EVALUATION AND MODELING OF GROUNDWATER SUPPLY

IN ARBUCKLE-SIMPSON AQUIFER,

OKLAHOMA

By

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CHAPTER I

INTRODUCTION

Groundwater is one of the most important natural resources of every nation. It is a source of drinking water to communities, industries and agriculture, and sustains streams and wetlands. Groundwater movement in sand and gravel aquifers has been understood to a great extent. Understanding of groundwater movement in fractured rock aquifers where the water moves through fractures in the rock is of great importance because of increasing demand for drinking water. The Arbuckle-Simpson Aquifer is vast source of fresh water, which is vital to the future of south central Oklahoma. The protection of water, in terms of both quantity and quality is critical to sustained municipal, agricultural, and recreational health of the area.

The legislature of Oklahoma imposed a moratorium on pumping groundwater from the Arbuckle-Simpson Aquifer in light of a recent proposal to transfer as much as 80,000 acre-feet per year of that water to central Oklahoma. Several cities and towns in Canadian County have exhibited interest in construction of an 88-mile pipeline to provide future water supply to those

communities. However, because of the lack of understanding, the existing quantity of groundwater supply in this aquifer and its interaction with natural springs, the legislature stopped any plans to supply groundwater. The Arbuckle-Simpson Aquifer is the only groundwater basin in Oklahoma. The moratorium prohibits the municipal and political subdivisions outside the basin from entering into contracts for use of the water. The moratorium will remain in effect until the OWRB completes its study of Arbuckle-Simpson and approves a maximum annual yield that will not reduce the natural flow of water from springs or streams emanating from the aquifer. A comprehensive multi-year study of South Central Oklahoma's Arbuckle-Simpson Aquifer has already been initiated. The objective of this study is to obtain more information about the aquifer, required to determine how water resources in the aquifer region should best be utilized without affecting the flow of springs and streams in the area (OWRB, 2003). The purpose of this research is to evaluate the potential groundwater supply in the aquifer and its relationship with existing natural springs in the aquifer area using modeling as a tool.

Objective

The purpose of this study was to evaluate the response of Arbuckle-Simpson Aquifer to natural recharge and withdrawal of groundwater in a pumping well. The objectives were as follows:

1. To integrate data for application of a finite element model of two-dimensional groundwater flow in the Arbuckle-Simpson Aquifer.
2. To apply the groundwater flow model for predicting future water levels in Arbuckle-Simpson Aquifer.
3. To study the impact of high pumping on the Arbuckle-Simpson Aquifer.

The FEFLOW 5.1 model was applied to the Arbuckle-Simpson Aquifer to predict its head distribution in response to recharge, discharge, and fluxes.

CHAPTER II

BACKGROUND

Location of Study Area

The Arbuckle-Simpson Aquifer in south-central Oklahoma underlies approximately 500 square miles primarily in Pontotoc, Johnston and Murray Counties as shown in Figure II-1. The Arbuckle-Simpson Aquifer is an important natural resource of water supply for approximately 39,000 people in the Cities of Ada and Sulphur (OWRB, 2003). Arbuckle-Simpson Aquifer is the source of water for a number of important springs and streams in the region, including those associated with the Chickasaw National Recreational Area, which are of great concern due to number of visitors who consume water of this area. The aquifer provides base flow to the Blue River, Pennington Creek, Mill Creek, Rock Creek, Oil Creek and Sycamore Creek. These streams discharge into the Washita and Red Rivers. The aquifer also discharges to numerous springs, with Byrds Mill Spring being the primary drinking water source for the City of Ada. The Arbuckle-Simpson Aquifer water is used by a large percentage of population

of Pontotoc, Johnston and Murray counties in addition to the citizens of Ada and it is the only source of water for the City of Ada. Due to this fact, the U.S. Environmental Protection Agency designated the eastern portion of Arbuckle-Simpson Aquifer as a "sole source aquifer" in 1989 (Fairchild et. al., 2003).

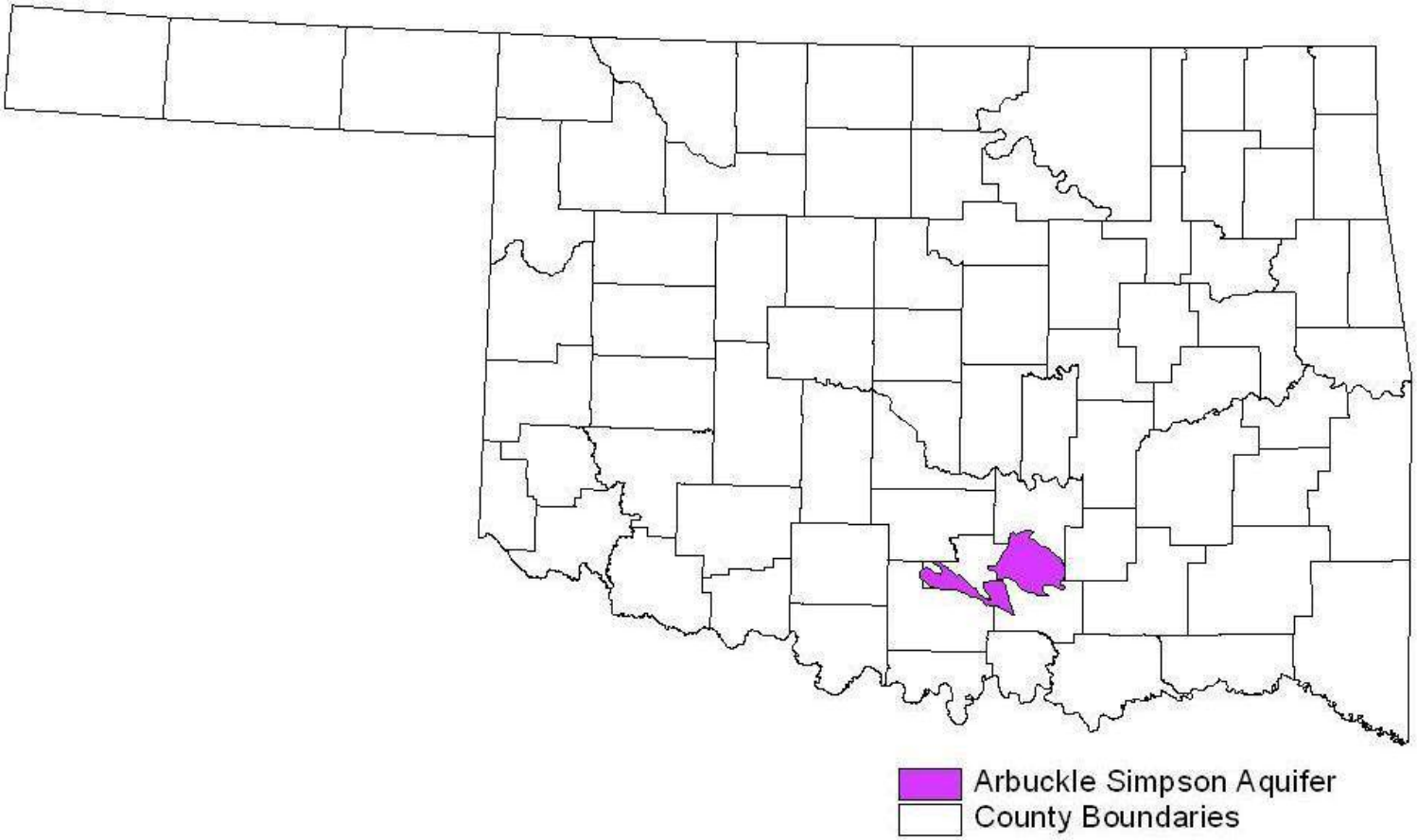

Figure II-1: Location of Study Area (USGS, 2003)

