OF-WTWI-1984-54

HYDRODYNAMIC DEVELOPMENT OF THE PALO DURO BASIN AND OTHER MECHANISMS CREATING POSSIBLE TRANSIENT FLOW CONDITIONS

by

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Prepared for the
U.S. Department of Energy
Office of Nuclear Waste Isolation
under contract no. DE-AC-97-83WM46615

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1984

INTRODUCTION

Characterization of the regional flow regime in the Palo Duro Basin is assisted by numerical ground-water flow models as described by INTERA (1984), Senger and Fogg (1984), and Wirojanagud and others (1984). In general, the models which incorporate the available hydrogeologic information simulate hydraulic head distribution and fluxes under steady-state conditions. The computed heads are then compared to measured heads in order to evaluate the adequacy of the conceptual model.

The conceptualized flow regime in the Palo Duro Basin is generally assumed to represent a steady-state, gravity-driven flow system of the type described by Hubbert (1940). Ground-water flow is governed by the fluid potential along the topographic surface and permeability of the hydrostratigraphic units. In the Palo Duro Basin, extensive modification of the topography as a result of tectonic and geomorphologic processes has occurred within the last 15 million years (McGookey, 1984; Gustavson and others, 1981). Accordingly, it is possible that hydraulic heads observed in the Deep-Basin Brine aquifer represent transient conditions and that they are still equilibrating to modifications of topography in the past.

Significant hydrocarbon occurrences in the Texas Panhandle suggest other possible mechanisms creating transient flow conditions as a result of reservoir-pressure decline due to hydrocarbon production.

The purpose of this study is to investigate transient flow conditions and to identify possible flow patterns resulting from changing hydrologic conditions with time. For this purpose, the model herein is used to simulate possible ground-water flow patterns caused by different tectonic and geomorphologic processes. The hydrodynamic development of the basin is crucial to the origin and hydrochemical evolution of the fluids in the deep basin. Changing hydraulic head distributions with time results in changes of ground-water flow paths. Consequently, transport of chemical constituents could have traveled along ancient pathways much different than is suggested by the present-day hydraulic head distribution observed in the basin.

HYDROGEOLOGY

Geologic Setting

The Palo Duro Basin, located in the southern part of the Texas Panhandle, is a cratonic basin that formed as a result of late Paleozoic tectonic activity. Major structural features such as Bravo Dome, the Amarillo Uplift, and the Matador Arch, shown in figure 1, represent the northern and southern boundaries of the Palo Duro Basin (Nicholson, 1960). The basin extends from the Tucumcari Basin in the west to the Hardeman Basin in the east.

The stratigraphy of the basin shows extreme hydrogeologic inhomogeneities which are the result of long-lived cycles of sedimentation in different environments (table 1). Handford and Dutton (1980) distinguish four depositional cycles, reflecting the geologic development of the basin: (1) formation of the basin and subsequent deposition of basement-derived, fan-delta granite wash from uplifts flanking the basin, (2) planation and burial of the uplifts through Early Permian time and infilling of the deep basin with shelf-margin carbonate and basinal facies, (3) encroachment of continental red-bed facies from sources in New Mexico and Oklahoma and deposition of thick Middle to Upper Permian marine evaporites in arid environments, and (4) marine retreat during late Permian time and development of a Triassic lacustrine basin brought about as a result of continental rifting and drainage reversal. For detailed information on the tectonostratigraphic setting and depositional environment of the

Palo Duro Basin, refer to Handford and Dutton (1980) and Dutton and others (1982).

The most recent major tectonic events occurring during Cenozoic time caused uplift and tilting of the basin. McGookey (1984) reported that the basin was uplifted to 730 m (2,400 ft) in the southeast and to 1,220 m (4,000 ft) in the northwest, probably largely during the last 10 to 15 million years. Prior to the uplift, the Palo Duro Basin was at or below sea level in Cretaceous time at about 70 million years (McGookey, 1984).

Uplift of the basin created significant topographic relief and most significantly affected the hydrodynamics of the basin. Prior to the beginning of uplift in Miocene time (15 m.y.), it is assumed that significant hydraulic gradients across the uplift probably did not exist since Cretaceous time (70 m.y.). During that time period, no major geologic events occurred that would have significantly modified the geometry of the Palo Duro Basin. The transition from a compactional basin to a gravity-driven flow system (Hubbert, 1940) is unknown in its time-stratigraphic context. Thus, this investigation is limited to the hydrodynamic development of the Palo Duro Basin as a gravity-driven flow system, where ground-water flow is governed by the fluid potential along the topographic surface.

Besides tectonic events, other mechanisms such as deposition and erosion modify topography and can significantly affect the ground-water flow pattern. In the Palo Duro Basin, three major post-Oligocene geomorphologic events can be identified: (1) deposition of the Ogallala Formation, (2) erosion of the Pecos River valley, and (3) westward retreat (erosion) of the Caprock Escarpment.

Deposition of the Ogallala Formation started at the end of Miocene time (13 m.y.) (Bergren and Van Couvering, 1974; Tedford, 1981). The youngest caliche deposits were dated at about 2 to 6 million years (Izett and others, 1972, 1981), bracketing the time period of Ogallala deposition. Limited geologic data from the Pecos River valley indicate that erosion occurred during the last 3 to 5 million years since the end of the Ogallala deposition (Thomas, 1972). Regional rates of westward retreat of the Caprock escarpment were determined from time periods that range from 7,900 to 3,000,000 years and vary from 11 to 18 cm/yr (4.3 to 7.1 inches/yr) (Gustavson and others, 1981).

The major hydrogeologic unit (Bassett and Bentley, 1982) in the Palo Duro Basin (fig. 2) are the Deep-Basin Brine aquifer of Wolfcampian and Pennsylvanian age and the shallow Ogallala and Dockum aquifers, separated by a thick aquitard of Middle and Upper Permian evaporites (table 1). The San Andres Cycle 4 dolomite within the evaporite section can be considered an individual hydrologic unit. Dutton (1984) identified a regional flow system in the San Andres Formation, based on pressure and hydrochemical data.

HYDROGEOLOGIC CHARACTERIZATION

Hydraulic Conductivity

The shallow aquifer system on the High Plains includes fluvial deposits of the Tertiary Ogallala Formation and fluvial/lacustrine deposits of the Triassic Dockum Group. Average hydraulic conductivity assigned to the Ogallala and Dockum range, respectively, from 0.8 m/day to 8.0 m/day and from 0.08 m/day to 0.8 m/day (table 2). In the preceding modeling effort (Senger and Fogg, 1984), hydraulic heads computed by the model in the shallow Ogallala aquifer agreed reasonably well with observed water levels along the cross-sectional traverse on the High Plains. A prescribed flux-boundary condition, based on recharge rates reported by Knowles and others (1982), was used along the Ogallala surface. It was shown that a significant hydraulic head difference between the Ogallala and the Dockum indicated by Fink (1963) and Stevens (unpublished data) could be achieved by reducing vertical permeability of the Dockum by at least four orders of magnitude compared to horizontal permeability.

The vertical hydraulic conductivity value of 3.2×10^{-7} m/day assigned to the Evaporite aquitard (table 2) was derived from the harmonic means of permeabilities using typical and measured values of permeabilities for each substrata (Wirojanagud and others, 1984). Results of the steady-state cross-sectional model presented earlier (Senger and Fogg, 1984) suggested that Kv of 3.2×10^{-7} m/day represents the upper limit of possible hydraulic conductivities for the Evaporite aquitard.

The San Andres Cycle 4 dolomite is incorporated in the present model as an individual hydrologic unit. Hydraulic conductivity of $K = 1.2 \times 10^{-4}$ m/day, assigned to the San Andres Formation, is based on limited permeability data derived from pumping tests and drill-stem tests (Dutton and Orr, in preparation).

Within the Deep-Basin Brine aquifer, hydraulic conductivities for shelf carbonates and granite-wash deposits, shown in table 2, represent geometric means of permeabilities obtained from analyses of pumping tests, drill-stem tests and data compiled by Core Laboratories (1972). However, permeabilities for proximal granite-wash deposits in the vicinity of the sediment source, Amarillo Uplift and Bravo Dome (fig. 1) were assumed to be approximately one order of magnitude higher than permeability of distal granite wash ($k = 8.6$ md); the latter represents the geometric mean of the compiled data. Relatively higher permeabilities for proximal granite wash are supported by recent pumping test results in J. Friemel No. 1 well and by previous modeling efforts (Senger and Fogg, 1984; Wirojanagud and others, 1984).

The remaining hydrologic units for which measured permeabilities are not available were assigned hydrogeologic properties typical for corresponding geologic material as obtained from the literature (table 2). The model was then used to test and eventually calibrate the assigned permeabilities in order to yield reasonable results (Senger and Fogg, 1984).

Specific Storage

Investigating transient ground-water flow conditions requires detailed information on the specific storage of the different hydrologic units. In-situ measurements of storativity in deep formations are difficult to obtain and therefore generally unavailable. Values of specific storage used in the model are based on data obtained for geologic materials as reported by Domenico and Miflin (1965). Their data on specific storage were used by several investigations dealing with non-steady flow of fluids in sedimentary basins as described by Bredehoft and Hanshaw (1968), and Toth and Millar (1983). In the present model, the value of specific storage for all the different hydrologic units is assumed to be 0.0001 1/m. This value is comparable to values used by Toth and Millar (1983) for the deeper units in the Alberta Basin. For the shallow Ogallala aquifer, the assigned value is no doubt too low because of the water-table conditions. However, the discrepancy is probably negligible in view of the scope of this investigation, namely, to investigate possible transient effects in the Deep-Basin Brine aquifer.

REGIONAL GROUND-WATER FLOW

Characterization of the regional ground-water flow in the Palo Duro Basin, based on results from the steady-state ground-water flow model (Senger and Fogg, 1984), can be summarized as follows: distinction of a shallow flow system governed primarily by topography, and a deeper flow regime recharging in the New Mexico area and passing deep beneath the Pecos River into the deep section of the Palo Duro Basin (fig. 1).

The observed underpressuring in the Deep-Basin Brine aquifer underlying the High Plains surface can be explained by the presence of relatively permeable granite-wash deposits within the Lower Permian and Pennsylvanian strata adjacent to the Bravo Dome and Amarillo Uplift. The proximal granite wash effectively drains the deeper section more easily than it can be recharged. Ground-water flow in the eastern part of the deep section is primarily through the more permeable granite wash which supplies a good hydraulic connection between the area beneath the High Plains and the area of relatively lower heads along the eastern boundary of the model.

Though leakage through the Evaporite aquitard could contribute up to 26 percent of water passing through the deep section, the aquitard effectively separates the deeper flow regime from the relatively steep hydraulic gradients of the shallow aquifer system, creating underpressured conditions in the Deep-Basin Brine aquifer.

The model also indicated that the Pecos River enhances underpressuring beneath the western half of the High Plains by serving as a discharge area for some of the ground water that would otherwise move downdip into the Deep-Basin Brine aquifer.

The San Andres Cycle 4 dolomite within the evaporite sequence (fig. 2) is incorporated in the present model as an individual hydrologic unit. Dutton (1983) identified a regional flow regime in the San Andres Formation, where the capture of recharge by the Pecos River and the distribution of evaporite facies in the Palo Duro Basin control the regional pattern of ground-water flow in the San Andres.

