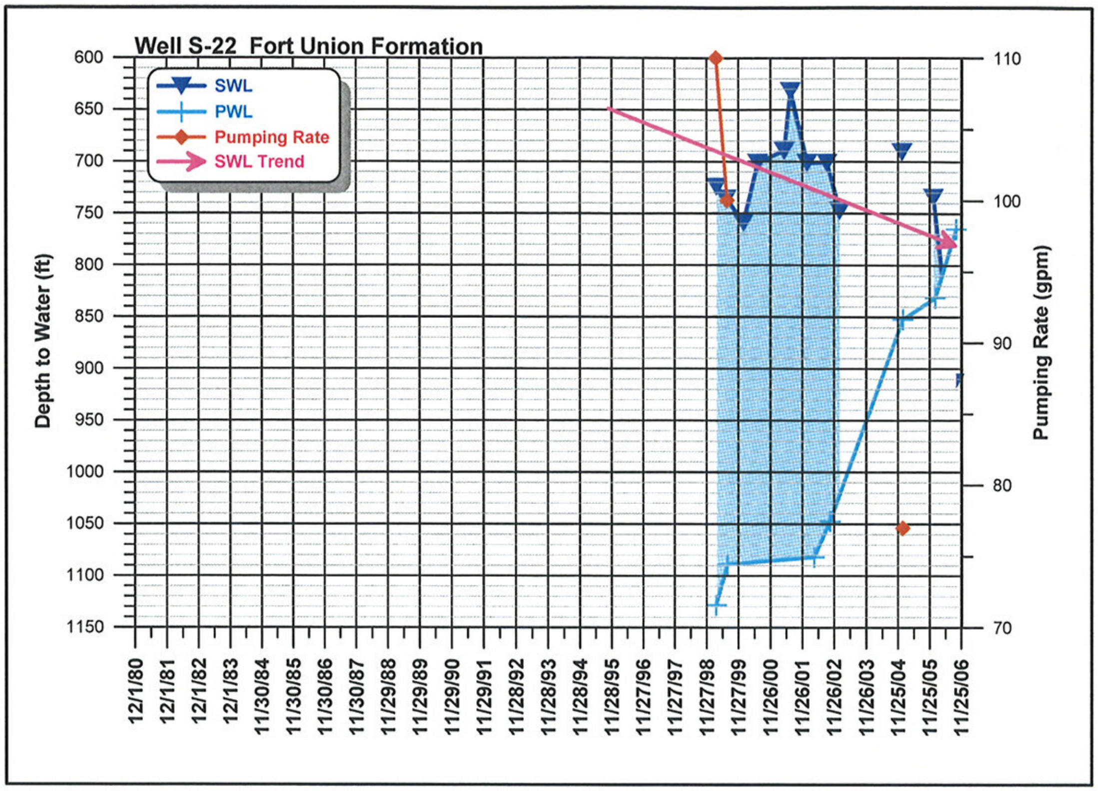


Figure 5-64
Hydrograph of Fort Union production well S-22

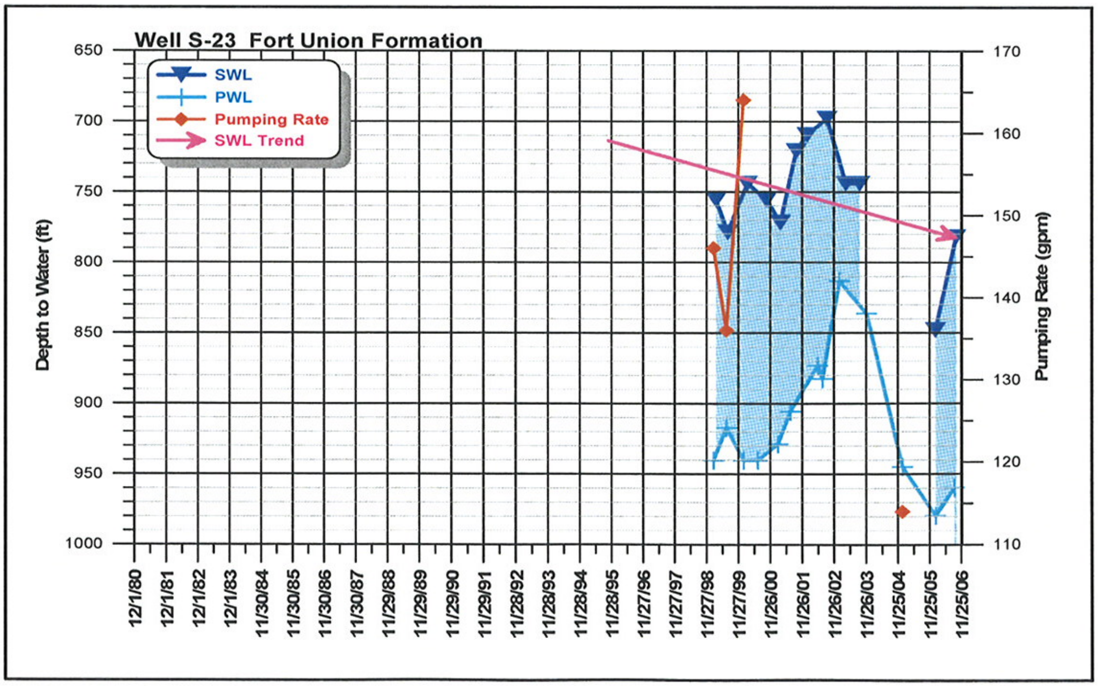


Figure 5-65
Hydrograph of Fort Union production well S-24

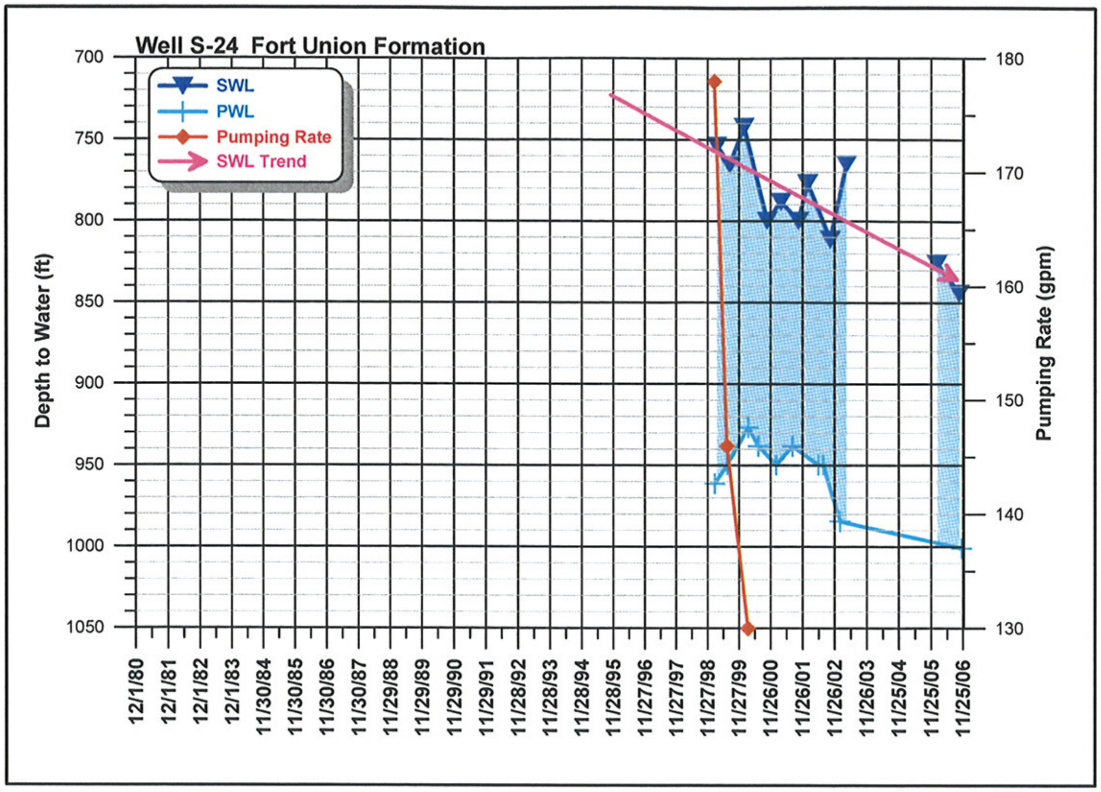


Figure 5-66
Hydrograph of Fort Union production well S-25

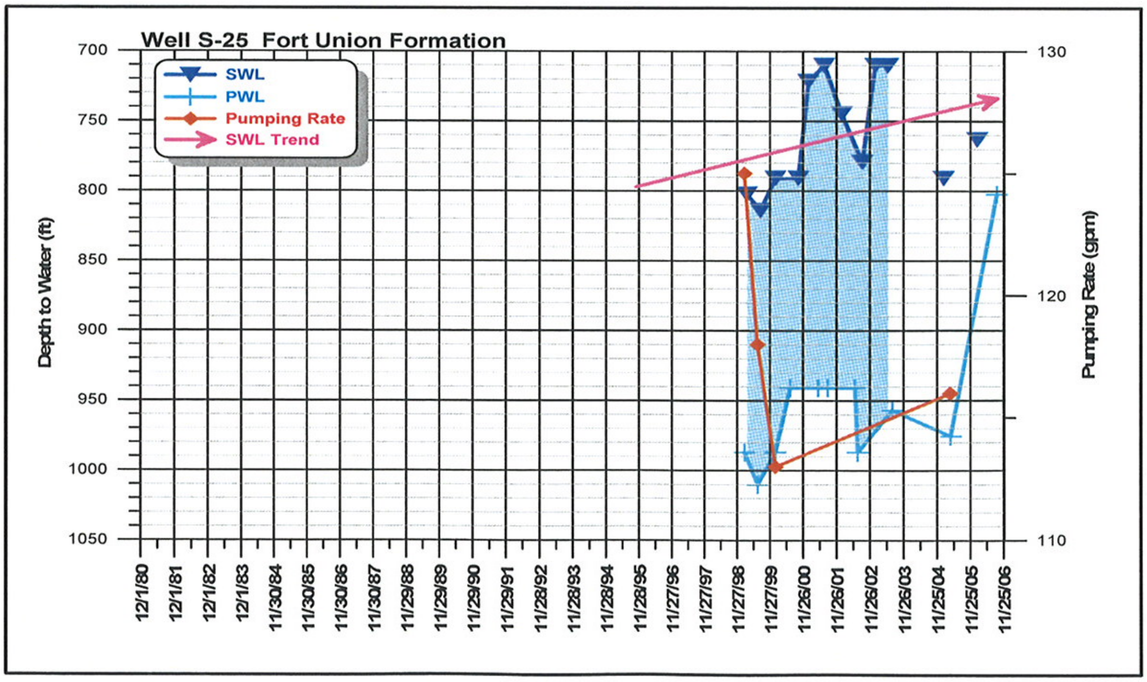


Figure 5-67
Hydrograph of Fort Union production well S-26

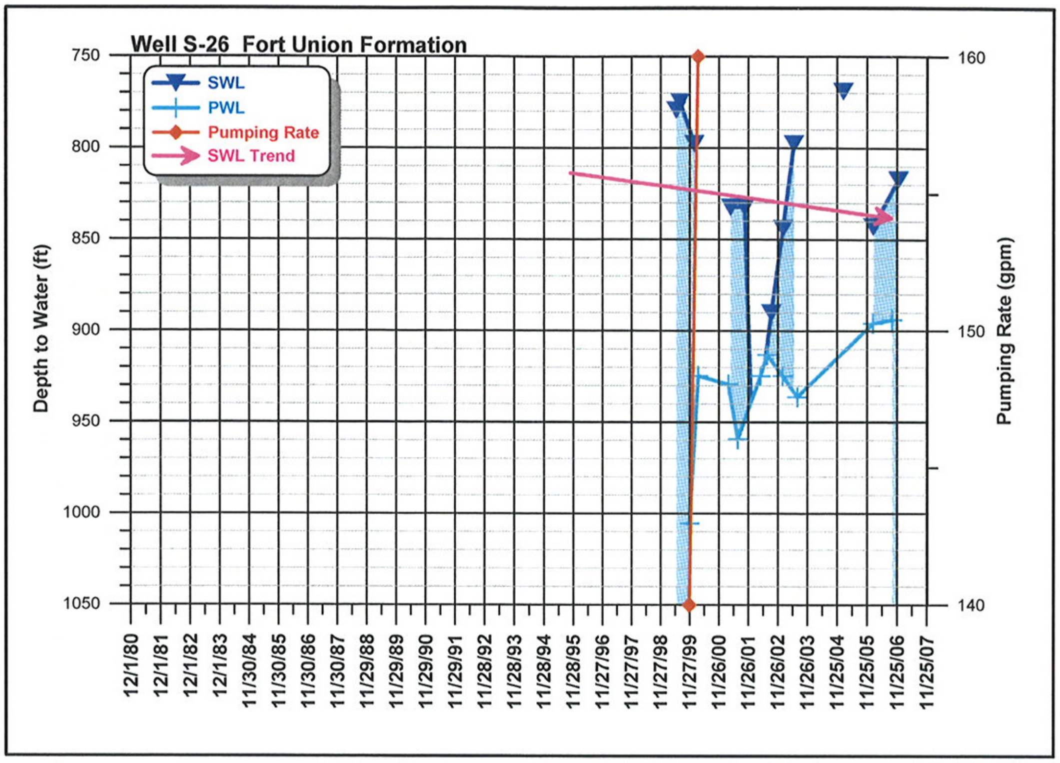
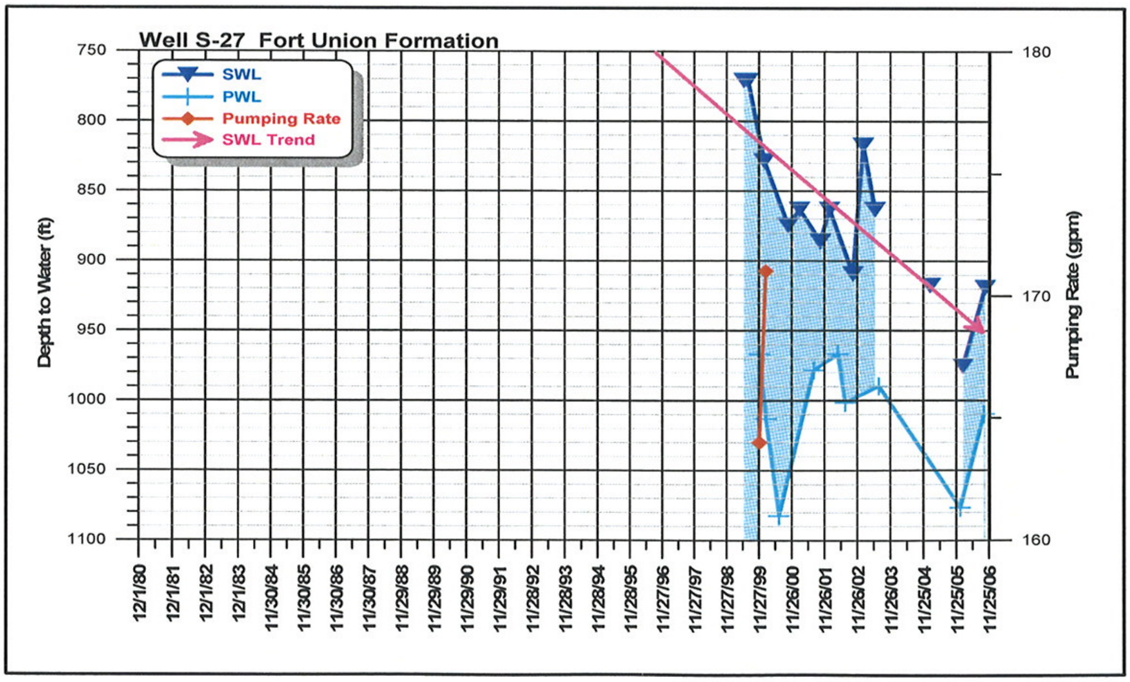


Figure 5-68
Hydrograph of Fort Union production well S-27



5.10.1 Fort Union Production Wells

The groundwater level declines in the Fort Union aquifer production wells are similar to those in the dedicated monitoring wells and, in fact, are the likely cause of the groundwater declines (and recovery in some cases) observed in the monitoring wells. The relationship between pumping rate is reasonably evident on the graphs, although the source data do not indicate pumping duration, a fact that obscures the relationship between pumping and groundwater fluctuations in some cases. Other complicating factors include the condition of the pumping equipment. In some cases, the pumping rates shown on the graphs are a function of pump condition, not potential well yield or well use.