Hydrogeology of Arbuckle-Simpson Aquifer

The Arbuckle-Simpson Aquifer consists of limestone, dolomite, and sandstone within the Simpson and the Arbuckle Groups of Ordovician and Cambrian age (Hanson and Cates, 1994). The Arbuckle-Simpson Aquifer consists of several formations that make up the Arbuckle and Simpson Groups. Although each formation in each group may have different water yielding characteristics, they are considered together to make up the Arbuckle-Simpson Aquifer because of the similarity of rocks in both of these groups (Savoca et. al., 1994; Hanson and Cates, 1994). The Arbuckle group is the oldest stratum, which is present beneath several hundred square miles of South Central Oklahoma. The thickness of these groups varies due to the erosional surface at the top (Hanson and Cates, 1994). The Arbuckle-Simpson Aquifer consists of a thick sequence of carbonate (dolomite and limestone) and clastic rocks (Savoca et. al., 1994). Approximately two thirds of the aquifer consists of limestone and dolomite. The Arbuckle mountain area in underlain mainly by dolomite in eastern part but mainly limestone in western part of the area (Fairchild et. al., 1990). These rocks are greatly folded, faulted and jointed in the region. The area is dominated by Northwest and Northeast trending faults. There are extreme variations in the geometry between strike-slip, dip-slip and over thrust faults (Hanson and Cates, 1994). Karst features are present throughout the area. The aquifer is as much as 9,000 feet thick. Freshwater may extend to depths of greater than 3,000 feet. The aquifer is a principal source of water for

municipal and rural users. Average annual precipitation in the region is about 34 to 39 inches. The rate of recharge, which is approximately 4.7 inches per year, limits the amount of water that can be pumped from the basin without severely drying up existing springs and streams. The aquifer discharges the excess water when it is full that supports the flow in approximately 100 springs.

Various studies on the aquifer were conducted to determine the hydraulic characteristics of the aquifer based on the several accepted analytical techniques According to a report by Fairchild, Hanson, and Davis (1990), the specific capacity of wells ranges from 0.17 to 104 gallons per minute per foot (gal/min/ft). The specific capacity for deep wells is higher because they penetrate more fractures and solution channels than the shallow wells that penetrate only the upper part of the aquifer. It has been found that the upper few hundred feet of the Arbuckle Group has a much lower permeability than the lower part. This increase in specific capacity and permeability with depth indicates the complexity in geologic and structural nature of the rocks. According to the report, "the average transmissivity of the aquifer is estimated to be 15,000 feet squared per day and the average storage coefficient where the aquifer is confined is estimated to be .008, and in unconfined areas, the aquifer has an estimated specific yield of 20 percent" (Fairchild et. al., 1990). The volume of water stored in the Arbuckle-Simpson Aquifer can be computed from the saturated thickness and the storage coefficient. The volume of water in the aquifer, assuming a storage coefficient of 0.008, is about 9 million acre-ft that is

available to wells with in the 500 mi^2 of outcrop area. An undetermined amount of fresh water probably exists a short distance down dip in the aquifer (Fairchild et. al., 1990). Wells completed in the Arbuckle-Simpson Aquifer commonly yield from 100 to 500 gallons per minute and locally yield as much as 2,500 gallons per minute. Springs that issue from the aquifer discharge from 50 to 18,000 gallons per minute (Fairchild et. al., 1990). According to a report by Barathel (1985), the effective porosity for Arbuckle Group ranges from 7.4 to 10.4 percent and from 2.3 to 11.4 for the Simpson Group (Barathel, 1985).

The data records for water levels in different wells indicate that the amount of water in storage averages about the same but varies seasonally and fluctuates with the high precipitation and low precipitation periods in the area (Fairchild et. al., 1990). Several flowing artesian wells have been drilled since the last few decades. Discharge from many of these springs and the numbers of flowing wells have declined substantially during the past 86 years (Savoca et. al., 1994). To determine the cause of these declines, a better understanding of the hydrologic system must be obtained since the hydraulic characteristics of an aquifer describe its ability to store and transmit water.

Recharge

The aquifer is confined at some places and unconfined at another. The Arbuckle-Simpson Aquifer is described as confined where it is bounded by impermeable layers. These layers usually do not run parallel to the ground and they intersect the ground's surface in some areas resulting in an area of higher elevation, like the mountains (Propst et. al, 2002). The aquifer is unconfined in the areas where the impermeable layers and ground surface intersect. The recharge of the aquifer through infiltration and percolation of surface water takes place in these areas. Areas whose runoff flows to this intersection of impermeable layers and ground surface, come in the recharge zone of the aquifer (Propst et. al, 2002). Some recharge to the aquifer also occurs from streams flowing in recharge zone infiltrating through deposits and rocks fractures in the stream channel. The drainage area for these streams may be outside of the recharge zone, however the runoff from this "source area" for stream flow may still reach the aquifer (Propst et. al, 2002). The activities with in both the recharge zone and "source area" for stream flow may have great impact on the water quality of entire aquifer. The precipitation on the outcrop area of the Arbuckle aquifer recharges the freshwater springs (Antelope and Buffalo Springs). The source of water from mineralized springs and flowing wells is believed to be a mix of waters from rocks of the Arbuckle and Simpson Groups. The source of water from two highly mineralized springs, Bromide and

Medicine that ceased to flow in the early 1970's is believed to be from the Simpson Group (Hanson and Cates, 1994). Water-quality characteristics reflect the sources of groundwater in the study area.

Most of the recharge to the aquifer occurs from precipitation that falls on aquifer outcrop areas and the rate of recharge varies from place to place because of differences in permeability of the aquifer and soil and the average recharge is estimated to be 4.7 inches per year (Fairchild et. al., 1990). Most natural recharge takes place by infiltration of precipitation into soil cover or outcrops of porous rock. In some places, water enters small sinkholes or solution pipes in the carbonate rocks. Intense faulting of the rocks affects the groundwater flow system because faults might act as barriers to groundwater movement or as conduits through which water travels to the surface. Water is discharged naturally from the aquifer by numerous springs and seeps; much of this discharge becomes the base flow of streams. The base flow of streams that drain the aquifer is estimated to be about 60 percent of the total annual runoff from the Arbuckle-Simpson outcrop area (Fairchild et. al., 1990).

Reduction in Discharge

There are critical ecosystems and springs that are threatened by human actions, in the Arbuckle-Simpson Aquifer area. The Arbuckle-Simpson Aquifer loses groundwater to streams, evapotranspiration and well withdrawals (Savoca et. al., 1994). A significant trend of decreased discharge from springs with in

the Chickasaw National Recreation area has been recorded since 1906, possibly due to over pumping and uncontrolled flow of wells. Flow from the artesian wells has declined substantially during the past 86 years and the wells are estimated to currently discharge only about 10 percent of the total flow reported in 1939 (Hanson and Cates, 1994). The depletion is believed to be caused by a gradual lowering of the hydraulic head within the aquifer. The influence on the hydrologic system of local municipal and industrial pumping from the Arbuckle-Simpson Aquifer is difficult to recognize or visualize because the system is much more sensitive to precipitation than to pumpage. Groundwater levels and spring flows in this region respond rapidly to precipitation. The effects of withdrawals from the City of Sulphur and Oklahoma Gas and Electric Company power-plant water-well field are not discernible at wells and springs. Pumping, particularly during extended dry periods of several years, may influence the hydrologic system but the impact of pumping on the system cannot be determined without further investigation.