COMPUTER PROGRAM

The model was implemented with the computer program FLUMPS (Neuman and others, 1982) which was modified from the original version of the program FLUMP developed by Neuman and Narasimhan (1977) and Narasimhan and others (1977, 1978a). FLUMPS was used to solve the partial differential equation describing two-dimensional transient ground-water flow in porous media:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) = S_s \frac{\partial h}{\partial t}$$

where Kx and Kz are horizontal and vertical hydraulic conductivities, respectively. FLUMPS employs the finite element method for solving linear and nonlinear subsurface flow problems in two-dimensional and quasi-three-dimensional configurations using either a direct solution technique or an iterative solution technique. Full description of the program and its capabilities are available in the user's guide for FLUMPS (Neuman, 1979). Examples of applications and its performance are documented according to QA guidelines by Senger and Fogg (1984).

The program computes hydraulic heads at each node, fluxes between adjacent nodes, and fluxes along prescribed head boundaries representing recharge and discharge. In addition, the model allows one to vary hydraulic head with time, and hydraulic properties with time or head.

MODELING PROCEDURE

Finite Element Mesh

The ground-water flow model is similar to the earlier presented model (Senger and Fogg, 1983, 1984), which was constructed along an east-west cross section extending from New Mexico across the Texas Panhandle into Oklahoma (fig. 2). The finite element mesh (fig. 3) was modified from the previously used grid by incorporating the San Andres dolomite as an individual hydrologic unit within the Evaporite aquitard. A comparison of steady-state hydraulic heads computed by the program FREESURF (Neuman and others, 1977) used in the previous modeling effort and subsequent computation by FLUMPS showed good agreement of the results. This indicates that the effect of extreme node-spacing differences between horizontal and vertical directions in the model, as discussed by Senger and Fogg (1984), does not produce a significant error when using the program FLUMPS.

Boundary Conditions of the Model

In this model, only prescribed head boundary conditions (Dirichlet boundary conditions) are applied. The upper surface of the finite element mesh corresponds approximately to the water table and generally is assumed to closely mimic the topography. The lower boundary of the model is assumed to be impervious and corresponds to the contact between Deep-Basin Brine aquifer and basement rocks.

Hydraulic head is assumed to be uniform with depth along the eastern boundary, implying horizontal flow at this boundary. Modification of topography as a result of tectonic and geomorphologic activity is simulated in the model by varying prescribed heads with time along the upper and eastern boundaries of the mesh. Along the eastern boundary of the mesh, heads are prescribed equal to the water table at the surface node. Similarly, hydrocarbon production and the resulting decline in reservoir pressures was simulated by reducing hydraulic heads with time at the particular node location in the model representing a hydrocarbon reservoir.

SIMULATION STRATEGY

Investigating the effects of tectonic and geomorphologic events was done in successive simulations depicting hypothetically the hydrodynamic development of the Palo Duro Basin during Cenozoic time (table 3). Although detailed information on timing of the different events is limited, the general sequence of events is reasonably accurate, and certainly accurate enough to provide a better understanding of how various tectonic and geomorphologic processes have affected the paleohydrology of the basin. Timing of some events may overlap to a certain extent; nevertheless, modeling of the tectonic and geomorphologic processes is performed in successive simulations, using the computed hydraulic head distribution from one simulation as initial conditions for the following simulation.

For convenience, the geometry of the finite element mesh is preserved and only prescribed heads along the surface of the model are varied in order to simulate the change in water table as a result of the modification of topography caused by the different tectonic and geomorphologic events.

Hydraulic conductivities assigned to the different hydrogeologic units shown in table 2 correspond largely to those used in the steady-state simulation A-2 (Senger and Fogg, 1984), which was considered to be the most realistic. Also, hydrogeologic properties of the individual units are assumed not to change with time throughout the different simulations.

Approximate steady-state hydrodynamic conditions prior to the uplift of the basin are created in simulation T-1. The resulting hydraulic head distribution in this simulation is used as initial condition for the subsequent simulation T-2 describing the uplift and tilting of the basin. Ogallala deposition was modeled in the following simulation T-3, which in turn uses the computed hydraulic head distribution from simulation T-2 as initial conditions.

Simulation T-4 investigates the effect of erosion of the Pecos River valley. Prescribed hydraulic heads along the surface nodes representing the Pecos valley area are lowered with time to the approximate present topographic elevation.

In simulation T-5, the latest major erosional event, the westward retreat of the Caprock Escarpment was simulated. Hydraulic heads prescribed to the surface nodes representing the Rolling Plains were lowered in order to mimic the cap-rock retreat.

Possible effects of hydrocarbon production on the regional flow regime were investigated in simulation H-1, where prescribed heads were lowered with time at particular nodes representing the pressure decline in a reservoir.

Limitations of the Model

General shortcomings of the cross-sectional model were discussed previously in Senger and Fogg (1984). They include simplification and conceptualization of the lithostratigraphy represented in the model, hydrologic properties assigned to the different hydrologic units, and the assumption of homogeneous fluid properties throughout the basin. In addition to the previous steady-state model, the presented model simulating transient flow conditions requires information on specific storage of the hydrogeologic units. Specific storage of a saturated aquifer represents the volume of water that can be removed from or taken into storage as a result of a change in hydraulic head. It, therefore, is important with regard to propagation of transient conditions through the aquifer.

DOE pumping tests performed in the Deep-Basin Brine aquifer did not include analysis of storativity. The assigned values of specific storage are based on typical and measured values reported in the literature (Domenico and Miflin, 1965; Freeze and Cherry, 1979) that range from 0.005 to 0.00005 1/m.

The value of specific storage of 0.0001 1/m used in the model agrees with the value used by Toth and Millar (1983) for the deeper units in the Red Earth region of the Alberta Basin.

It can be expected that by using relatively higher values of specific storage than those assumed in the model, hydraulic heads would generally equilibrate slower to modifications of boundary conditions. Consequently, lower values of specific storage would result in a quicker response of hydraulic heads to modified boundary conditions.

Simulation of uplift, deposition and erosion was performed in a simplistic way using the two-dimensional model which was not modified in terms of overall geometry of the finite element mesh. Only prescribed head boundary conditions along the upper surface and along the eastern boundary of the mesh are modified representing the change in water table as a result of the modification of topography.

Extensive modifications of prescribed head boundaries along the surface of the mesh without concomitant modifications of the geometry of the mesh could result in unrealistic fluxes computed by the model for the near-surface nodes. In general, however, extensive modifications of water-table configurations caused by the different events was represented by varying prescribed head boundaries over long periods of time (more than 100,000 years), and overall impact on the hydrodynamic conditions of the deeper units can be assumed negligible.

Detailed information on the timing and the extent of the different tectonic and geomorphologic events is limited. In successive simulations, the general sequence and timing of the different tectonic and geomorphologic processes were modeled, ignoring possible overlapping of events. However, the effect of this limitation is negligible with regard to the objective of the modeling effort, namely, to investigate the transient effects of the different tectonic and geomorphologic processes on the overall hydrodynamic conditions in the basin.

RESULTS AND DISCUSSION

Simulation of Hydrodynamic Development of the Basin

Pre-Uplift Conditions

Pre-uplift conditions are created in simulation T-1 (fig. 4). The boundary conditions in this simulation are represented by prescribed head boundaries along the upper surface with a maximum head difference of 100 m (330 ft) between the western boundary and eastern boundary. McGookey (1984) showed that prior to the uplift the Palo Duro Basin was at or near sea level during Cretaceous time, and no major tectonic events can be identified during that time period. Accordingly, large hydraulic gradients across the basin are not likely. The computed hydraulic head distribution in figure 4 represents a hypothetical ground-water flow regime prior to uplifting which indicates rather sluggish flow rates with very small hydraulic gradients (less than 2×10^{-4}).

Basin Uplift and Tilting

The computed hydraulic head distribution is used as initial conditions for simulation T-2, which investigates the effect of uplift and tilting of the basin on the hydraulic head distribution. Uplift and tilting of the basin was modeled by gradually increasing the hydraulic heads during a time period of one million years along the surface of the mesh relative to the fixed heads along the eastern boundary of the model. Heads along the surface boundary increase gradually from 0 meters at the eastern corner to up to 1,100 m (3,600 ft) at the western boundary in New Mexico. Along the High Plains surface heads increase between 750 m (2,460 ft) in the west and 220 m (720 ft) in the east which corresponds to the range of relative uplift amounts in the Palo Duro Basin (McGookey, 1984).

The computed hydraulic heads in figure 5 show the hydrodynamic conditions after 10 million years. Within the last million years, the maximum change in hydraulic head as computed by the model was only 6 x 10^{-4} m (2 x 10^{-3} ft), indicating approximate steady-state flow conditions. Hydraulic heads in the Deep-Basin Brine aquifer (fig. 5) are up to 100 m (330 ft) below surface water table, indicating some underpressuring in the eastern part of the cross section. In the western part, however, hydraulic heads in the deep sections are higher than water-table elevations, indicating the possibility of upward leakage of deep-basinal fluids across the Evaporite aquitard for the time period between uplifting of the basin and erosion of the Pecos River.

Deposition of the Ogallala Formation

Deposition of the Ogallala Formation was modeled separately in simulation T-3, despite the fact that uplifting and Ogallala deposition are probably overlapping events. Hydraulic heads along the surface boundary are increased 50 m (165 ft) in the east and up to 130 m (430 ft) in the west accounting for a general decrease in thickness of the Ogallala away from the sediment source to the west of the model. Along the High Plains surface, prescribed hydraulic heads were adjusted to the computed water table from the steady-state simulation A-2 of Senger and Fogg (1984). Again, prescribed heads along the upper surface are gradually increased during a time period of one million years. The computed hydraulic head distribution in simulation T-3 (fig. 6) describes the hydrodynamic condition 10 million years after the beginning of the Ogallala deposition.

Although prescribed heads along the High Plains surface increased by up to 125 m (410 ft), hydraulic heads in the Deep-Basin Brine aquifer generally increase by less than 70 m (230 ft). In comparison, computation of hydraulic head distribution for one-dimensional cross-formational flow as described by Toth and Millar (1983), whereby prescribed head at the surface of a 1,500 m (4,920 ft) thick aquitard ($Kv = 3.2 \times 10^{-7}$ m/day) is raised instantaneously by 125 m (410 ft), results in equilibration of head at the lower surface of the aquitard of about 75 percent or 94 m (310 ft) with respect to the head increase at the upper surface after a time period of 9 million years. The discrepancy between heads computed in the cross-sectional model and calculated heads based on mere vertical propagation of head changes suggests that the lateral flow component in the deep aquifers is significant in creating underpressured conditions. The increase in hydraulic head as a result of Ogallala deposition cannot fully account for the observed underpressuring in the deep section beneath the Evaporite aquitard.

Erosion of the Pecos River

The importance of the Pecos River on underpressuring in the western part of the Deep-Basin Brine aquifer was demonstrated previously by Senger and Fogg (1984). In simulation T-4, prescribed heads along the surface nodes representing the Pecos River valley are gradually lowered during a time period of 4 million years. At the end of the time period, the heads along the surface of the mesh correspond to the approximate present day water table which roughly follows the topography.