Similarly, some Fort Union wells that were used regularly in the early part of the hydrograph were limited to use only when the Madison well field was in use and the Fort Union aquifer water could be blended with Madison aquifer water to control fluoride concentrations. Accordingly, the trends and patterns of the hydrographs for the latter wells change when the frequency of well use changed after the Madison well field was completed in 1980. The City of Gillette did not begin recording groundwater levels until the Madison well field was under construction or completed, so the groundwater trends antecedent to the Madison well field are not recorded; however, the results of putting the Madison well field into service are evident on a number of the Fort Union well hydrographs that exhibit rising groundwater levels in 1980 through 1983 or very high groundwater levels in that same period of time. The rising or high groundwater levels reflect the reduction in use of the Fort Union wells after the Madison wells were put into service.

Wells S-21 and above were constructed and put into service in the late 1990's. In all but one instance, they show rapidly declining groundwater levels after they were put into service. These latter hydrographs are examples of the response of the Fort Union aquifer to pumping abstractions without the influence of a prior history of pumping and changes in pumping patterns in the well. The one example with rising groundwater levels is probably related to taking other nearby wells out of service.

5.10.2 Fox Hills Production Wells

The Lance/Fox Hills production wells, Figures 5-69 to 5-73, provide relatively high pumping rates. Despite their largely intermittent use only when their production can be blended with water of better quality, the hydrographs shown on-going groundwater level decline in the production wells, except for the relatively new FH-5 well.

5.10.3 Madison Production Wells

Hydrographs of the Madison aquifer production wells operated by the City of Gillette are shown on Figures 5-74 through 5-83. Hydrographs from wells M-1 and M-2 exhibit long-term groundwater level declines. These wells are wells with radial flow produced to the wells from porous rock and likely have generated localized long-term drawdown in the aquifer although the drawdown is not very much if the component of natural groundwater fluctuation in the aquifer is taken into account.

The hydrograph from well M-3 exhibits a dramatic change in pumping water levels after it was hydraulically fractured in 1992. The trend in groundwater levels in this well prior to hydraulic fracturing was downward, during a period of rising groundwater levels on the regional hydrographs. The trend in groundwater levels in the well after hydraulic fracturing was upward, during a period of groundwater recession on the regional hydrographs for the Madison aquifer. This demonstrates that prior to hydraulic fracturing, long-term drawdown was being created by the use of this well even though water levels were rising in the Madison aquifer throughout the region. It also demonstrates that after the hydraulic fracturing treatment, the vertical leakage into the high-transmissivity parts of the aquifer offset the effects of pumping at this well, including drawdown antecedent to fracturing, causing the drawdown around the well to recovery even though regional groundwater levels in the aquifer were in recession.

The hydrographs show that the Madison production wells in hydraulic communication with the large, highly transmissive fractures in the limestone, wells M-2, M-4, M-3 (after hydraulic fracturing) and the 1,400-gpm wells M-9 and M-10, exhibit less than