Springs

Springs are "singular points" of an aquifer system (Todd, 1980). Typically, an aquifer is recharged mainly by rainfall occurring over the catchment area and is discharged at few singular locations called springs. The discharge characteristics (head, flow rate, water temperature, water chemistry) at a spring are strongly governed by or modified by the physical nature of aquifer through which the

water has moved. Therefore, spring water provides good information about the aquifer and catchment area.

Arbuckle-Simpson Aquifer is the primary source of a number of important springs in the region, including Byrds Mill Spring, and Buffalo Spring. The springs are the areas of natural discharge from the aquifer. There are at least 100 springs, which are known to discharge water from the aquifer to streams that drain the outcrop area (Fairchild et. al., 1990). Most of the springs are gravity springs, which occur where the potentiometric surface intersects the land surface. Larger springs occur in the eastern part of the Arbuckle Mountain area (Fairchild et. al., 1990). The largest is Byrds Mill Spring, which is located about 12 miles south of Ada. Several large springs like Byrds Mill spring contribute sufficient discharge to sustain perennial flow in the receiving streams. Byrds Mill Spring is primary drinking water source of The City of Ada and The Chickasaw National Recreation Area, the destination for about 3.4 million visitors each year. With recorded flows in excess of 20 cubic feet per second (cfs) or 9,000 gallons per minute (gpm) of water, Byrd's Mill Spring is truly an incredible resource (Hanson and Cates, 1994). Acquired by forward-looking citizens in 1911, the famous spring has served as the primary water supply for the City of Ada for over 90 years. Water from Byrd’s Mill spring flows to the Ada storage reservoirs via gravity as shown in Figure II-3. From there, it is chlorinated and pumped to the water towers. Water towers distribute the water through the city's system to homes and businesses throughout Ada and Pontotoc County.

Most springs are near faults or other fractures that have been enlarged by solution in many places. In some places, springs occur on the upgradient side of faults. Many spring that discharge during, and for a short time after, the rainy season are known as "wet weather" seeps (Todd, 1980). Such springs occur where the water table is perched, and these springs cease flowing when the perched water level recedes below the spring outlet. The difference for discharge from springs in the region could also be due to the difference in the size of the catchment areas. For example, it is believed that larger springs occur in the eastern part of Arbuckle mountain area due to larger catchment area of the eastern part than the catchment area of the western part (Fairchild et. al., 1990).

The freshwater and mineralized springs in the Chickasaw National Recreation Area are also of great importance. The two principal freshwater springs are Antelope and Buffalo Springs. The Arbuckle aquifer is considered the source of freshwater for Antelope and Buffalo springs that discharge near the east boundary of Chickasaw National Recreation Area (Hanson and Cates, 1994). These springs provide the primary source of flow in Travertine Creek, a popular recreation spot. The water is chemically similar to Arbuckle-Simpson water, and recharge to the springs is most likely from the outcrop of Arbuckle-Simpson rocks to the east. Several springs in the park produce mineralized water, once valued for its medicinal qualities.

Figure II-2: Water from Byrd's Mill spring flowing to the Ada storage reservoirs via gravity (City of Ada, OK-www.adaok.com, 2004)

Streams draining the outcrop area of Arbuckle-Simpson Aquifer are sustained throughout the year by groundwater discharge to springs and seeps that discharge from the aquifer. Stream flow resulting from groundwater discharge is termed as base flow and varies in response to fluctuations in groundwater level. Because springs issue from the aquifer and discharge to the

streams in the area, the quality of water from springs and base flow in streams is similar to that of groundwater.

It was reported that many of the springs flow had dried up or had substantially decreased flows (Andrews and Burrough, 2000). Possible reasons for decreased yields from those springs include decreased pressure heads in the Arbuckle-Simpson Aquifer from free flowing artesian wells, greater withdrawals from other wells, greater evapotranspiration from introduced trees and decreases in rainfall, blockage of the spring conduits by natural collapses, and other unknown causes (Andrews and Burrough, 2000).

Figure II-3, Figure II-4 and Figure II-5 show the springs, river flowing and network of lakes in Arbuckle-Simpson Aquifer region respectively.

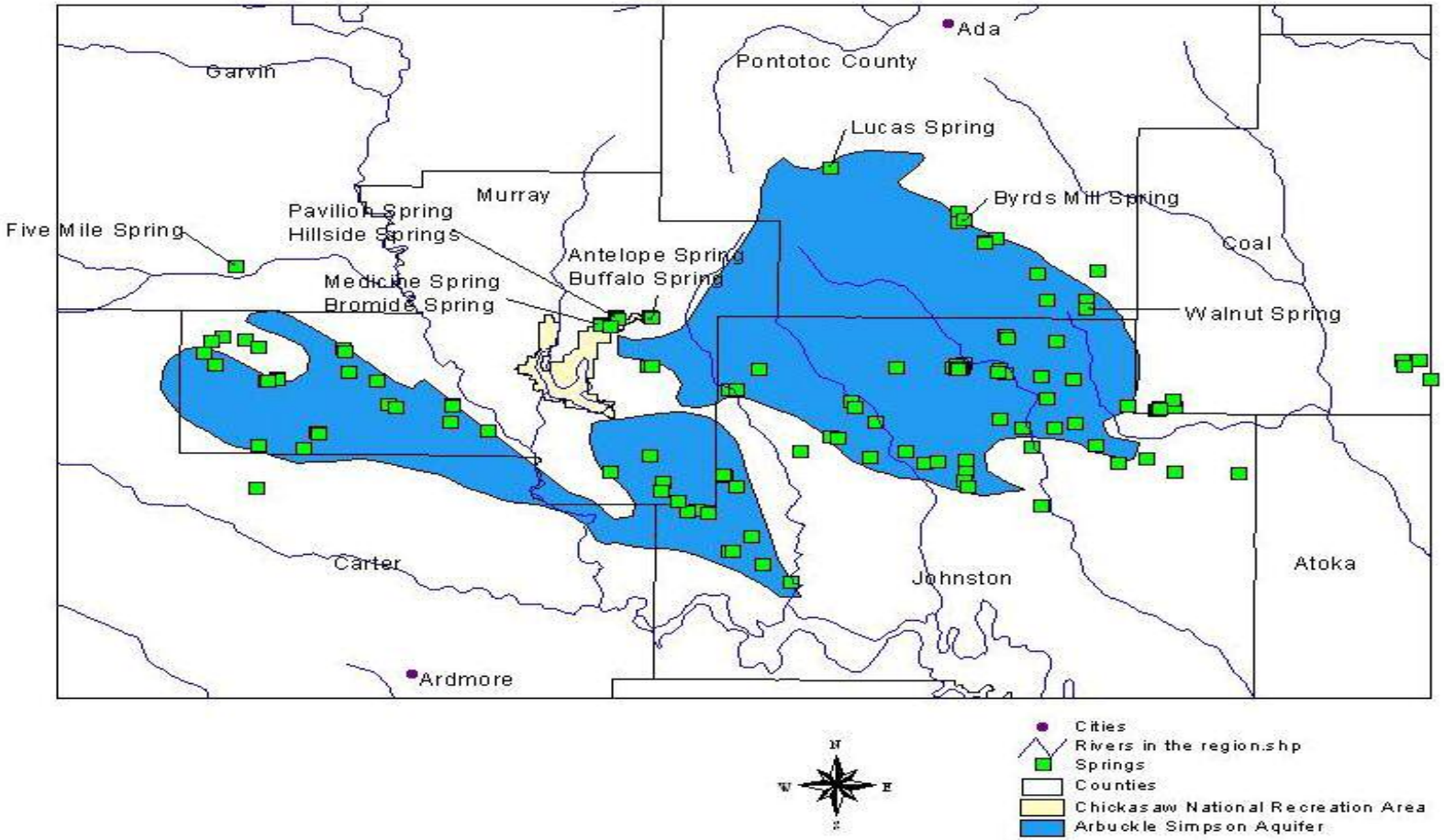

Figure II-3: Springs in Arbuckle-Simpson Aquifer Region (USGS, 2003)