Figure 7 shows a significant reduction of hydraulic heads in the western part of the Deep-Basin Brine aquifer 5 million years after the start of the stream erosion. The maximum change in hydraulic heads during the last one million years of the simulation was about 1.7 m (5.6 ft), indicating that overall steady-state flow conditions can be assumed at the end of the simulation. Underpressuring in the deep section as indicated by the head difference between shallow aquifer and deep section which increases from a maximum of 125 m (410 ft) in simulation T-3 (fig. 6) to a maximum of 175 m (575 ft) in this simulation (fig. 7).

The impact of the Pecos River erosion on the hydraulic head distribution is documented in figure 8, which shows the difference in heads before and after stream erosion. The head change decreases away from the Pecos, indicating that in the western part of the Deep-Basin Brine aquifer hydraulic heads are significantly affected by stream erosion, while towards the eastern part the impact on the heads is small. Keep in mind t at the westward retreat of the Caprock Escarpment is not included in this simulation, which can be assumed to overlap to a certain extent with the erosion of the Pecos River.

Erosion of the Eastern Caprock Escarpment

The effect of westward retreat of the Caprock Escarpment on the hydrologic conditions in the Palo Duro Basin was investigated in simulation T-5. Prescribed hydraulic heads along the surface nodes representing the present-day Rolling Plains surface were subsequently reduced to mimic the erosion of the High Plains according to the reported rate of cap-rock retreat of 18 cm/yr (7.1 inches/year). At the "end of the cap-rock retreat" (about 1.0 million years), hydraulic heads along the surface of the model correspond to the modern water-table configuration along the cross-sectional traverse. Hydraulic heads along the eastern boundary of the mesh are lowered simultaneously with the water-table at the surface (during a time period of 100,000 years), maintaining hydrostatic conditions along the eastern boundary. Pressure-depth data from the deep section in the Hardeman Basin, located approximately at the eastern edge of the cross section indicate roughly fresh-water hydrostatic conditions (Richter, in preparation).

Permian and Pennsylvanian formations crop out along the Wichita Mountains in Oklahoma about 100 km (62 mi) from the eastern edge of the cross section. Erosion of the High Plains in that area and resulting subareal exposure of the deep aquifers can be assumed to create approximate fresh-water hydrostatic conditions in the deep aquifers.

In the model it is assumed that heads along the eastern boundary decrease simultaneously with the water table at the surface. However, it is conceivable that heads in the deep section decrease prior to the water-level drop at the surface as a result of equilibration with relatively lower heads in the outcrop area further to the east, where water levels decrease earlier than those at the eastern boundary of the model (probably less than 500,000 years earlier). The impact of possible delay in head decline in the deep section along the eastern boundary of the model can be considered small and certainly does not change the resulting hydrodynamic conditions in the simulation.

Computed hydraulic heads in simulation T-5 (fig. 9), representing the hydrodynamic conditions after 1.1 million years, show a significant drop in hydraulic heads in the deep section. Underpressuring (head difference between water table and deep section) increases from about 175 m (575 ft) in simulation 4 (fig. 7) to more than 350 m (1,150 ft) in this simulation (fig. 9). The impact of cap-rock retreat on the hydrologic regime is shown in figure 10. In the deep section, the difference in heads before and after the cap-rock retreat are greatest in the center of the deep basin of up to 250 m (820 ft). Towards New Mexico, the head difference decreases, indicating diminished influence of cap-rock retreat on the hydraulic heads.

Maximum computed head changes within the last 100,000 years of simulation T-5 was about 3.2 m (10.5 ft), which indicates that during the recent geologic history, hydraulic heads were still equilibrating to the modified hydrologic boundary conditions created by the westward retreat of the Caprock Escarpment. Computed hydraulic head distribution in simulation T-5 (fig. 9) agrees reasonably well with the equivalent steady-state simulation A-2 (Senger and Fogg, 1984) shown in figure 11, indicating that the present day hydraulic head distribution in the basin can be assumed to represent approximate steady-state flow conditions.

The presence of a good hydrologic connection between the area beneath the High Plains and the area of relatively lower hydraulic heads along the eastern boundary of the model is considered an important factor for creating underpressured conditions (Senger and Fogg, 1984). Therefore, water-level changes along the surface nodes representing the cap-rock retreat might have a negligible impact on underpressuring as compared to the decrease in hydraulic heads along the eastern boundary of the model.

In order to evaluate the significance of water-level decline along the present day Rolling Plains surface, simulation of the Pecos-River erosion (simulation T-4) and of the cap-rock retreat (simulation T-5) were repeated with the initial hydraulic head distribution represented by hydrodynamic conditions that were in equilibrium with artificially reduced prescribed heads (430 m; 1,410 ft) in the deeper aquifer along the eastern boundary.

The computed head distribution of the modified simulation (Pecos River erosion) showed generally lower heads in the central part of the deep aquifer of up to 120 m (395 ft) compared to computed heads in simulation T-4 (fig. 7), in which prescribed heads along the eastern boundary were equivalent to surface water table of 650 m (2,130 ft). Subsequent simulation of cap-rock retreat was performed whereby prescribed heads along the present day Rolling Plains surface were decreased. The resulting hydraulic head distribution indicated an additional decrease of hydraulic heads of up to 130 m (430 ft) for the central part of the Deep-Basin Brine aquifer. The overall hydraulic head distribution agreed reasonably well with results of simulation T-5 (fig. 9).

The good agreement of computed head distributions and, moreover, the considerable head decline in the deep aquifer caused solely by the decline in surface water table along the present day Rolling Plains indicate that both the reduction in hydraulic heads along the eastern boundary and the water-table decline along the surface as a result of the cap-rock retreat are equally important for creating significant underpressuring in the Deep-Basin Brine aquifer. The thinning of the evaporite sequence towards Oklahoma and the assumed relatively higher permeability of the Permian mud flat system (fig. 2) provides an additional mechanism for equilibration between relatively low hydraulic heads of shallow ground water east of the Caprock Escarpment and heads in the deeper aquifer system.

Effect of Erosional Unloading

Erosion and the resulting unloading of underlying formations has been suggested to cause significant underpressuring under appropriate conditions (Fertl, 1976; Neuzil and Pollock, 1983). Erosional unloading could result in dilation of clayey material causing reduced pore pressures within the aquitard section. Fluids from the adjacent aquifer could flow into the shale sections creating reduced fluid pressures in the surrounding aquifer (Ferran, 1972). Criteria for potential underpressuring in relatively tight formations were documented by Neuzil and Pollock (1983). In general, the extent of underpressuring depends on the rate of erosion, the hydraulic diffusivity of the aquitard, and the compressibility of the material.

The westward retreat of the Caprock Escarpment represents the removal of 300 m (1,000 ft) of overburden. Assuming that the underlying aquitard is capable of expanding, subhydrostatic conditions could be created within the aquitard. Subsequent fluid movement from the adjacent deep aquifer into the overlying aquitard could then result in large-scale underpressuring in the Deep-Basin Brine aquifer.

Erosion of the High Plains, however, occurs laterally, indicating that erosional unloading affects the underlying aquitard only in the vicinity of the Caprock Escarpment. After the position of the escarpment retreats further to the west, the effect of erosional unloading ceases and possible subhydrostatic pressures within the aquitard can then equilibrate with hydrostatic heads at the surface.

In addition, salt dissolution in the underlying Evaporite aquitard caused partly by the retreat of the escarpment may create significant fracturing which increases hydraulic conductivities in shales and allows fluids in the underpressured formations to equilibrate more easily with hydrostatic heads at the land surface. This reduces the possibility that underpressured conditions in the aquitard could be maintained for a long time after the effect of erosional unloading ceased. Therefore, only in the immediate vicinity of the Caprock Escarpment is underpressuring likely within the underlying aquitard.

Further modeling will investigate possible occurrence and extent of underpressuring in the aquitard sequence underlying the Rolling Plains surface.

Hydrocarbon Production

Extensive oil and gas production has been found to cause significant pressure reduction in the Woodbine Formation as a result of extensive hydrocarbon production in the East Texas oil and gas field (Bell and Shephard, 1951).

To determine if oil and gas production from the Panhandle oil and gas field would affect the potentiometric surface of the deep aquifer in the Palo Duro Basin on a regional scale, the effect of reservoir pressure drop on the hydrodynamics of the Deep-Basin Brine aquifer was investigated using the cross-sectional model. Reservoir pressures in the Panhandle oil and gas field over the Amarillo Uplift dropped approximately 400 psi before water injection was started to enhance oil and gas recovery.

In simulation H-1 the effect of hydrocarbon production was simulated in a simplified manner by gradually reducing prescribed hydraulic heads at two arbitrary node locations representing a hypothetical reservoir in the cross-sectional model. The selected "reservoir" nodes are located at the approximate distance between the center of the Palo Duro Basin and the Panhandle oil and gas field to the north of the basin and, therefore, provide a reasonable scenario for the effect of hydrocarbon production from the Panhandle field on the hydrodynamic conditions in the rest of the basin.

The computed hydraulic head in figure 12 represents the hydrodynamic conditions at the end of 100 years after the start of hydrocarbon production. In this simulation, prescribed hydraulic heads at the two "reservoir" nodes were gradually decreased from the initial head values computed in the previous simulation by about 200 m during a time period of 50 years after which prescribed heads were kept constant for another 50 years.

The computed head distribution (fig. 12) indicates that the effect of reservoir-pressure drop is restricted to the immediate vicinity of the reservoir and does not affect the overall ground-water flow pattern in the deep section.

In a subsequent simulation, the prescribed head boundary conditions at the particular "reservoir" nodes were removed to investigate how long it would take to reach the original head distribution prior to the pressure drop caused by hydrocarbon production. It can be shown that after 1,000 years, hydraulic heads at the "reservoir" nodes equilibrated to over 75 percent and after 10,000 years to over 90 percent of the steady-state hydraulic heads (fig. 11).

In general, potentiometric surface maps for the deeper hydrologic units are based on pressure data from drill-stem tests and should not incorporate data from oil fields that indicate depressured conditions, because depressuring is restricted to local areas and does not reflect regional fluid pressure distribution.

Simulating the effects of hydrocarbon production assumed that the reservoir has a strong water-drive indicating that the reservoir is hydraulically connected to the regional hydrodynamic regime. However, most reservoirs in the Panhandle oil and gas field have either depletion-drive or solution-gas drive. This suggests that these reservoirs are hydraulically isolated from the fluid pressures in the surrounding formations. In contrast, Hubbert (1967) identified a hydrodynamic component responsible for the entrapment of the Panhandle oil and gas field which would suggest some hydraulic interconnection with the regional ground-water flow. Wirojanagud and others (1984) implied in their ground-water flow model that ground water in the Wolfcamp aquifer could flow across the northwestern part of the Amarillo Uplift, which suggests hydraulic connection with the regional hydrodynamics.

SUMMARY

The results of the different ground-water flow simulations indicate that uplift and tilting of the basin caused increased flow rates in the Palo Duro Basin about 10 to 15 million years ago. Erosion of the Pecos River valley and the more recent retreat of the Caprock Escarpment in combination with the vertical and lateral distribution of the relatively permeable granite-wash deposits contribute to the observed underpressuring in the Deep-Basin Brine aquifer.