Figure 5-69
Hydrograph of Fox Hills production well FH-1

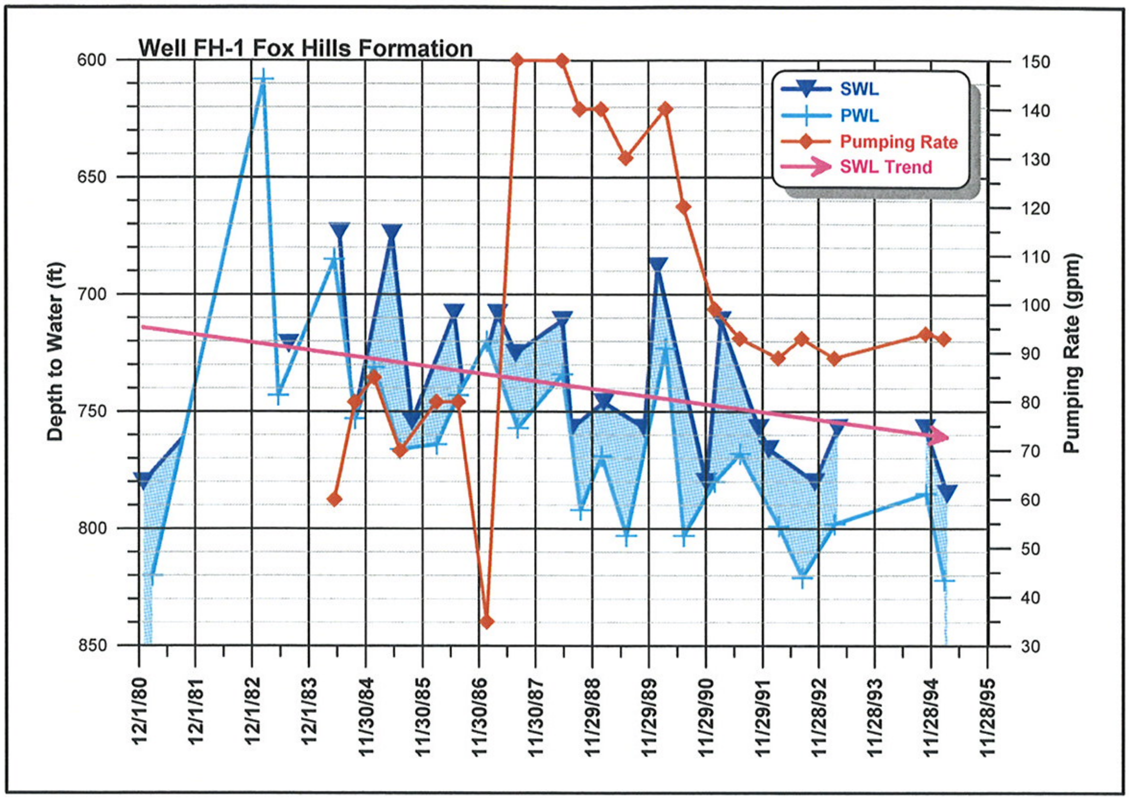


Figure 5-70
Hydrograph of Fox Hills production well FH-2

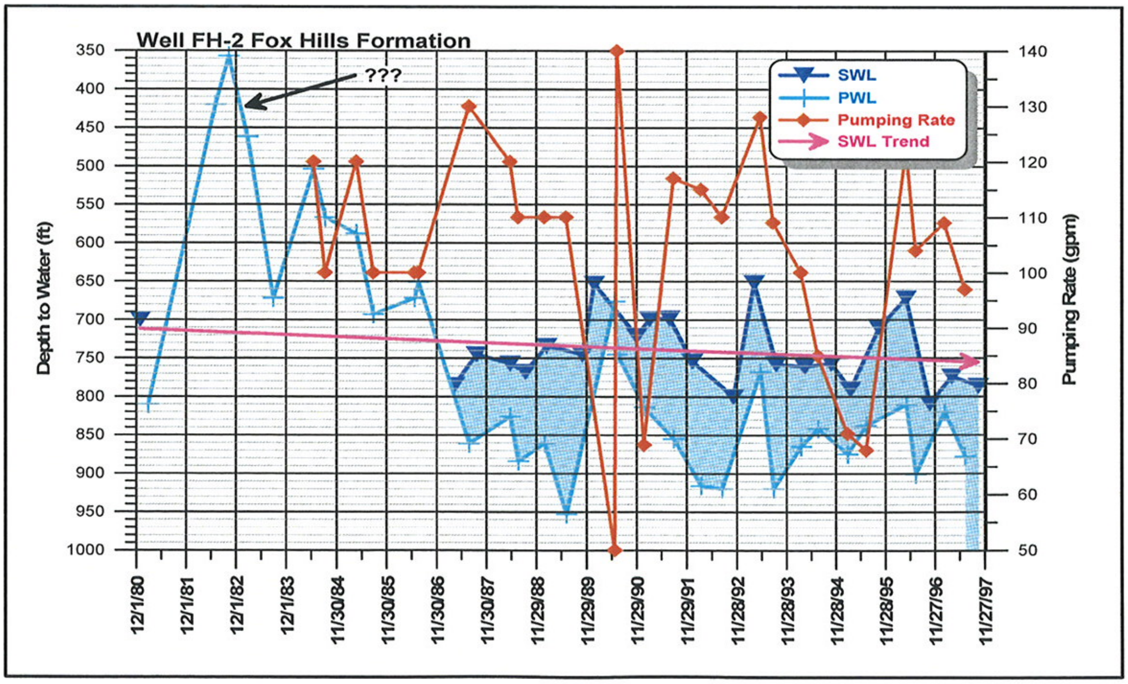


Figure 5-71
Hydrograph of Fox Hills production well FH-3

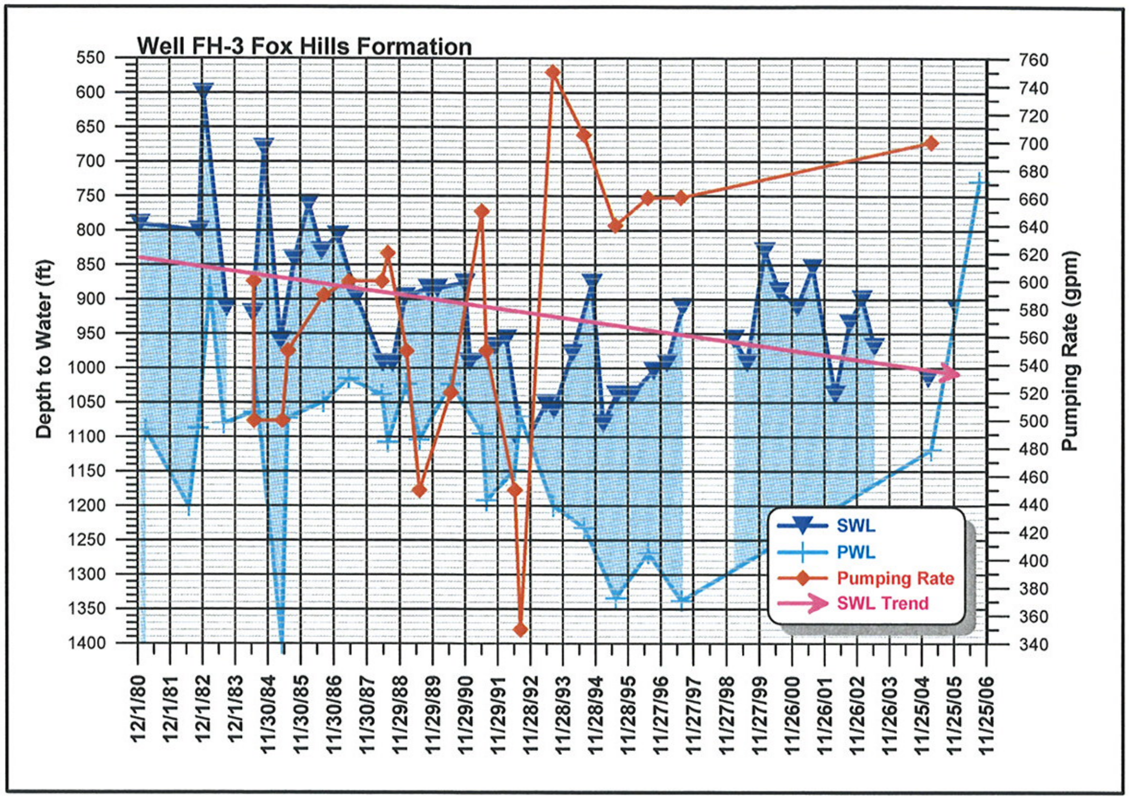


Figure 5-72
Hydrograph of Fox Hills production well FH-4