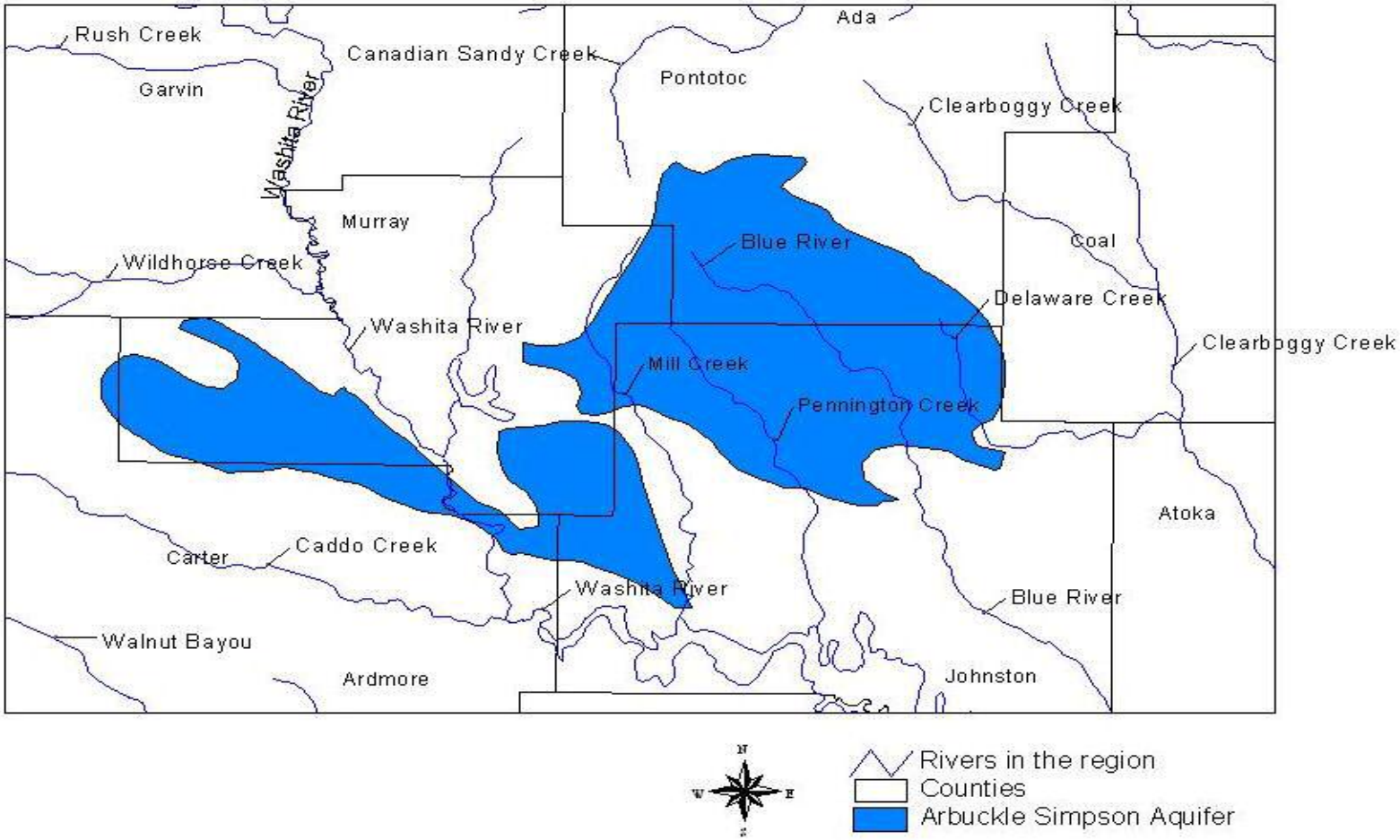

Figure II-4: Rivers flowing in Arbuckle-Simpson Aquifer (USGS, 2003)