The westward retreat of the Caprock Escarpment, which results in a drop in water table in the shallow aquifer, significantly affects the hydraulic heads in the deep seciton (head decline of up to 250 m in the deep section). The model shows that because of the relatively permeable granite wash in the eastern part of the cross section (proximal deposits), hydraulic heads beneath the evaporite sequence can adjust more readily to the lower hydrostatic heads at the eastern boundary of the model than to the higher heads of the High Plains aquifer.

Results of simulation T-5 (retreat of the Caprock Escarpment) imply that significant underpressuring (head difference between shallow aquifer and deep section is in excess of 175 m) observed beneath the Evaporite aquitard occurred within the last one to two million years as a result of the cap-rock retreat. The resulting change of hydraulic head distribution during that period suggests a significant effect on the overall ground-water flow pattern in the deep section within the last one to two million years. This could be an important factor with regard to the chemical evolution of deep basinal brines.

The modeling effort also suggested that hydrocarbon production and the concomitant reduction in reservoir pressure affect hydraulic heads only locally and do not influence the regional ground-water flow regime in the Deep-Basin Brine aquifer. Similarly, erosional unloading in connection with the retreat of the Caprock Escarpment can be considered ineffective in creating large-scale underpressuring in the Deep-Basin Brine aquifer. Only in the direct vicinity of the escarpment might erosional unloading cause relativley lower pressure in the underlying aquitard.

Evaluation of the hydrodynamic development in the past can be used to assess changes in hydrologic conditions caused by possible tectonic and geomorphologic processes during the lifetime of a nuclear repository. In the context of the time period (10,000 years) that has to be evaluated according to the waste isolation performance assessment, the modeling results indicate that the regional hydrodynamics of the basin will not be significantly affected by tectonic or geomorphologic processes occurring in such time frames observed in the past. However, local hydrologic conditions could be significantly affected in the vicinity of the Caprock Escarpment by cap-rock retreat and in the vicinity of depleted hydrocarbon reservoirs as a result of depressured conditions.

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TABLE CAPTIONS

Table 1. Generalized stratigraphic column of the Palo Duro Basin (modified fromn Bassett and Bentley, 1983).

Table 2. Assigned hydraulic conductivity values for the major hydrologic systems.

Table 3. Summary of transient simulations describing the different tectonic and geomorphologic processes during Cenozoic time.

FIGURE CAPTIONS

Figure 1. Structural features of Texas Panhandle and adjacent areas (modified from Nicholson, 1960).

Figure 2. Regional east-west cross section illustrating spatial relationships of the major depositional systems in the Palo Duro Basin (after Bassett and others, 1981).

Figure 3. Finite Element Mesh representing the major hydrologic units (after Senger and Fogg, 1983). Each element is assigned a hydraulic conductivity value. Numbered labels on the elements correspond to geologic facies listed in Table 2. The upper surface of the mesh is represented with prescribed head boundary conditions and reflects the water-table conditions. Heads are assumed to be uniform with depth along the eastern boundary. The lower surface of the mesh is a no-flow boundary which corresponds to the contact between Deep-Basin Brine aquifer and basement rock.

Figure 4. Simulation T-1 of computed hydraulic head distribution with hydraulic conductivities from Table 2. Hydraulic head distribution represents the hypothetical pre-uplift hydrodynamic conditions assuming an overall hydraulic gradient across the surface of the model of 100 m.

Figure 5. Simulation T-2 of computed hydraulic head distribution, representing hydrodynamic conditions 10 million years after the beginning of the uplift event. During the first million years, hydraulic heads at the surface nodes were gradually increased by up to 1,100 m (3,600 ft) for the westernmost node relative to the heads along the eastern boundary which were kept constant. Initial conditions represent the results from simulation T-1.

Figure 6. Simulation T-3 of computed hydraulic head distribution representing hydrodynamic conditions 10 million years after the beginning of Ogallala deposition. During the first million years, hydraulic heads at the surface nodes

were gradually increased by up to 130 m (430 ft). Prescribed hydraulic heads along the High Plains surface were correlated with heads computed in simulation A-2 (Senger and Fogg, 1984). Initial conditions are the computed heads from simulation T-2.

Figure 7. Simulation T-4 of computed hydraulic head distribution representing hydrodynamic conditions 5 million years after the onset of the Pecos valley erosion. Hydraulic heads at the boundary nodes of the area were gradually reduced during the first 4 million years to a level corresponding to the approximate valley topography. Initial conditions are the computed heads from simulation T-3.

Figure 8. Difference in hydraulic heads before and after Pecos River erosion.

Figure 9. Simulation T-5 of computed hydraulic head distribution representing hydrodynamic conditions 1.1 million years after the gradual retreat (18 cm/yr) of the Caprock Escarpment starting at the eastern boundary of the model. Initial conditions are the computed heads from simulation T-4.

Figure 10. Difference in hydraulic head before and after Caprock retreat.

Figure 11. Steady-state hydraulic head distribution based on simulation A-2 (Senger and Fogg, 1984), which was considered to be the most realistic representation of the hydrologic flow regime in the Palo Duro Basin.

Figure 12. Simulation H-1 of computed hydraulic head distribution representing the hydrodynamic conditions as a result of hydrocarbon production 100 years after the beginning of gradual reservoir pressure decline.

Table 1. Generalized stratigraphic column of the Palo Duro Basin (modified from Bassett and Bentley, 1983).

System	Series	Group	General lithology and depositional setting	Hydrogeologic element	Hydrogeologic unit
Quaternary			Fluvial and lacustrine clastics		
Tertiary				Ogallala aquifer	Shallow aquifer
Cretaceous			Nearshore marine clastics		
Triassic		Dockum	Fluvial deltaic and lacustrine clastics and limestones	Dockum aquifer	
Permian	Ochoa				
	Guadalupe	Artesia	Salt, anhydrite, red beds and peritidal dolomite	Evaporite Aquitard	Evaporite Aquitard
		Pease River			
	Leonard	Clear Fork			
		Wichita			
	Wolfcamp			Wolfcamp carbonate aquifer	Deep-Basin Brine Aquifer: Wolfcamp carbonate
Pennsylvanian			Shelf and platform carbonates, basin shale and deltaic sandstones	Pennsylvanian carbonate aquifer	Wolfcamp granite wash
			Basin shale	Upper Paleozoic granite wash aquifer	Basin shale
					Pennsylvanian carbonate
Mississippian			Shelf limestone and chert	Lower Paleozoic carbonate aquifer	Pennsylvanian granite wash
Ordovician		Ellenburger	Shelf dolomite		
Cambrian			Shallow marine (?) sandstone	Lower Paleozoic sandstone aquifer	Pre-Pennsylvanian-age rock
	Precambrian		Igneous and metamorphic	Basement aquiclude	Basement aquiclude

Table 2. Assigned Hydraulic Conductivity Values for the Major Hydrologic Systems.

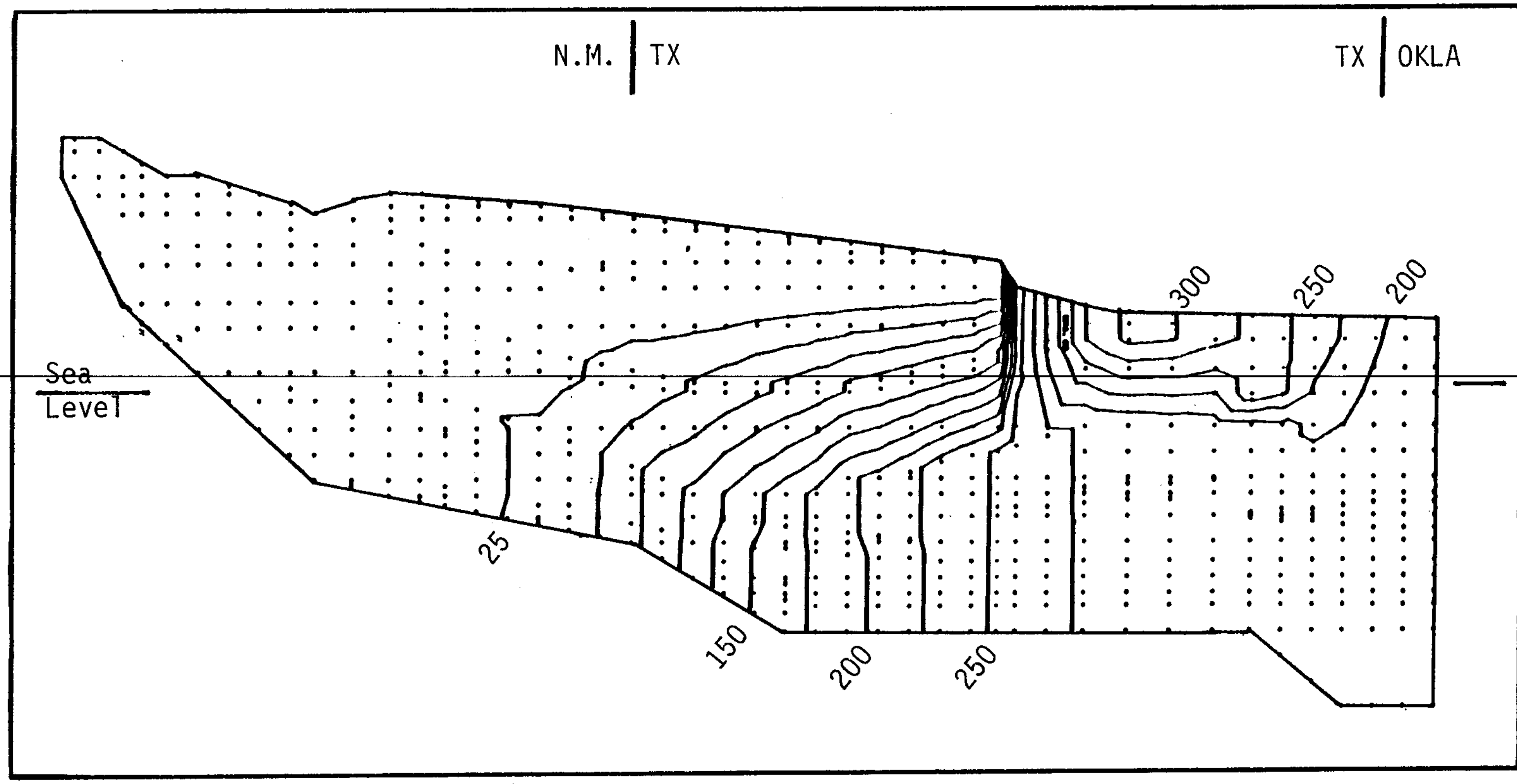
Hydrologic Unit	Hydraulic Conductivity (m/day) Horizontal (K_x)	Vertical (K_z)	Specific Storage[6] (m^{-1})
1. Ogallala fluvial system[1]	8.0×10^{0}	8.0×10^{-1}	10^{-4}
2. Triassic fluvial/lacustrine system[1]	8.0×10^{-1}	8.0×10^{-2}	10^{-4}
3. Permian (salt dissolution zone)[3]	8.2×10^{-2}	8.2×10^{-4}	10^{-4}
4. Permian sabkha system[4]	3.2×10^{-7}	3.2×10^{-7}	10^{-4}
5. Permian mudflat system[2]	8.2×10^{-5}	8.2×10^{-5}	10^{-4}
6. Permian/Pennsylvanian shelf carbonates[4]	1.3×10^{-2}	1.3×10^{-4}	10^{-4}
7. Permian/Pennsylvanian basinal systems[4]	1.1×10^{-7}	1.0×10^{-7}	10^{-4}
8. Permian/Pennsylvanian mudflat and alluvial/fan delta system[2]	8.2×10^{-2}	8.2×10^{-4}	10^{-4}
9. Permian/Pennsylvanian fan delta system	$1.0\text{-}12. \times 10^{-2}$	$1.0\text{-}12. \times 10^{-4}$	10^{-4}
10. Inner shelf and coastal sabkha systems (San Andres Cycle 4 dolomite)[5]	1.2×10^{-4}	1.2×10^{-4}	10^{-4}

Sources of data:

1. K_x from Myers (1969); assumed $K_x/K_z = 10$
2. Typical value of geologic material (Freeze and Cherry, 1979).
3. K_x from U.S. Geological Survey open-file data; assumed $K_x/K_z = 100$.
4. After Wirojanagud and others (1984).
5. After Dutton (1983).
6. After Toth and Millar (1983).