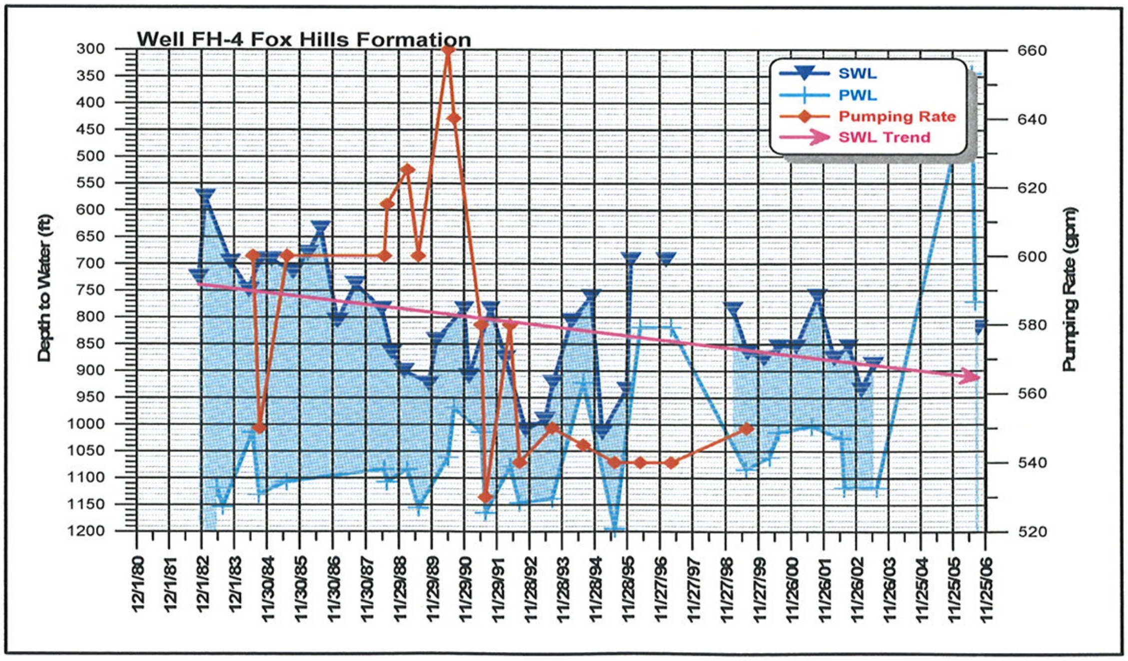


Figure 5-73
Hydrograph of Fox Hills production well FH-5

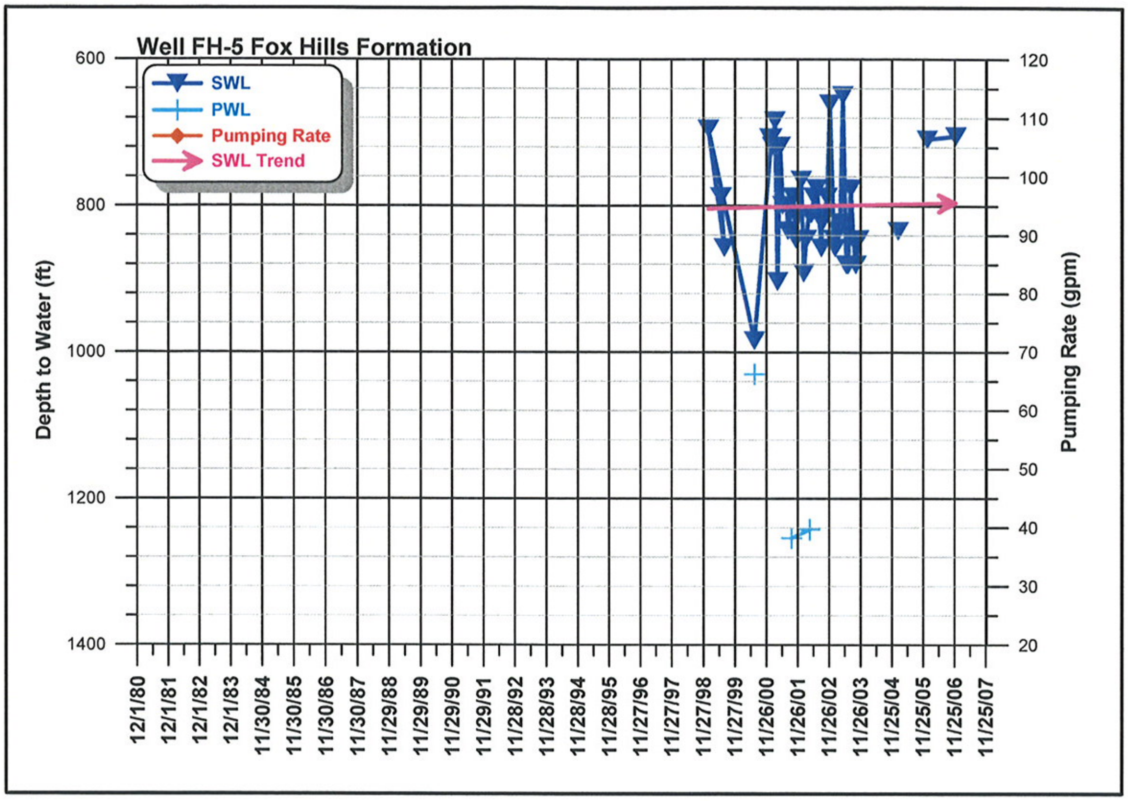


Figure 5-74
Hydrograph of Madison production well M-1

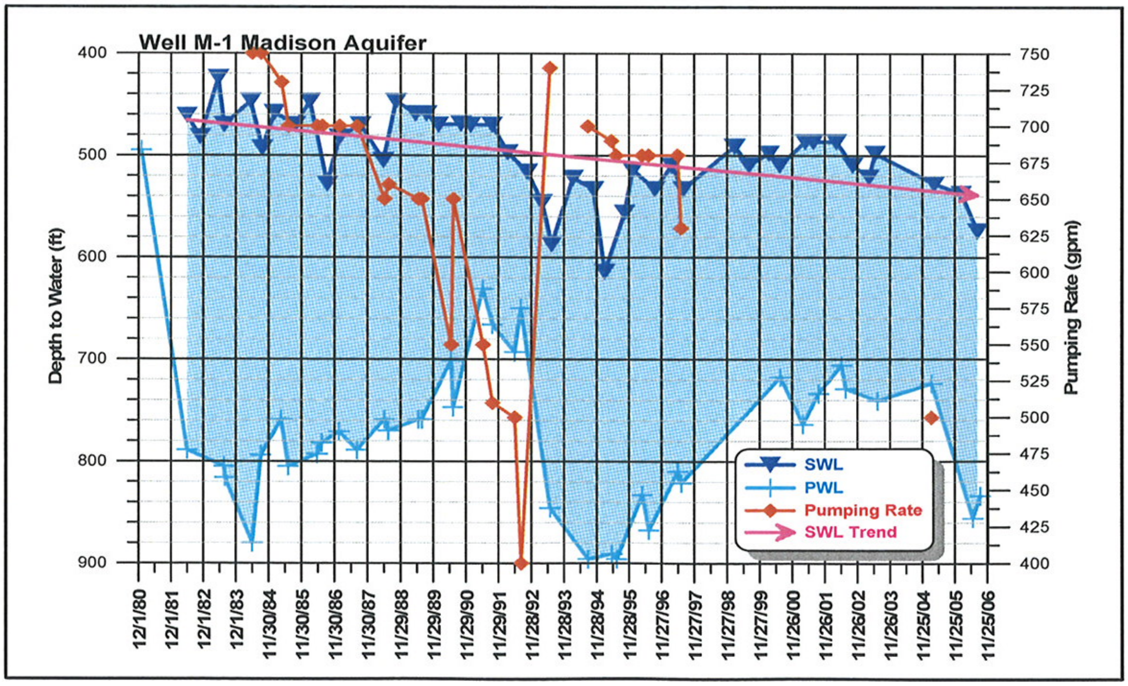


Figure 5-75
Hydrograph of Madison production well M-2

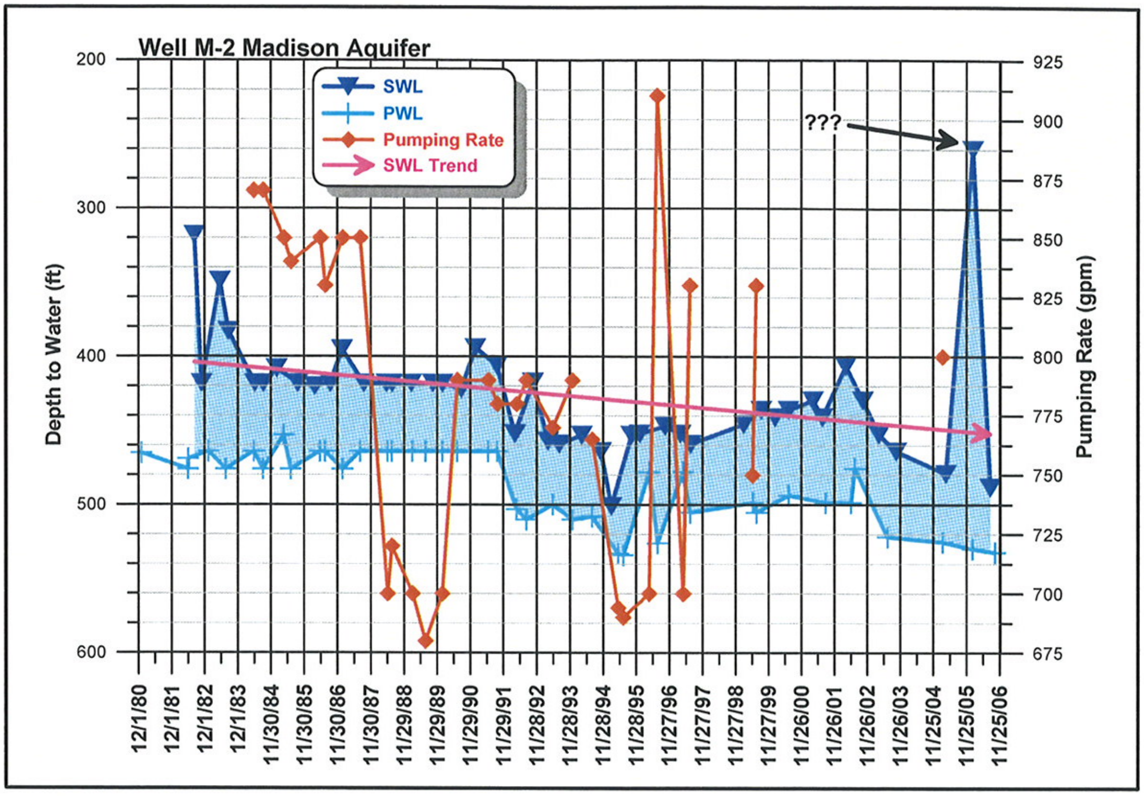


Figure 5-76