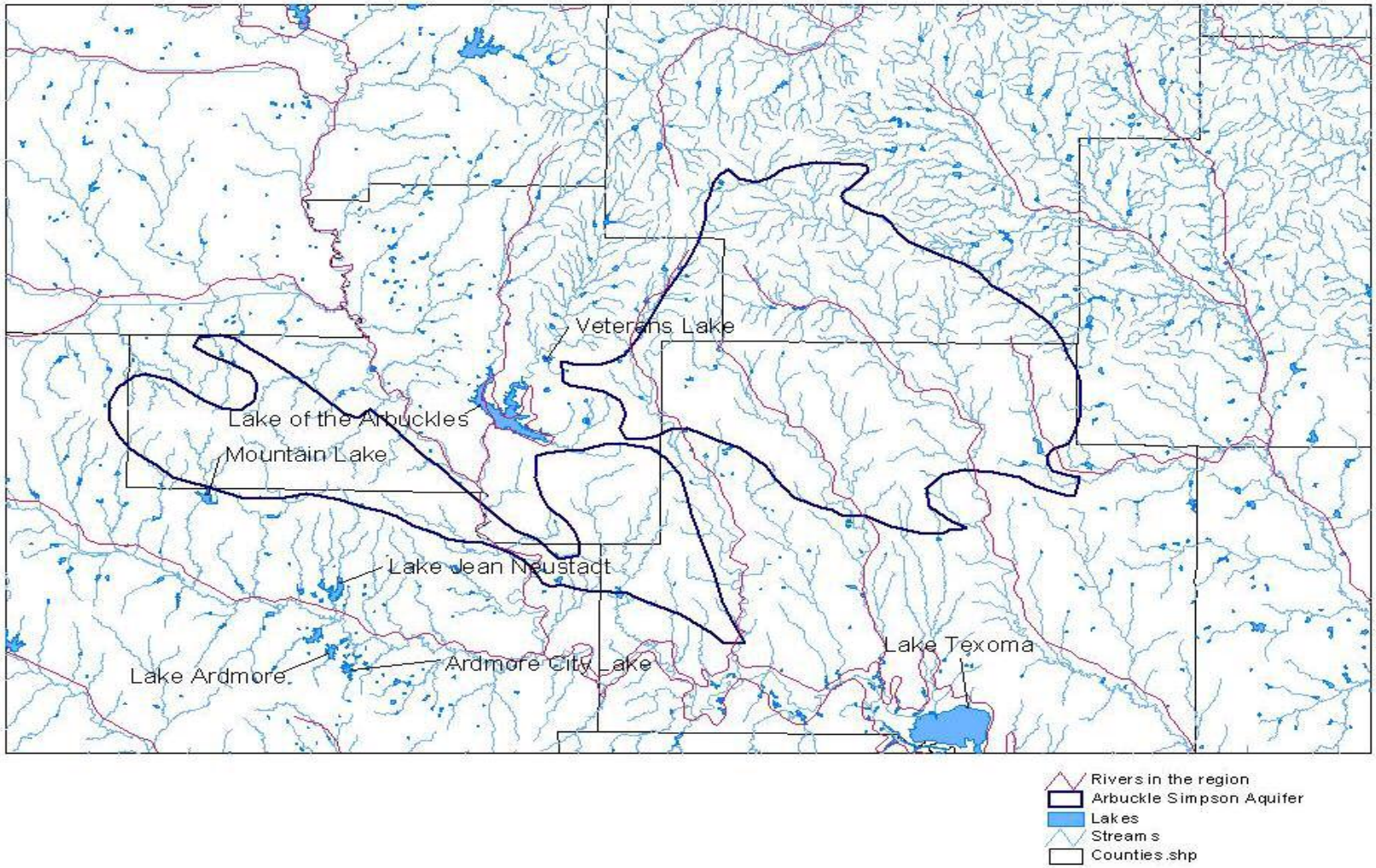

Figure II-5: Streams network and Lakes in Arbuckle-Simpson Aquifer Region (USGS, 2003)

Groundwater Flow System

The Arbuckle-Simpson Aquifer rocks contain numerous faults and joints. Its high permeability is the result of the enlargement of fractures, joints, and solution channels by partial dissolution of the rocks. The occurrence and movement of groundwater in the Arbuckle-Simpson Aquifer mainly depends on lithology and structure. Geologic structure plays a great role in groundwater flow movement because fractures caused by folding and faulting provide channels for groundwater movement (Fairchild et. al., 1990). Fractures and karst features of the aquifer locally increase its capacity to transmit, store, and discharge groundwater. Faults exist side by side in different rock types that may have different types of hydraulic conductivity (Savoca et. al., 1994). Variations in hydraulic conductivity across faults can either facilitate or impede groundwater flow. Therefore, the location and orientation of faults may influence groundwater flow paths. Much of the aquifer consists of carbonate rocks, which are readily dissolved in the naturally occurring, mildly acidic water derived from the atmosphere, soil, and vegetation in the area. The total amount of acid in the water is low so the rate at which rocks dissolve is very slow but over long periods, larger volumes of rock are dissolved. Infiltrating water slowly dissolves soluble carbonate rocks, leading to the formation of networks of channels like openings of varying size, shape and orientation, known as karst (Savoca et. al., 1994). Karst is a type of landscape that is formed by the

dissolution of soluble rocks (limestone and dolomite) of the region. Karst regions contain aquifers that are capable of providing large supplies of water. The formation of karst is greatest where fractures, bedding planes and other incipient openings have enhanced groundwater circulation. Karst features increase the aquifer's capacity to transmit and store large quantities of water due to large openings. The rate at which water moves through the aquifer can vary greatly. Water moves slowly through fine fractures and pores and rapidly through enlarged fractures and joints (Savoca et. al., 1994).

The Arbuckle-Simpson Aquifer receives water (in the form of recharge) primarily from infiltration of precipitation and from losing streams (Blue River and tributary channels) that cross the outcrop area. Infiltration occurs through permeable rocks, fractures, sink holes, and other openings.

"Unconsolidated surficial sediments" and vegetation at the surface commonly cover faults and Joints. Karst depressions can be seen in fields and dry streambeds, but other karst features are hidden under the land surface. The groundwater system in Arbuckle-Simpson Aquifer is very complex and not well understood (Hanson and Cates, 1994). A better understanding of groundwater flow system can be obtained by detailed knowledge of hydraulic characteristics of the aquifer, occurrence and movement of water through the aquifer. Uncertainties about the location of fractures and karst features are a major hindrance in the understanding of groundwater flow and storage in Arbuckle-Simpson Aquifer.

Groundwater flows from high areas to low areas, where it discharges to springs and streams. Recharge to confined parts of the aquifer typically occurs in up gradient areas where hydraulically connected rocks crop out; as a result, groundwater pressures may be higher in confined than in unconfined zones. Water levels in wells that penetrate confined zones may be higher than those of the overlying unconfined aquifer, and can result in wells (artesian wells) from which water flows at land surface all or part of the year. Therefore, where the Arbuckle-Simpson Aquifer comes under rocks of lower permeability, the aquifer is confined, and wells that penetrate below the confining layer may be artesian. Several artesian wells flow in the valley of Rock Creek, near Sulphur and Chickasaw National Recreation Area (Andrews and Burrough, 2000). Figure II-7 shows one of important artesian wells in Chickasaw National Recreation Area known as Vendome Well.

Tyagi and Kumar (2004) presented the groundwater management issues in Arbuckle-Simpson Aquifer and included modeling aspects of the aquifer.

Figure II-6: Vendome well in Chickasaw National Recreation Area, 2000

(Andrews and Burrough, 2000)

CHAPTER III

LITERATURE REVIEW

Most rocks, soils and unconsolidated materials have fractures in them. Fractured rocks act as natural stores and conductors of fluid resources worldwide. The world's largest and most important oil production fields are associated with fractured rocks. The groundwater flow in fractured formations and basic hydraulic properties controlling the flow are very important to determine the flow behavior in fractured rocks. Flow of groundwater through highly fractured media is very unpredictable and is controlled by fracture network consisting of large fractures and faults regardless of the direction of the hydraulic gradient. Fractures impart a large anisotropy to the permeability field. The hydraulic properties of rock masses are highly heterogeneous if the rock is fractured. The main problem in flow modeling in fractured rock is to describe this heterogeneity (NRC, 1996). The investigations in this field of research has recognized that fluid flow behavior and basic flow parameters like permeability and storage capacity of fractured formations differ from the behavior and parameters of a porous medium.

Researchers with diverse backgrounds in hydrology, geology, soil science, engineering, chemistry, physics, and mathematics have conducted a broad range of theoretical, numerical, laboratory and field investigations in the fractured networks and fractured porous formations. The research in several key areas relevant to groundwater hydrology in fractured formations is still underway.

The term fractures refers to all cracks, fissures, joints and faults that may be present in a formation. The size of the fractures may vary from microns to several hundreds of kilometers (Berkowitz, 2002). It is well known that fractures (in all sizes) have a significant effect on flow and transport processes. Fractured formations, in addition to intergranular porosity, may have large number of fractures and faults that may serve as channels or barriers of the flow depending on the permeabilites of the in-fill materials (Wang et. al, 2002). The flow in the fractured formations is primarily due to fractures, which provide the flow channels, and storage in the rocks is due to the rock porosity, which is also known as the primary porosity of the rock or intergranular porosity. The fractured rock porosity consists of rock blocks and numerous small fractures which contribute insignificantly to the groundwater flow because of low permeability, however due to large number of fractures their total porosity is very large which makes them able to store a large volume of groundwater [Streltsova, 1976; Wang et. al., 2002].