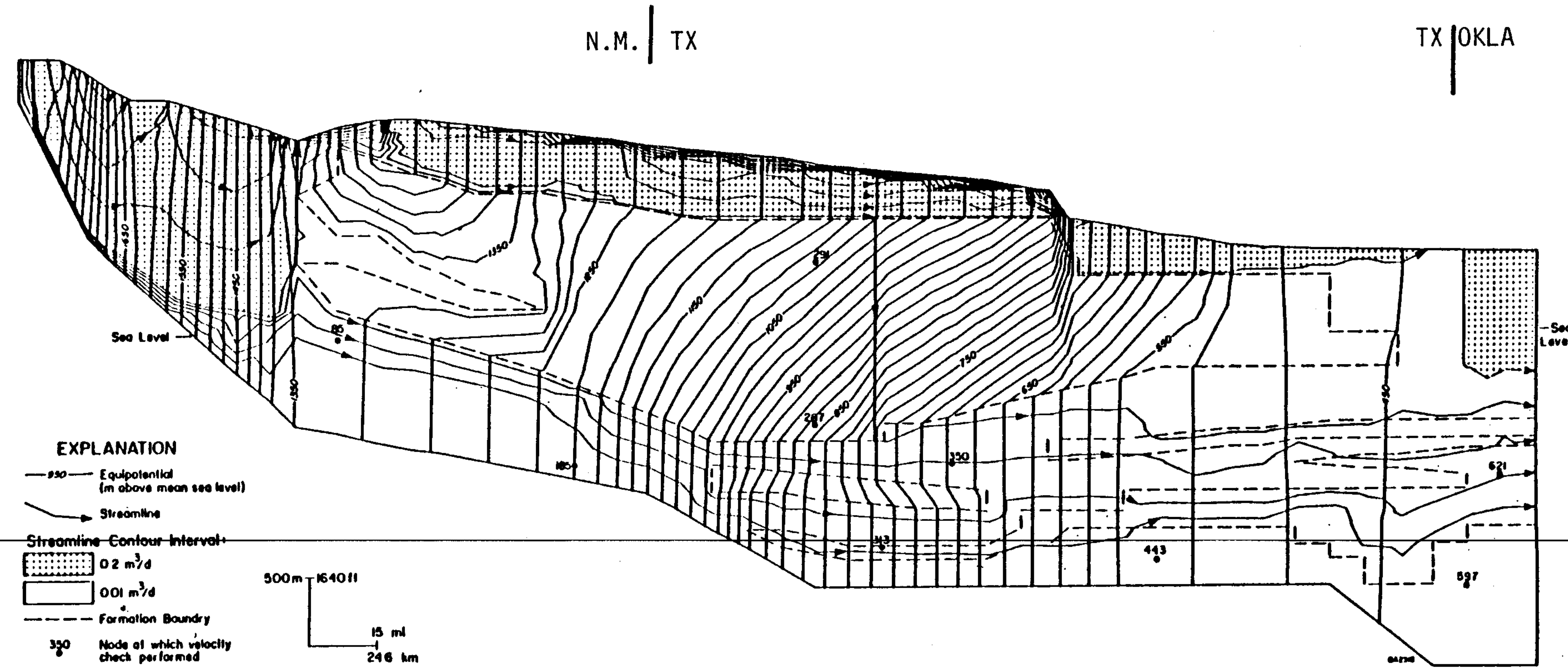
Table 3. Summary of Simulations Representing the Different Tectonic and Geomorphologic Events

Simulation	Event/Process	Geologic Time Period	Simulated Time Period	Boundary Conditions	Hydrodynamic Conditions at the End of Simulation
T-1	Pre-Uplift	Prior to 15 m.y.	w.a.	Prescribed heads along the surface ranging from 600 m in the east to 700 m in the west	Steady-state
T-2	Uplift and Tilting	~15 m.y. to ?	10 m.y.	Increase prescribed heads along the surface from 0 m at the east to 1,100 m at the west during first 1 m.y.	Approximate steady-state
T-3	Deposition of Ogallala	~13 m.y. to ~3 m.y.	10 m.y.	Increase prescribed heads along the surface from 50 m in the east to 130 m in the west during first 1 m.y.	Approximate steady-state
T-4	Erosion of the Pecos River Valley	Within the last 5 m.y.	5 m.y.	Decrease of prescribed heads along the Pecos River valley by up to 325 m during the first 4 m.y.	Overall steady-state
T-5	Westward Retreat of Caprock	Within the last 3 m.y.	1.1 m.y.	Decrease of prescribed heads along the present day Rolling Plains surface corresponding to rate of caprock retreat of 18 cm/yr	Local transient conditions
H-1	Effect of Hydro-carbon Production	Within the last 60 yrs	100 yrs	Decrease prescribed heads of two node locations by 200 m during the first 50 yrs	Local transient conditions



—— Hydraulic head difference (negative) between simulations T-4 and T-5
Contour interval = 25 m

Figure 10. Difference in hydraulic head before and after Caprock retreat.



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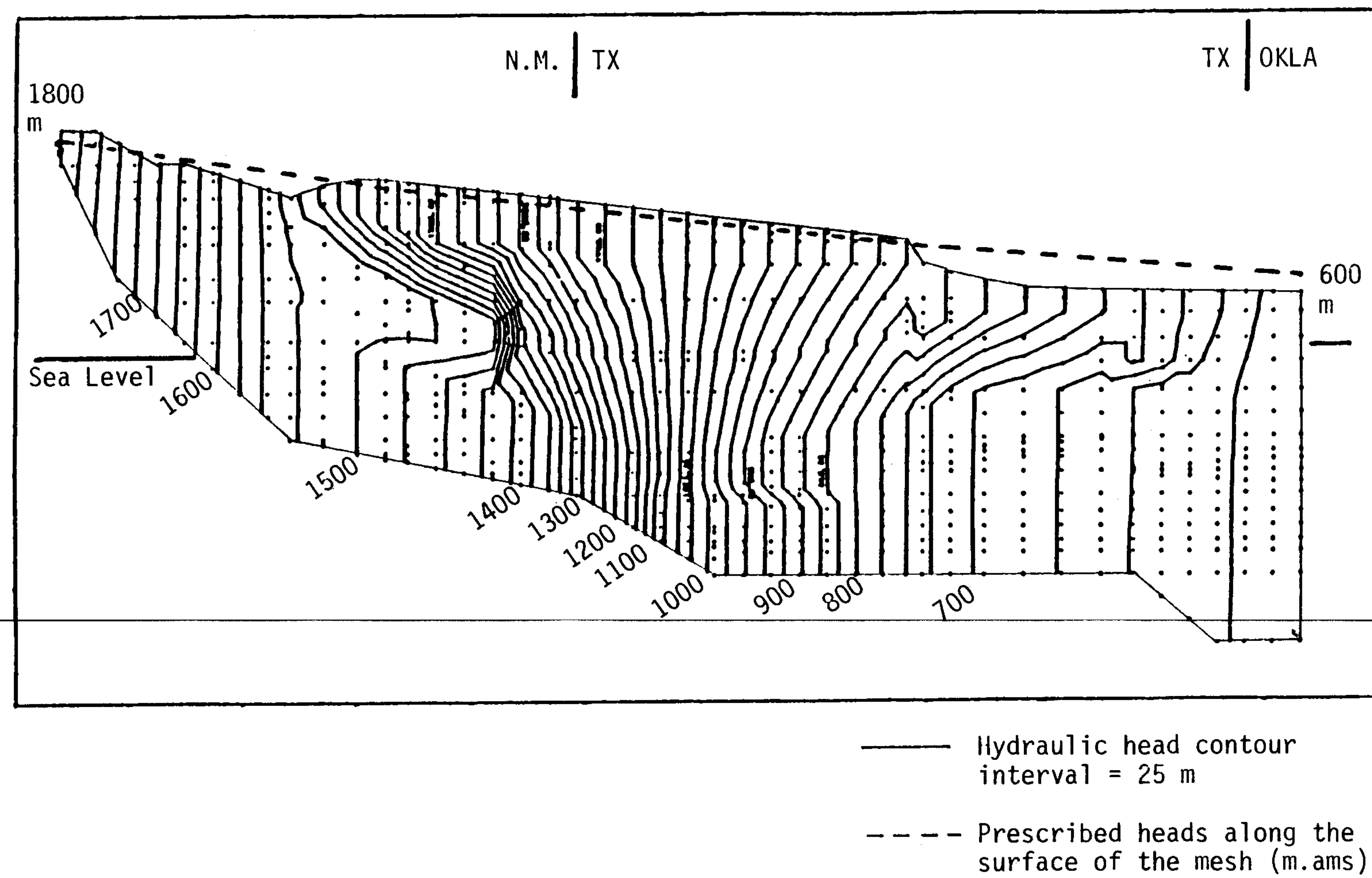