Hydrograph of Madison production well M-3

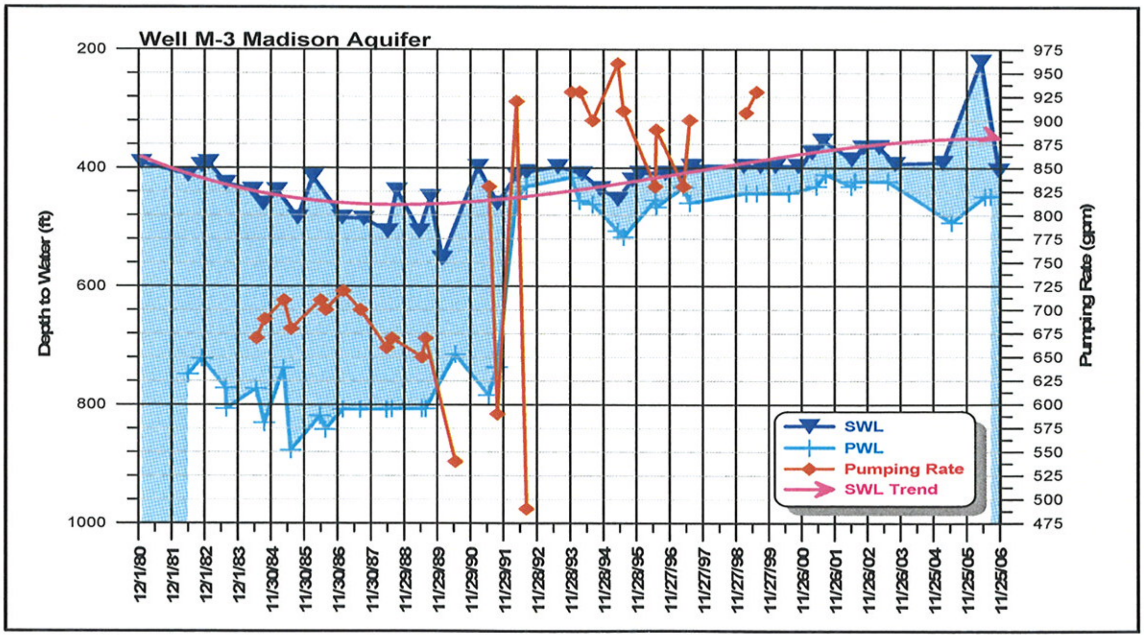


Figure 5-77
Hydrograph of Madison production well M-4

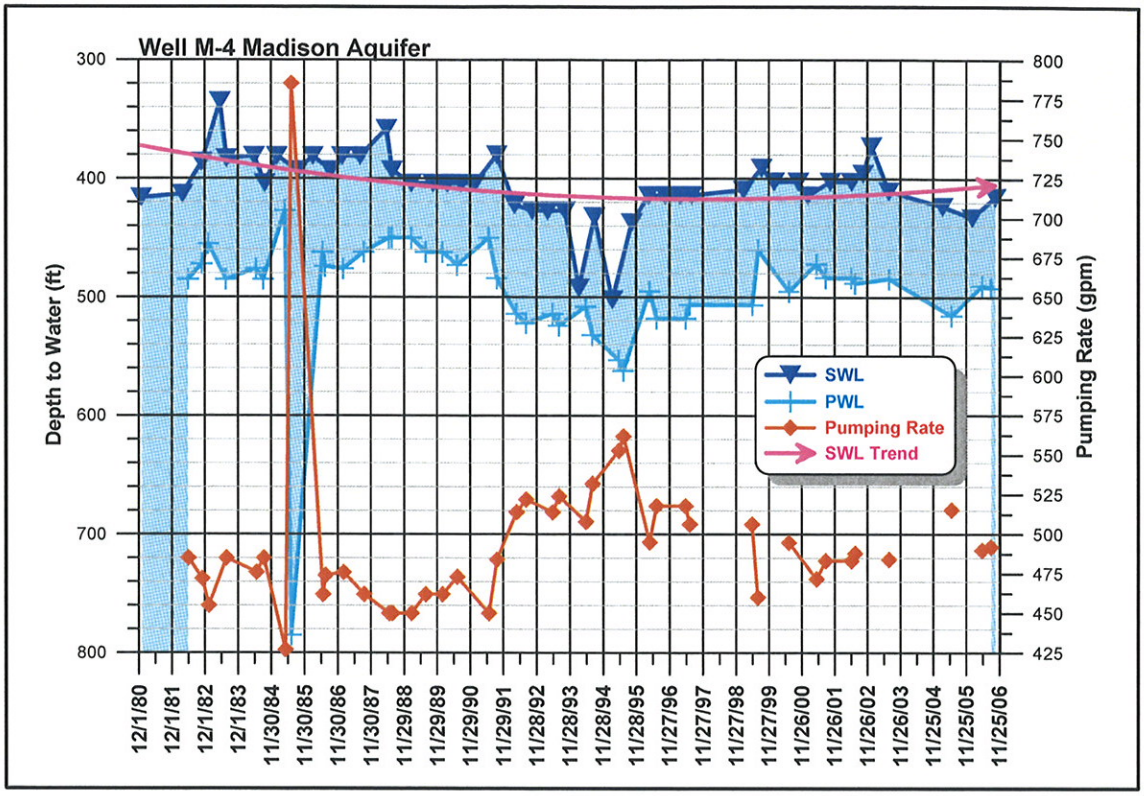


Figure 5-78
Hydrograph of Madison production well M-5

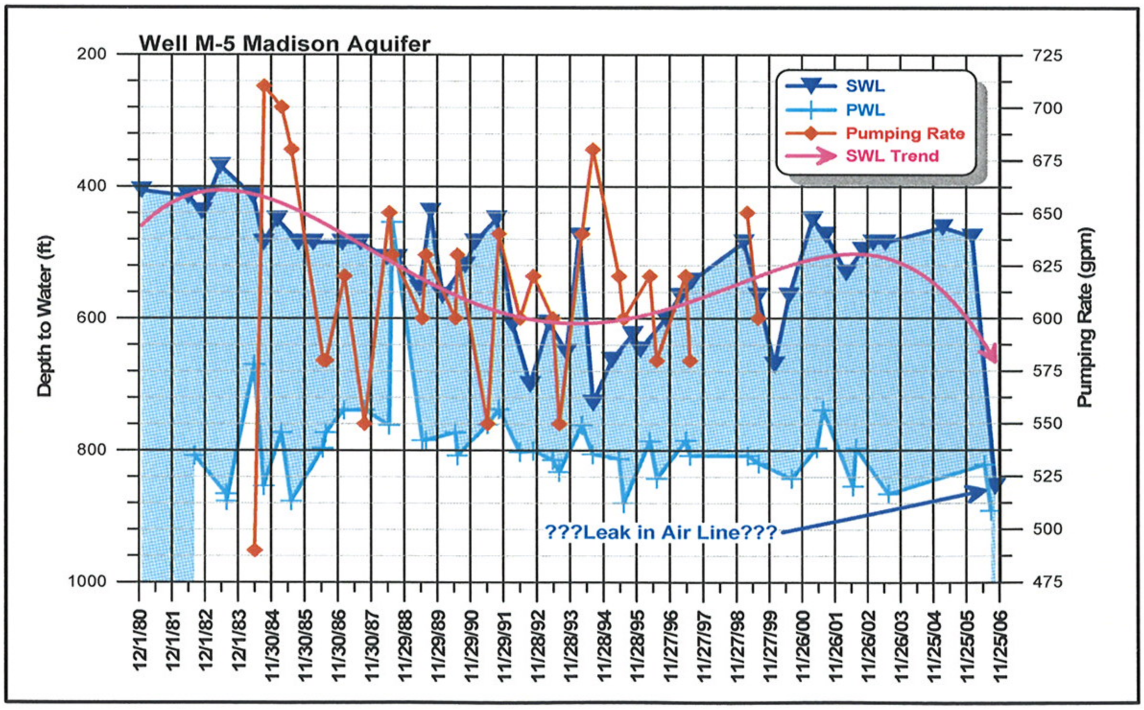


Figure 5-79
Hydrograph of Madison production well M-6