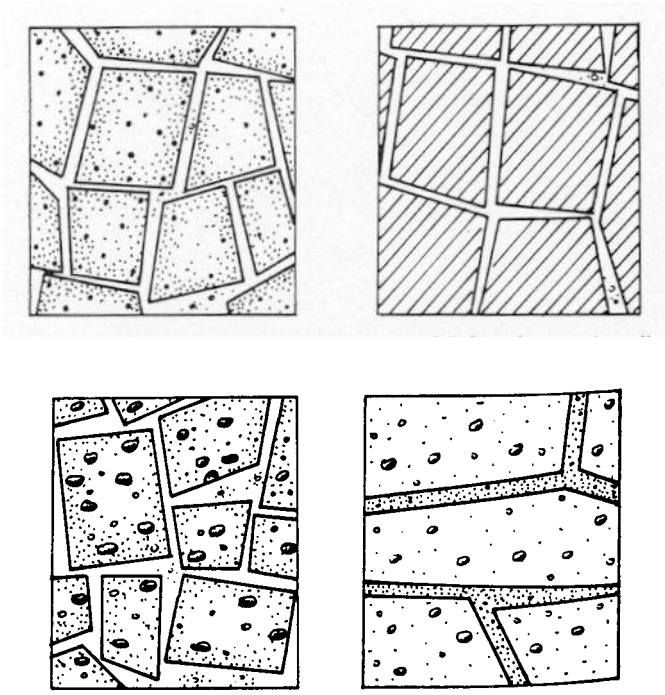

Figure III-1: Schematic representation of a fractured medium (top left), a purely fractured medium (top right), a double porosity medium (bottom left), and a heterogeneous medium (bottom right) (Streltsova, 1976).

For a better conceptual understanding of hydro-geological processes in any region, it is very important to characterize the geologic materials. Fracture networks can be characterized geometrically by several distributions- length, orientation, location, density, spacing, aperture and connectivity (Berkowitz, 2002). Information on fracture distributions can be collected on a number of scales. The orientation of fracture plane is defined in terms of dip direction (angle with respect to north) and dip amount (angle from horizontal). The fracture strike is perpendicular to dip direction. The fracture spacing is the

average perpendicular distance between two adjacent fractures (Cook, 2003). The connectivity of fractures is a critical feature controlling fluid and chemical movement in subsurface systems as the ability of fractures to act as conduits of flow is affected by the degree to which the fractures are interconnected (Berkowitz, 2002). Fracture connectivity depends on fracture length and fracture density, as there are more chances of intersection of fractures with the increase of fracture length and fracture density, which increases the overall connectivity of fractures (Cook, 2003).

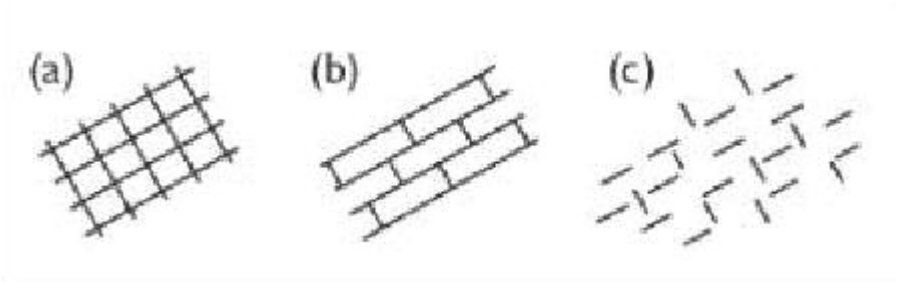

Figure III-2: The influence of fracture length on fracture connectivity (Singhal and Gupta, 1999).

Fracture connectivity is of great importance in controlling fluid flow. At Fanay-Augeres site, a uranium mine in France, it was found that the fracture system was not hardly connected and about 0.1% of the fractures control permeability. This means that only 0.1% of the fractures contributed to flow (Long et. al., 1987). Thus, the permeability of these few fractures were mainly responsible for the flow even though the site had large number of fractures.

Therefore, it can be concluded that even domains that appear to be heavily connected or having dense networks of fractures may not be necessarily hydraulically connected.

Modeling groundwater flow in fractured rocks is relatively complex because fractures can be difficult to observe and characterize, the permeability values are highly variable and uncertain. The flow pathways in fractured media are highly heterogeneous and difficult to identify from the observations available in the field. Flow paths are controlled by geometry of fractures and their open void spaces. Moreover, the structural and hydraulic complexity of fractured formations limits the type and quality of data that can be obtained from field investigations (Berkowitz, 2002). All these factors make fluid flow and transport in the fractured medium a sensitive issue, which is subjected to a considerable degree of uncertainty.

Numerous modeling approaches and flow models have been used to simulate the flow behavior in the fractured media. Mathematical flow models of fractured rocks can be categorized into three classes (NRC, 1996)

1. Equivalent Continuum Models
2. Discrete Network Models
3. Hybrid Approaches

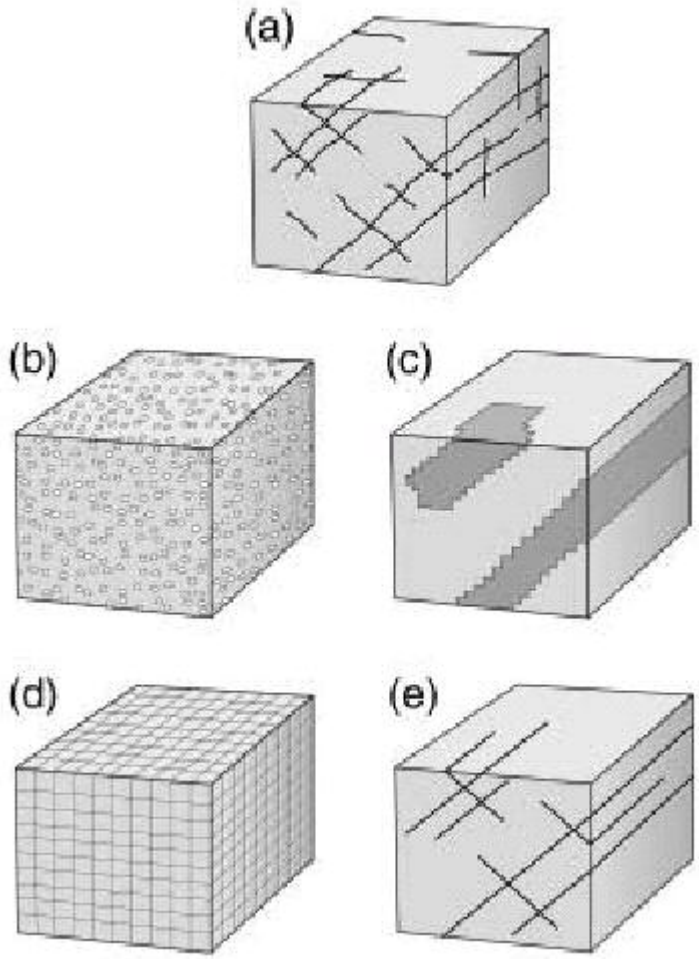

Figure III-3: Different modeling approaches for fractured rock aquifers. (a) Actual fracture network; (b) Equivalent porous media using uniform aquifer parameters; (c) Equivalent porous media in which highly fractured zones are represented by regions for hydraulic conductivity; (d) Dual porosity model; (e) Discrete fracture model in which major fractures are explicitly modeled. (Cook, 2003)

The models differ in their representation of the heterogeneity of the fractured medium. These models work by taking into account a range of possible fracture distributions, densities, hydraulic characteristics, rock properties, boundary conditions, and flow and transport processes.