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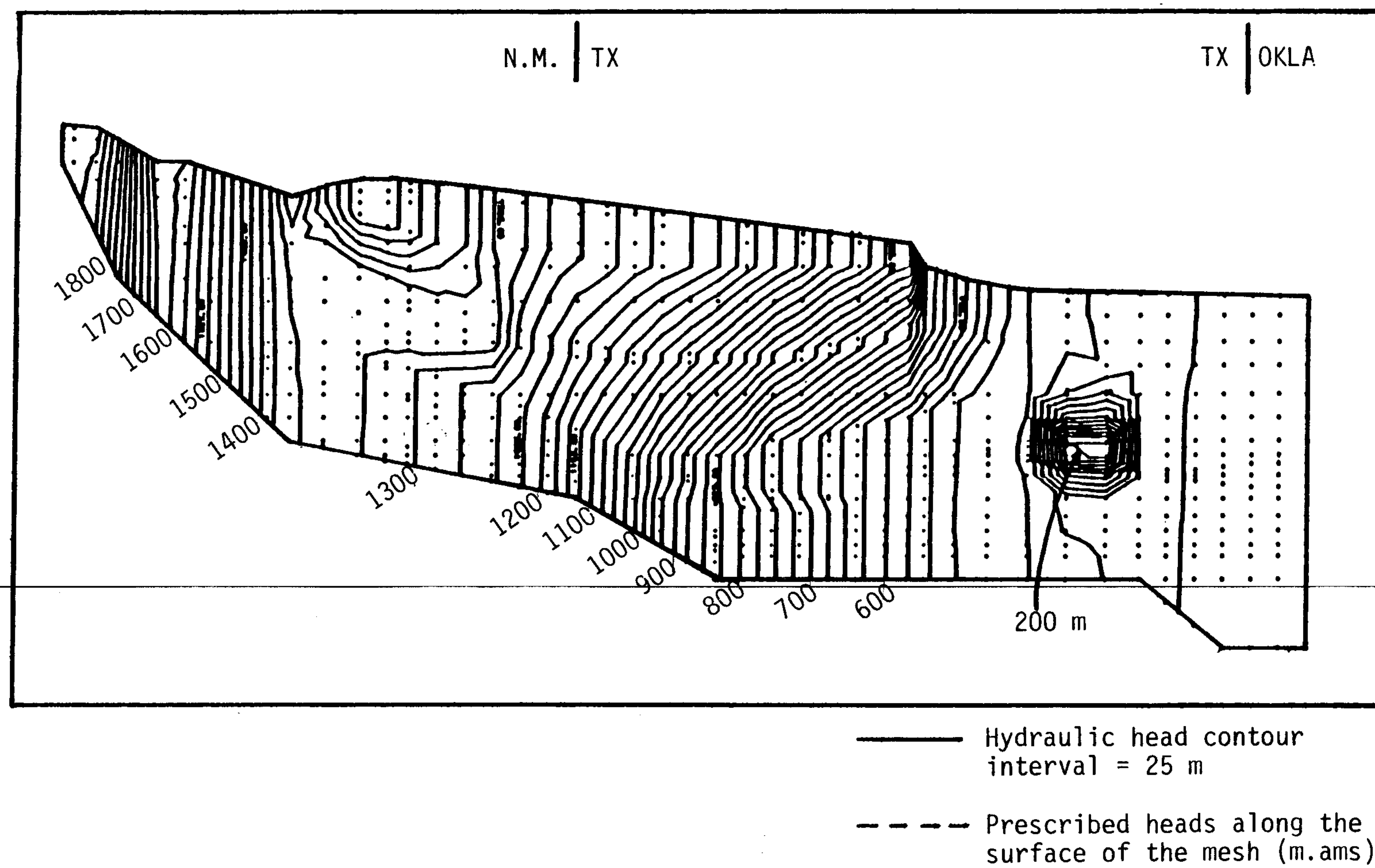

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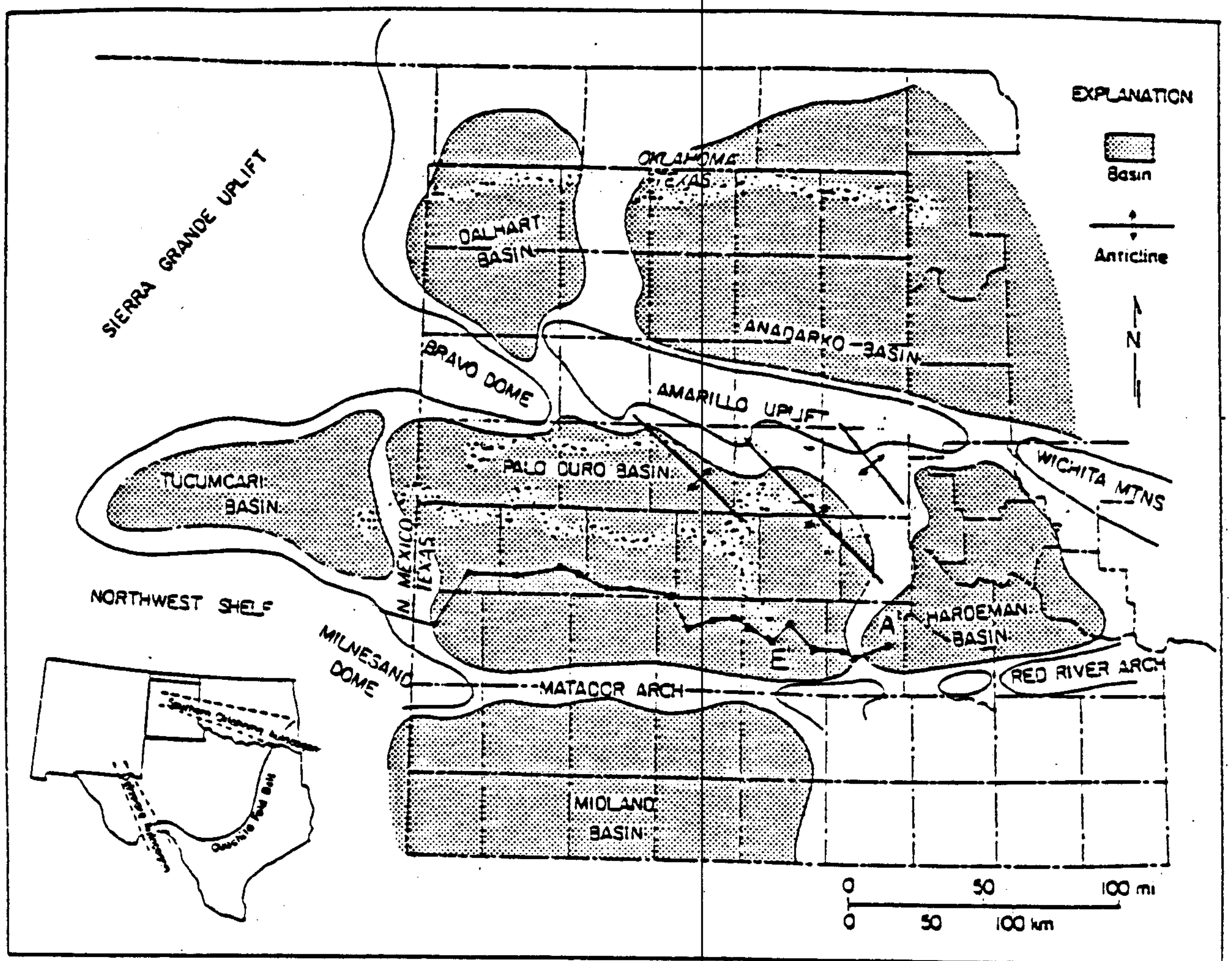

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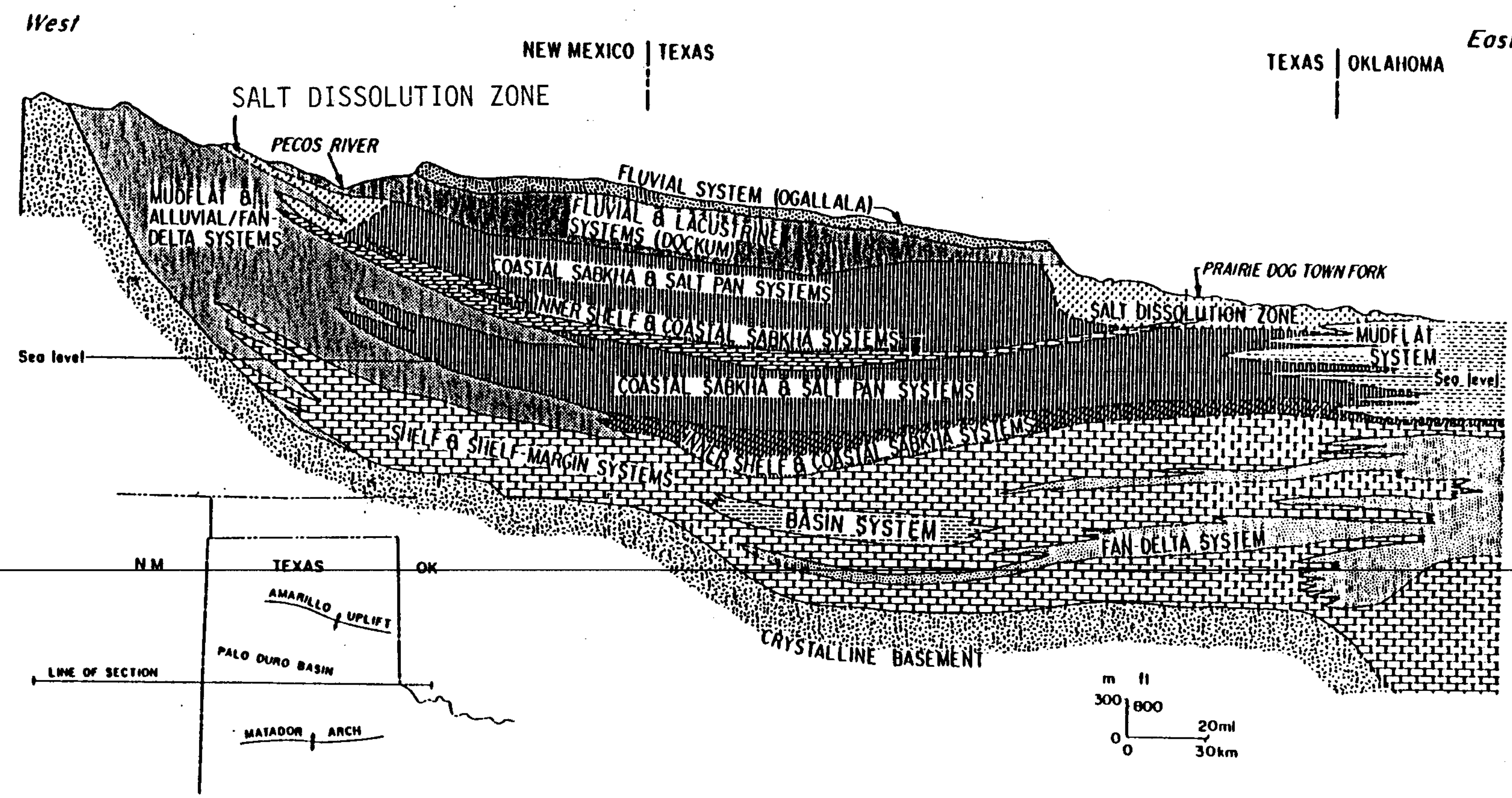