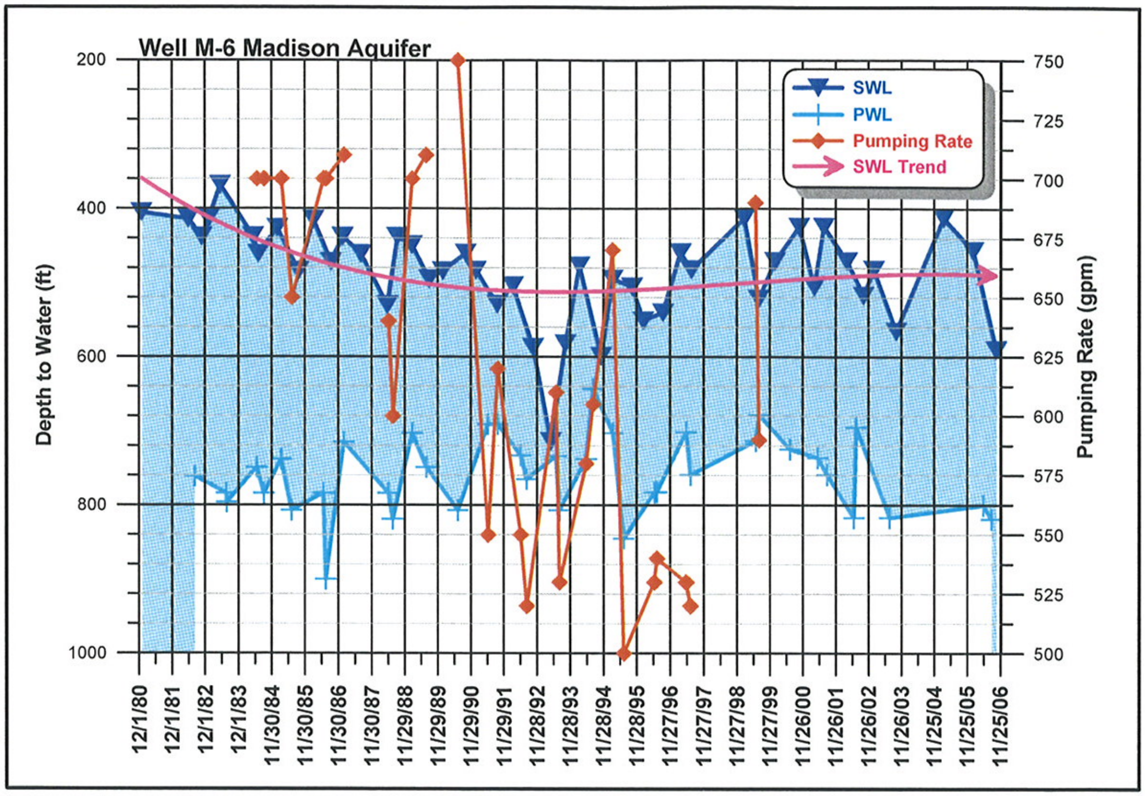


Figure 5-80
Hydrograph of Madison production well M-7

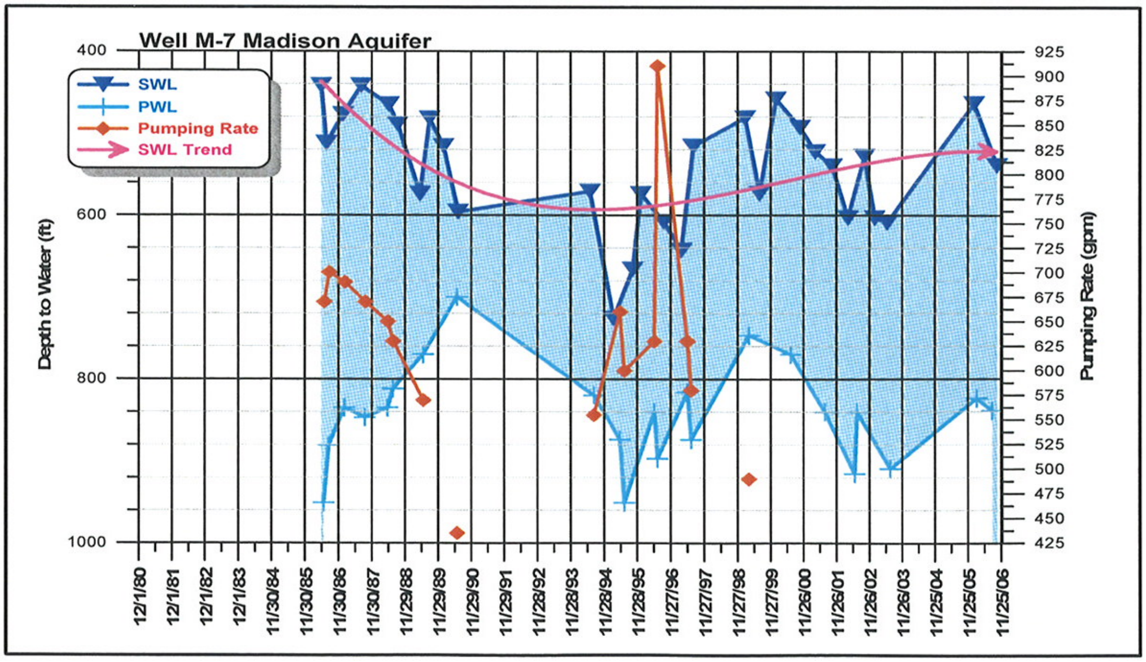


Figure 5-81
Hydrograph of Madison production well M-8

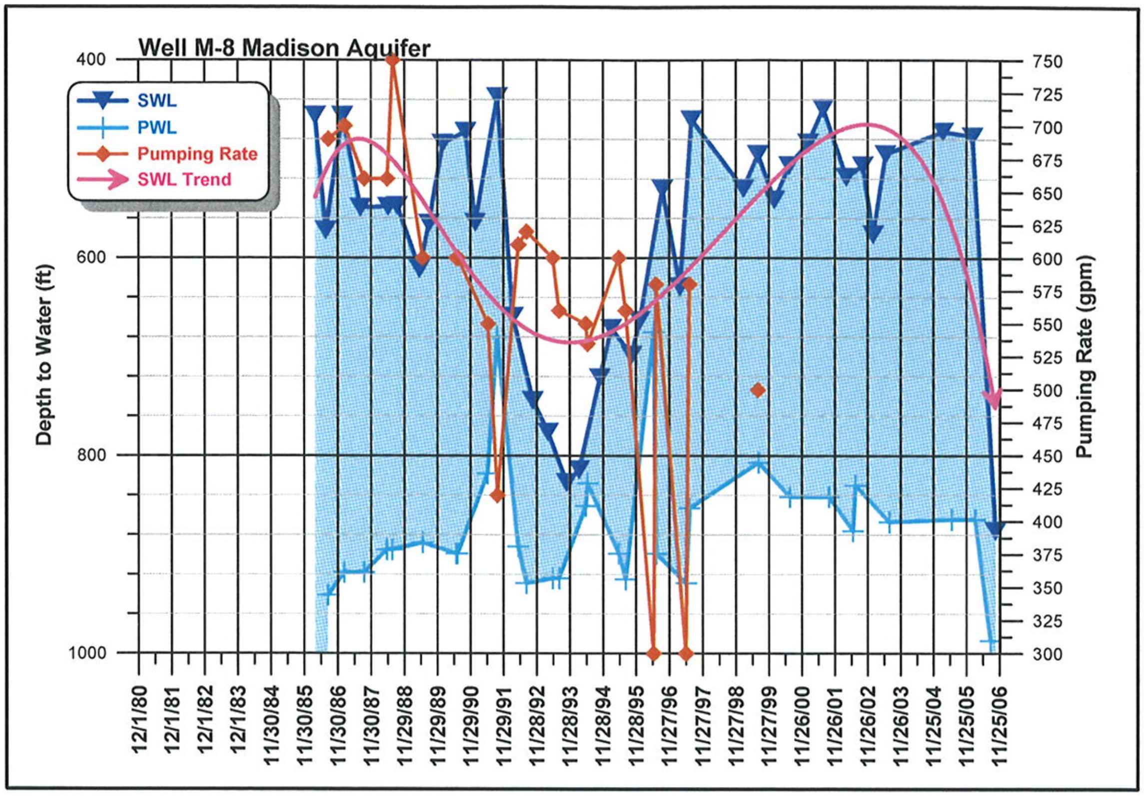


Figure 5-82
Hydrograph of Madison production well M-9

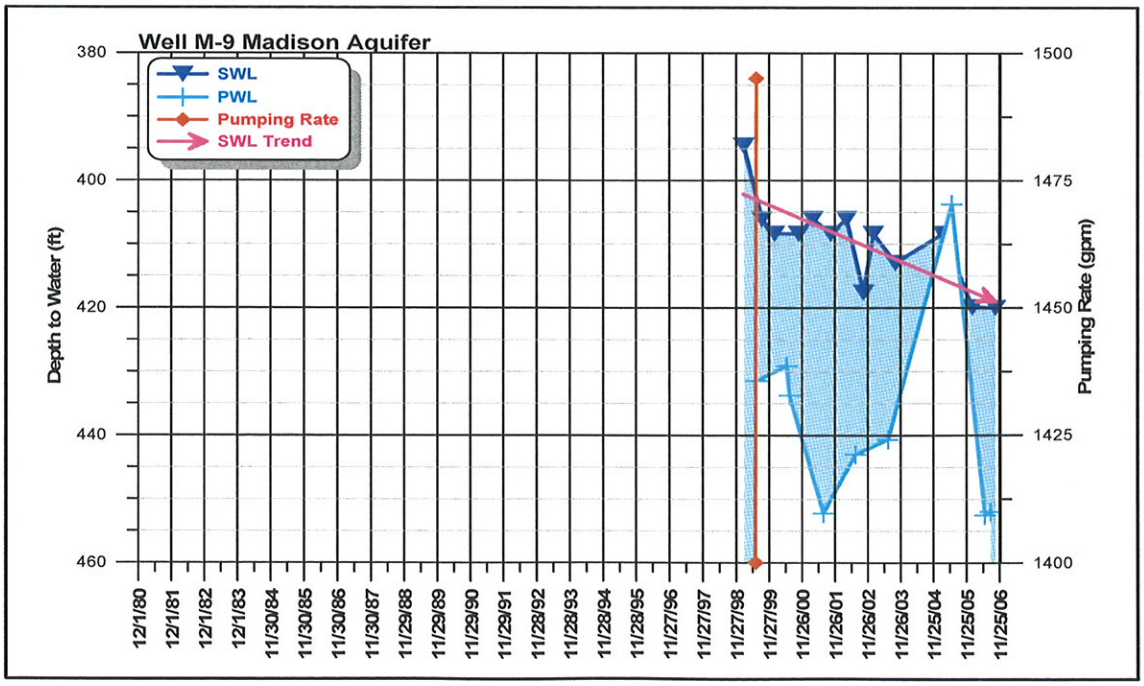
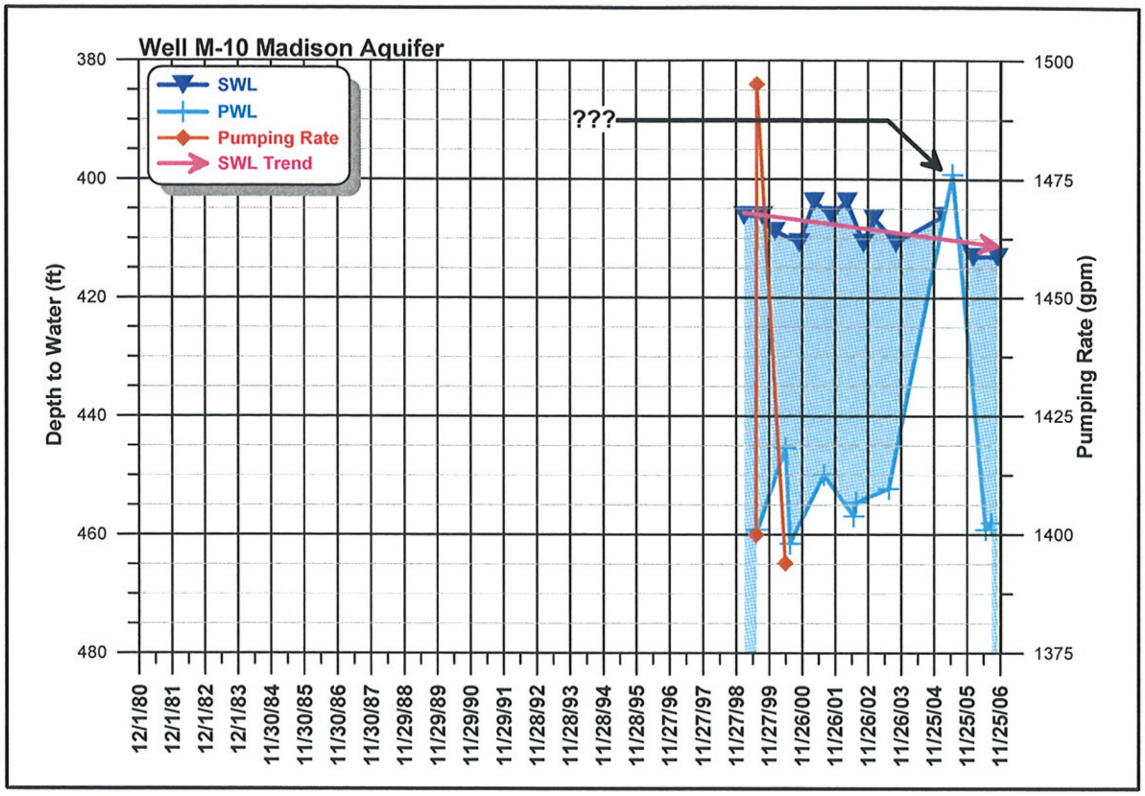