Equivalent Continuum Models

In equivalent continuum models, hydraulic properties and heterogeneity of the fractured rock is modeled by using a limited number of regions, each of which is modeled as an equivalent porous medium with uniform properties such as permeability and effective porosity. Equivalent continuum models assume fractured mass to be equivalent to a homogenous porous medium with groundwater flow governed by Darcy's law. Thus, the individual fracture details need not to be known. Equivalent continuum modeling includes single porosity models, dual porosity models and stochastic models. In single porosity models, all porosity is assumed to reside in the fractures and the porosity in the matrix blocks between the conducting fractures is neglected (NRC, 1996). The single porosity approach is best utilized when it is used to predict average flow features of the system in steady state analysis. There is a need to consider the fluid released from the storage for problems that involve transient flow. A distinction is made between fluid residing in the fractures and the matrix. However, if fracture densities are high and matrix units are small, the medium

can be considered as one continuum and hydraulic properties represent the values accounting for fractures and matrix (NRC, 1996).

If the matrix blocks containing fractures have significant permeability then the dual porosity models may be used. Thus, the fluid flow and transport is considered both in fractures as well as in the matrix blocks in the dual porosity models. Dual porosity models have been used in cases where there was a need to account for the fluid flowing from storage in the matrix block to the fracture network. The main advantage of dual porosity models is in transient flow modeling where they provide a mechanism to simulate the delay in the hydraulic response of the rock mass caused by fluid resident in less permeable matrix blocks. In such cases, due to pressure gradient created between the water contained in matrix and water contained in fractures the fluid is first released from the fractures and then from the matrix. As in the saturated zone, the fractures provide the primary pathways for fluid flow and mass transfer. Matrix blocks between the conducting fractures significantly increase the storage properties of the rock mass. The simple conceptual basis of the dual porosity models makes them a valid choice for analysis of fluid and transport in fractured formations. However, there are also limitations of this approach, which include the tendency to over-regularize the geometry of the fracture network and difficulty in obtaining the good parameter estimates (NRC, 1996).

The continuum approach reduces the geometric complexity of flow patterns in a fractured rock mass to a simple mathematical form, which is easier

to evaluate and implement. The continuum approach is only valid as long as the fracture spacing is sufficiently dense that the fractured media acts in a hydraulically similar fashion to granular porous media. The limitation of this approach is that it can not exactly simulate the behavior of each fracture. Since the fractured media is highly heterogeneous and flow pathways are highly dependent on the fractures, these models cannot fully describe the hydraulic characteristics of the fractured media (NRC, 1996; Cook, 2003).

Discrete Network Models

In discrete fractures network model, the rock masses consist of blocks separated by fractures, which are treated as discontinuous media (NRC, 1996). Discontinuities occur at different scales and they have different geometries and flow properties. These flow properties may vary with the location and direction. Discrete fracture models are based on the premise that groundwater flow and transport in rocks occur primarily with in fractures and fluid flow behavior can be predicted from knowledge of the fracture geometry and data of individual fractures. All flow is restricted to the fractures. The groundwater is assumed to flow along the fractures, as the fractured rock blocks are assumed impermeable. Fractures in this model are represented as lines or planes in two or three dimensions. Thus, this approach simulates individual fractures in the rock, then solve for flow and transport in the interconnected fracture system. Joint systems in rocks can exhibit complexities that can affect discrete modeling of

fractures. Extensive folding and faulting of jointed rocks may be responsible for the development of large flow structures that are not well represented in flow model (Wang et. al, 2002). Multiple deformations can lead to preferential fracturing along preexisting planes of weakness, resulting in a style of fracturing that is very heterogeneous and complex. Due to a variety of geological processes occurring in fractured rocks, large parts of fracture system may not be circulating fluid. A large proportion of fractures may be nonconductive, because they are either closed or sealed by mineral precipitates. Due to this reason, discrete fracture approach uses the observable fracture geometry to predict flow and transport behavior. However, it is very difficult to separate the conductive fracture geometry from the nonconductive fracture geometry (Cook, 2003). These models can be effectively used by simulating each fracture where the fractures are limited, but for large-scale problems where the rock masses have enormous amount of fractures, it becomes very hard to describe the characteristics like permeability, orientation and length of each fracture and the model tends to be more complex if all the fractures are included. There are difficulties in applying these models, as the input parameters like permeability are not known for each fracture. The main advantage of discrete fracture model is that it can simulate the effect of individual fractures on flow and transport. Discrete fracture models have become popular for investigation in the field of flow and transport in fractured formations in spite of their computational limitations for large scale flow and transport problems because of great

demands on computer storage and calculation necessary to handle a system that comprises of large number of fractures and matrix blocks (Berkowitz, 2002).

Hybrid Approaches

The terms discrete fracture models and continuum models can be confusing sometimes, because in most cases discrete fracture models employ continuum approaches to treat flow with in each fracture and also continuum models can be applied to investigation of discrete feature of fracture systems by representing them as different level heterogeneities of the continuum medium (Berkowitz, 2002).

Discrete models may also provide a method for obtaining the parameters used in continuum models (NRC, 1996). Discrete fracture flow models have been used to estimate the permeability of a rock mass by capturing the permeability characteristics of a representative rock based on the fractures in the unit. Numerical analysis was carried out to estimate the permeabilities for the units. The estimated permeability of the representative unit is assumed to be equal to the permeability of rock mass and permeability coefficients thus determined can be used in flow analysis of the rock mass by considering it as a continuum. The rock mass can also be divided into different zones if the fracture characteristics vary significantly. The permeability value can be calculated for each zone by considering a single representative unit for each zone. Flow analysis of each zone of the rock can be carried out by taking it as a

continuum with the same permeability as its representative unit. However, if the rock contains large number of fractures, it becomes difficult to find an appropriate representative unit simulating the behavior of the rock mass. Analysis of flow and transport in such real world situations might best be carried out by use of "hybrid" approaches, which combines both continuum models and discrete fracture models (Wang et. al, 2002).

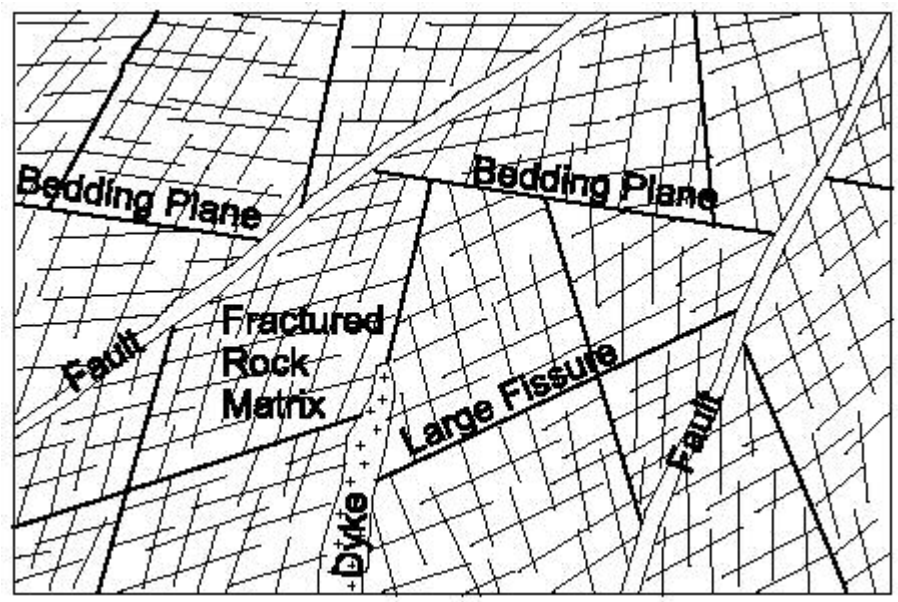

Figure III-4: Schematic diagram of Dual Fracture System (Wang et. al, 2002).