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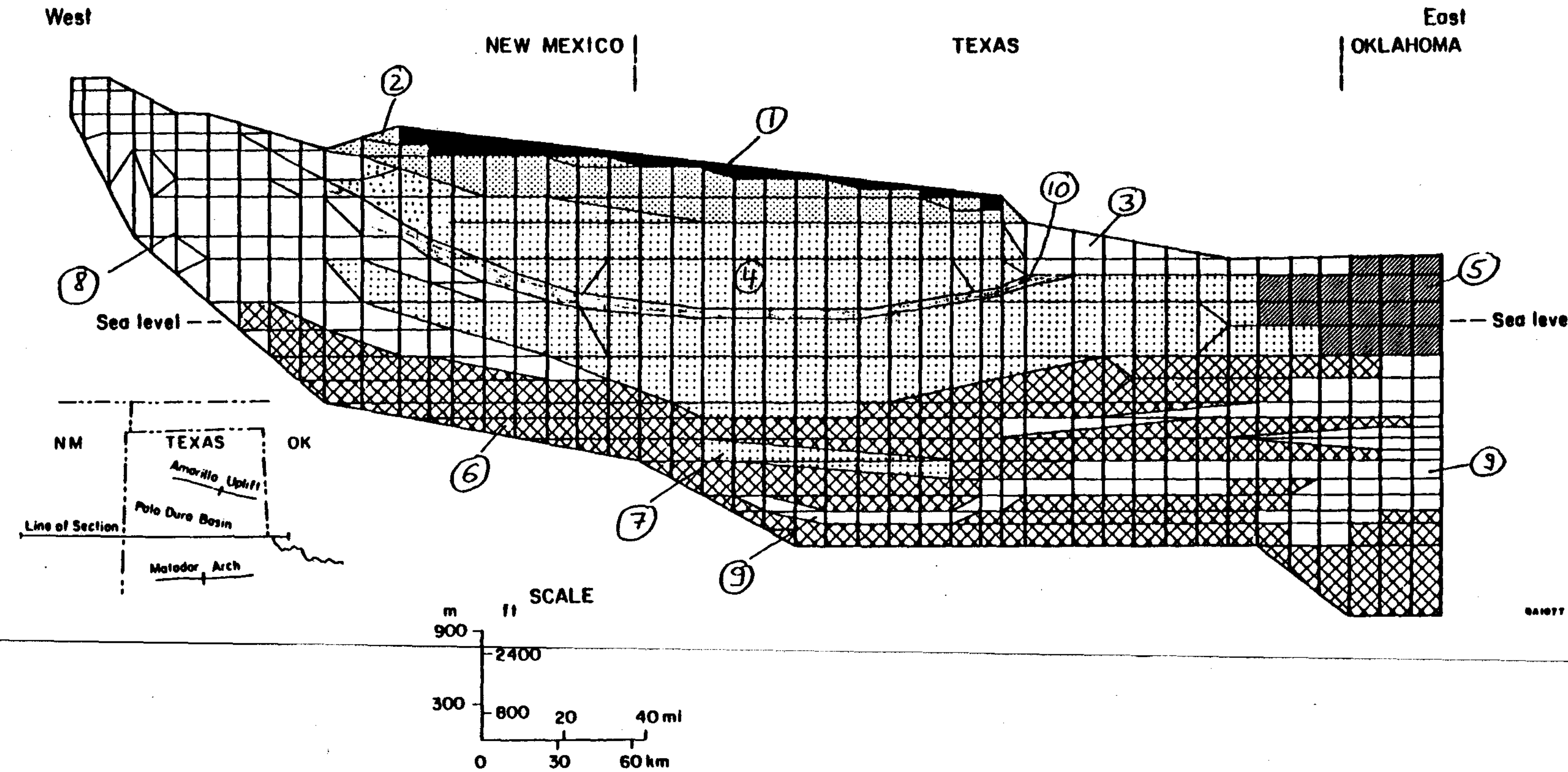

(3) Hydrologic units listed in Table 2.

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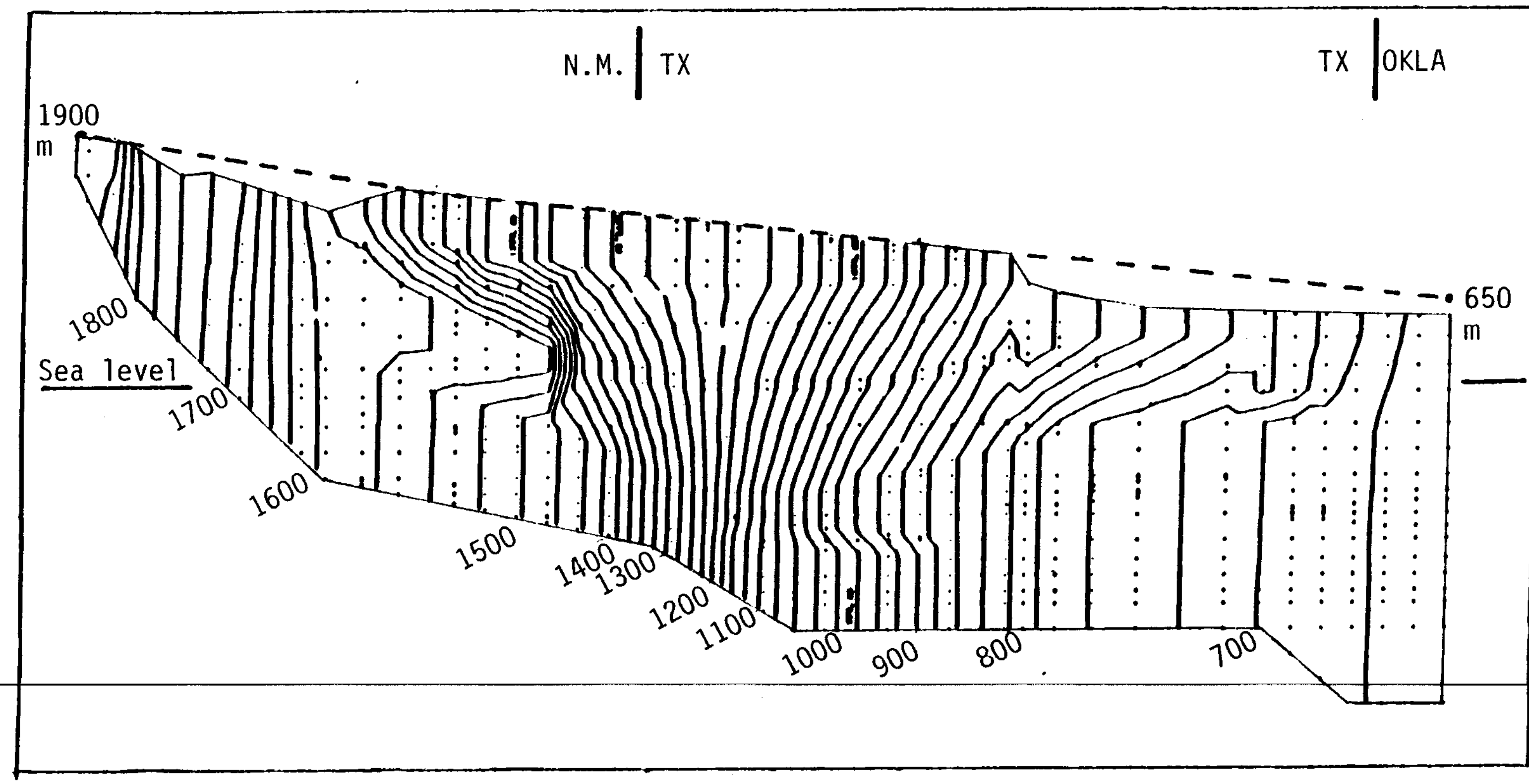

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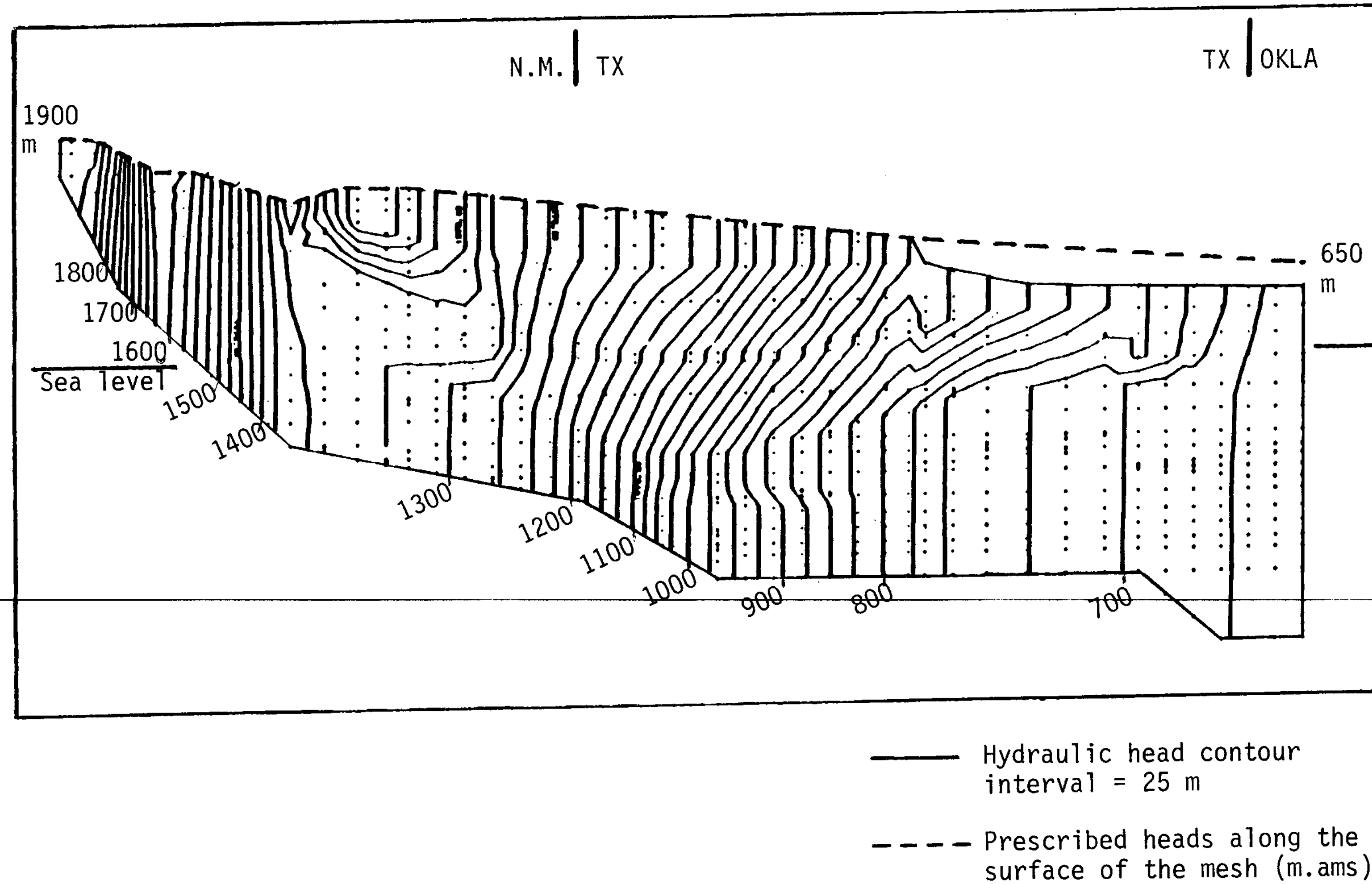