Figure 5-83
Hydrograph of Madison production well M-10



approximately 20 feet of groundwater level decline which is approximately the groundwater level decline since the mid-1990's. This indicates that if there is in fact any long-term drawdown associated with operation of these wells, it is obscured by the long-term fluctuation in groundwater levels in the Madison aquifer due to natural fluctuations in recharge and discharge in the regional Madison aquifer system.

5.11 CONCLUSIONS

The Fort Union and Madison aquifers both offer considerable groundwater resources as potential sources of future municipal water supply to the City of Gillette and the surrounding area. However, the potential for sustainable development of the groundwater resources in the future is considerably different in the two aquifers.

Production of groundwater from the Fort Union aquifer is from multiple layers of sandstone that are embedded in shale and mudstone which are very slowly pervious to water. The sandstone layers consist of discontinuous lenses bounded by the less pervious material. The less pervious material presents no-flow boundaries that limit the area of sandstone that can produce groundwater to wells penetrating the individual lenses. A well may penetrate 10 to 15 productive layers of sandstone in the Tongue River Member of the Fort Union aquifer; however, these lenses are not well connected hydraulically to other sandstone lenses at greater distances from the well because of the intervening beds of shale and mudstone.

Accordingly, the "cone of depression" expanding out from the well in each productive lens when it is pumped encounters the limits of each productive sandstone lens; limits beyond which groundwater is not released from storage to support the discharge out of the pumped well. These limits are referred to in the mathematical analysis of aquifer response as negative boundary conditions. When the depressurized area around the pumped well – the "cone of depression" – reaches the boundaries of the productive lenses, the rate of drawdown in the aquifer around the pumped well greatly accelerates in order to continue to release groundwater from storage at the pumping rate while lateral expansion of the depressurized zone into a larger part of the aquifer is prevented by the boundaries of essentially impervious (relative to the pumping rate) material consisting of the shale and mudstone.

The physical boundaries to groundwater production from the laterally discontinuous sandstone lenses that produce to individual wells completed in the Fort Union Formation have a profound effect on the amount of time over which groundwater yields can be sustained. The length of time that a specific pumping scheme can be reliably sustained is greatly reduced by the internal boundaries in the Fort Union aquifer as compared to the time it could be sustained without the boundary conditions. Therefore, projections of future drawdown that will occur around a well or well field, based on tests of the hydraulic properties of the aquifer, will provide unrealistically optimistic predictions of the sustainable life of a pumping scheme if the boundary conditions are not taken into account. As demonstrated by groundwater modeling herein of the proposed Southern Well Field in the Fort Union aquifer (Wester-Wetstien, 2004) the range of likely hydraulic properties of the Fort Union aquifer indicate that the life of such a well field at the design pumping rates may be less than 20 years, not taking into account negative boundary conditions or on-going groundwater level declines in the Fort Union aquifer. If on-going rates of groundwater level recession and the effects of the hydraulic boundaries within the aquifer are considered, it is clear that the proposed well field in the Fort Union aquifer is unlikely to offer sustained yield for 20 years, assuming it were put into operation all at the same time. If construction of the proposed well field in the Fort Union was accomplished in stages over a period of years, consistent with growth of water demand, the sustainable duration of the well field operation would be extended accordingly.

Data sufficient to support the type of analysis presented herein for the Fort Union aquifer were not found for the Lance/Fox Hills aquifer. The Lance/Fox Hills aquifer wells operated by the City of Gillette offer good yields during seasonal pumping use; however, water quality is very poor and requires treatment or blending for use as drinking water. Hydrographs from the production wells exhibit long-term decline in the groundwater levels, even with pumping limited to seasonal use. The long-term decline is not so great as to indicate the wells will decrease in yield dramatically in the near future; however, imposition of significantly increased demand on the aquifer, such as would occur if the aquifer became the primary source of water for the City of Gillette, would greatly accelerate the rate of groundwater drawdown and eventually result in decreasing well yields. Geologically, the internal structure and stratification of the Lance/Fox Hills Formation is somewhat similar to that of the Fort Union aquifer and may be subject to some degree of the same limiting boundary conditions that limit the longevity of sustainable development from the Fort Union aquifer. Therefore, the Lance/Fox Hills aquifer is regarded in this investigation as a close cousin to the Fort Union aquifer in terms of long-term sustainable development, potentially offering the same types of limitations.

The Madison aquifer offers substantially different hydraulic conditions when compared to the Fort Union aquifer. Instead of internal boundaries that limit the area over which groundwater storage can be released to a pumped well, the Madison aquifer offers internal zones of solution-enlarged cavities through which groundwater can flow to wells from large extents of aquifer. Accordingly, the area over which groundwater is released from storage in the Madison aquifer can expand as necessary to support pumping discharge rates, without encountering boundaries that limit the size of the productive area within which groundwater storage is released.

In addition to enhancement of the hydraulic properties of the Madison aquifer by solution-enlarged openings that provide conduits for high-capacity flow through the aquifer, the Madison aquifer in the existing well field operated by the City of Gillette receives the benefit of vertical leakage of groundwater into the aquifer from adjacent formations when the aquifer is depressurized by a pumped well. The vertical leakage is through imperfect confining layers that separate the Madison aquifer from the adjacent aquifer. When the depressurized area expands around a pumped well in the existing well field, the surface area over which water passes through the leaky confining layer and into the Madison aquifer expands accordingly. Eventually, the depressurized surface area becomes large enough that the rate of leakage through the leaky confining layer equals the pumping rate from the well and drawdown in the Madison aquifer stabilizes. When the leakage through the leaking confining layer equals the pumping rate from a well or wells, the Madison aquifer no longer releases groundwater from storage to support the pumping rate. This is why the drawdown stabilizes and this means the cone of depression or depressurized area around the well stops expanding outward from the well.

The latter hydraulic conditions are tremendously more favorable to sustainable groundwater development of the magnitude required in the future for the City of Gillette than the conditions in the Fort Union and Lance/Fox Hills aquifers. Preliminary groundwater modeling of the Madison aquifer without taking into account either the vertical leakage or the high-capacity flow conduits in the Madison conservatively projects groundwater development at the rates required by the City of Gillette can be sustained well beyond the planning period for this report and well beyond the foreseeable future. Therefore, in terms of sustainable development, the Madison aquifer offers greatly more favorable conditions for sustainable groundwater development at the rate and volume of annual demands projected for the City of Gillette than does either the Fort Union or Lance/Fox Hills aquifers.

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