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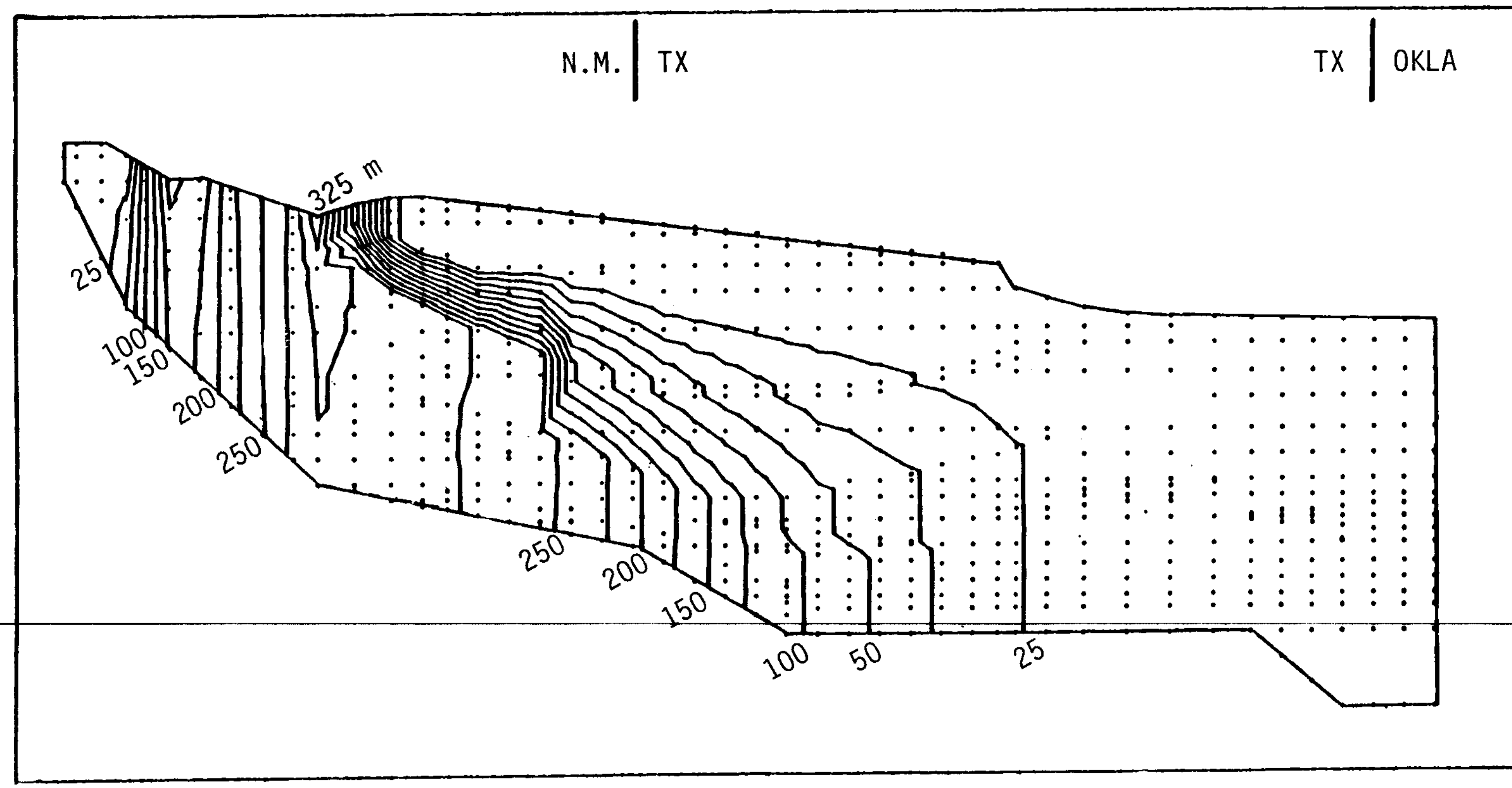
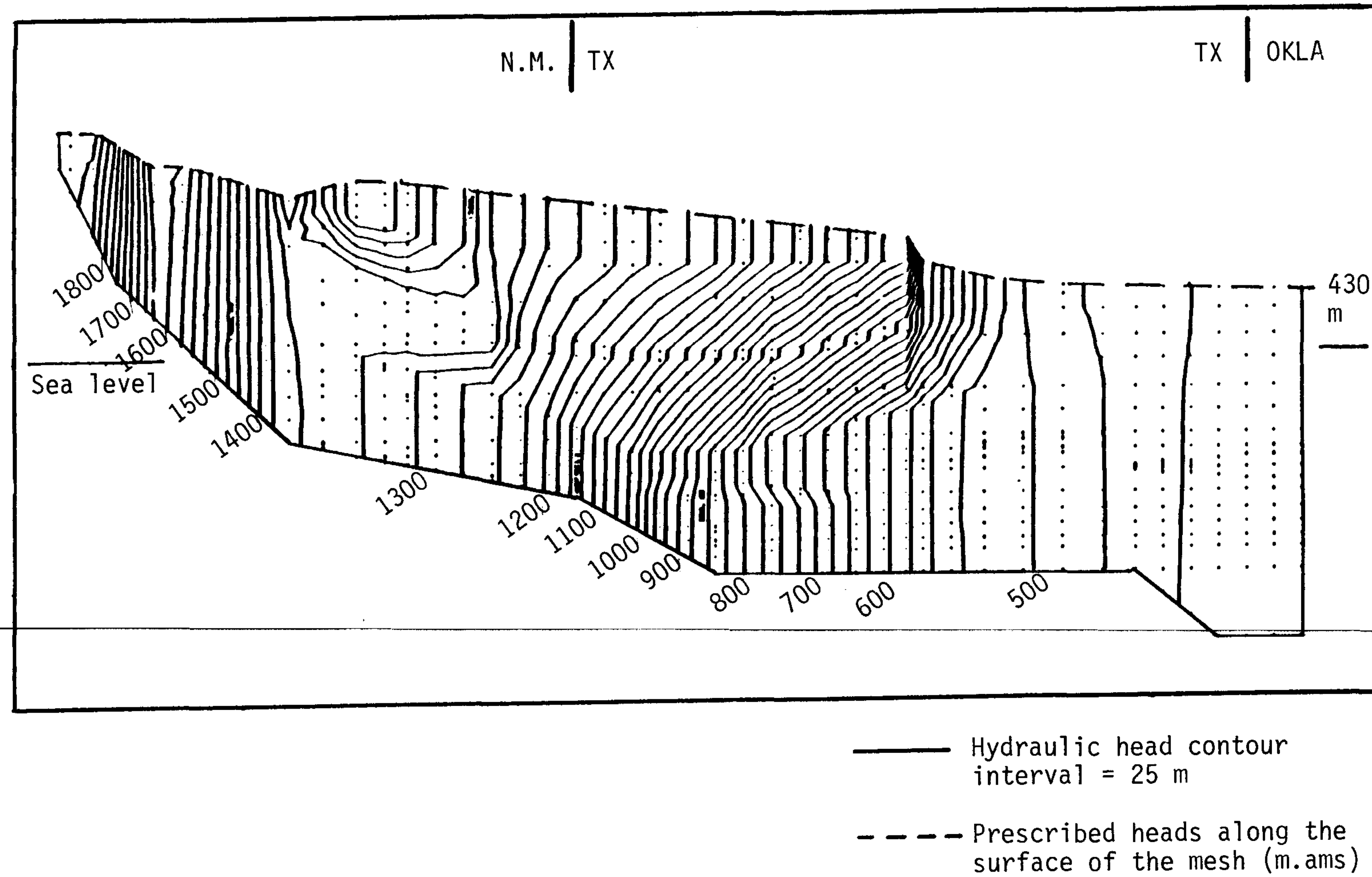


Hydraulic head difference (negative) between simulations T-3 and T-4. Contour interval = 25 m

Figure 8. Difference in hydraulic heads before and after Pecos River erosion.



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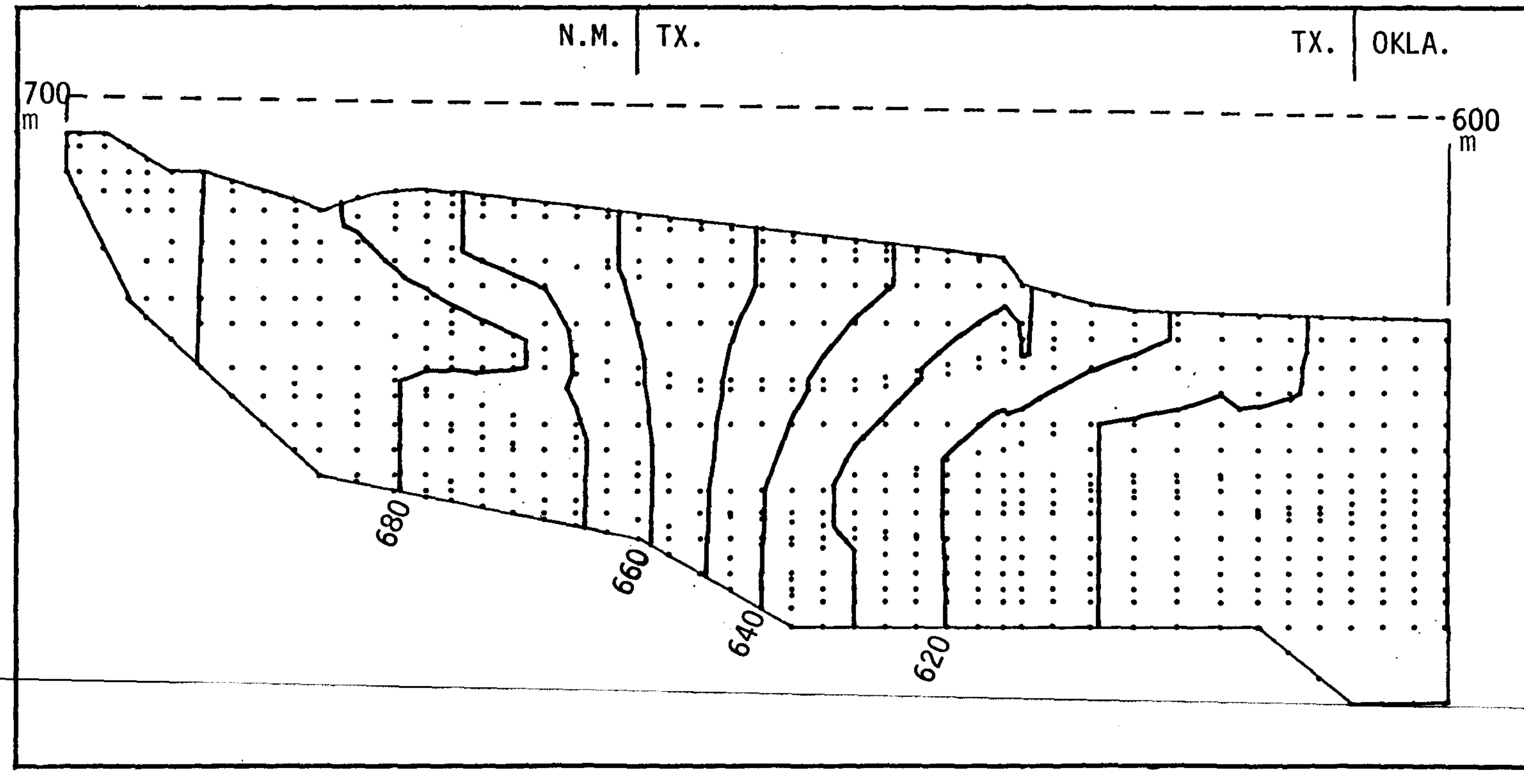

Hydraulic head contour interval = 10 m

Prescribed heads along the surface of the mesh (m.ams)

Figure 4. Simulation T-1 of computed hydraulic head distribution with hydraulic conductivities from Table 2. Hydraulic head distribution represents the hypothetical pre-uplift hydrodynamic conditions assuming an overall hydraulic gradient across the surface of the model of 100 m.