The fracture networks and fractured rock matrices play different roles in controlling the movement of groundwater with in the rock masses. The fractures are of different sizes and extents. The large fractures play predominant roles, either as conduits or barriers, in determining the flow of groundwater and these fracture networks divide the rock masses into blocks that

further contain small fractures and pores. These fractures and pores are small but they are present in large numbers. A large volume of groundwater can be stored in the spaces created by the fractures. It is also observed that water will flow into and out of the fractured rock matrices through the dominant fractures as water pumped into and out of the rock masses which can be modeled by dual fracture approach as shown in Figure III-4. The dominant fracture networks and fractured rock matrices play different roles in controlling the movement of groundwater with in the rock masses. The fracture networks make different type of structures that connect with each other in the form of 1D, 2D and 3D elements. Based on Darcy's law a general equation of groundwater flow in all directions can be written as (Wang et. al, 2002).

$$\frac{\partial}{\partial x'}\left(K_{x'}\frac{\partial H_f}{\partial x'}\right)+\frac{\partial}{\partial y'}\left(K_{y'}\frac{\partial H_f}{\partial y'}\right)+\frac{\partial}{\partial z'}\left(K_{z'}\frac{\partial H_f}{\partial z'}\right)+Q_f=S_f\frac{\partial H_f}{\partial t} \qquad \text{(III-1)}$$

Where H_f is the total head, Q_f is the volume of flux per unit volume (inflow or outflow), $K_{x'}$ is the coefficient of permeability in the x' direction, $K_{y'}$ is the coefficient of permeability in the y' direction. $K_{z'}$ is the coefficient of permeability of the fracture in the z' direction. S_f is the specific storage, and t is the time. The subscript f implies fracture.

As the fractured rock matrix consists small fractures as well as pores. The permeability tensor (K) reflecting the continuum properties of the fractured rock matrix can be obtained. For fractured rock matrix, the groundwater flow equation in all the three principal directions can be written as (Wang et. al, 2002).

$$\frac{\partial}{\partial x'}\left(K_{x'}\frac{\partial H_s}{\partial x'}\right)+\frac{\partial}{\partial y'}\left(K_{y'}\frac{\partial H_s}{\partial y'}\right)+\frac{\partial}{\partial z'}\left(K_{z'}\frac{\partial H_s}{\partial z'}\right)+Q_s=S_s\frac{\partial H_s}{\partial t} \qquad \text{(III-2)}$$

Where $K_{x'}$, $K_{y'}$, and $K_{z'}$ are the coefficients of permeability (K) along the three directions. The subscript s implies the fractured rock matrix.

CHAPTER IV

Overview of FEFLOW Model

A 3D model using finite element code, FEFLOW, is used to simulate groundwater flow in Arbuckle-Simpson Aquifer. FEFLOW has extensive modeling possibilities. The model can be used for saturated as well as unsaturated conditions. The model has sophisticated functions and tools like time-varying boundary conditions and material parameters, complementary constraints or grouped balance points. FEFLOW is capable of solving full 3D and 2D problems. Among 2D problems vertical plane, horizontal plane and axisymmetric domains can be schematized.

In this investigation the FEFLOW 5.1 model was used to simulate groundwater flow in Arbuckle-Simpson Aquifer. This model uses the finite element method to numerically solve the following transient flow equation

$$\underbrace{S_o B}_{\bar{S}_o}\frac{\partial h}{\partial t} + \frac{\partial \bar{q}_i^{\,f}}{\partial x_i} \qquad \text{(IV-1)}$$

$$\overline{q}_i^{\,f} = -T_{ij}\frac{\partial h}{\partial x_j}$$

where

So= specific storage coefficient (compressibility),

B= aquifer Thickness, L

h= hydraulic head, L

$\overline{Q}_p = B.Q_p$, depth integrated specific sink/source rate of fluid, LT^{-1}

$\overline{q}_i^{\,f}$ = depth integrated Darcy Velocity of fluid phase, L^2T^{-1}

T_{ij} = Tensor of transmissivity of fluid, L^2T^{-1}

The above equation is essentially horizontal model equation for confined conditions. This equation is for porous medium for confined aquifer in 2D.

The general equation, which the model solves for discrete fracture elements, is

$$L(h) = S\frac{\partial h}{\partial t} - \nabla.(K\, f_\mu\, B.(\nabla h + \Theta e)) - Q = 0 \qquad \text{(IV-2)}$$

where,

$S = bB\gamma$, Storage term for Poiseuille law, (1)

γ = fluid compressibility, (L^{-1})

K **=** tensor function for Poiseuille law of motion, (LT^{-1}) = $\frac{r_{hydr}^{2}\rho_o g}{3\mu_o} I$

f_μ= Viscosity relation function,

$\Theta = (\rho - \rho_o) / \rho_o$ density ratio or buoyancy coefficient, (1)

e = gravitational unit vector,(1)

μ_o = Reference dynamic viscosity of fluid, ($ML^{-1}T^{-1}$)

ρ_o = Reference fluid density, (ML^{-3})

I = unit (identity) tensor, (1)

r_{hydr} = Hydraulic radius, (L)

$Q = bBQ_\rho$, discharge

b = hydraulic aperture, (L)

B = thickness or depth, (L)

Q_ρ = fluid mass sink/source, (T^{-1})

which is basically based on the cubic law of Hagen-Poiseuille flow.

The fracture flow is assumed to occur between two parallel plates or in a circular tube in Hagen-Poiseuille law

The cubic law equation of Hagen-Poiseuille flow is

$$Q = \bar{u}b = -\frac{b^3}{12\mu}\left(\frac{dp}{dx} - \rho g_x\right) \qquad \text{(IV-3)}$$

where

$$\bar{u} = -\frac{r_{hydr}^2}{3\mu}\left(\frac{dp}{dx} - \rho g_x\right) \qquad \text{(IV-4)}$$

$\bar{u}$ = Average velocity in aperture b

Q = Discharge in aperture b

μ = Dynamic viscosity of fluid, ($ML^{-1}T^{-1}$)

ρ = Fluid density, (ML^{-3})

Hagen-Poiseuille's law of laminar fluid motion for 1D and 2D and for axisymmetric flow represent linear relationship with respect to pressure gradient and gravity $(\nabla p - \rho g)$. Generalized form is

$$v = -K f_{\mu}(\nabla h + \Theta e) \qquad \text{(IV-5)}$$

where

$$K = \frac{r_{hydr}^{2} \rho_{o} g}{a \mu_{o}} I \quad with \begin{cases} r_{hydr} = b/2, a = 3 \; for \quad 1D/2D \; plane \\ r_{hydr} = R/2, a = 2 \; for \quad axisymmetry \end{cases} \qquad \text{(IV-6)}$$

v = velocity vector of fluid, (LT^{-1})

a= coefficient to specify boundary conditions

FEFLOW uses a Galerkin-based finite element numerical analysis approach with a selection of different numerical solvers and tools for controlling and optimizing the solution process. FEFLOW groundwater model can be quickly developed with the help of ARC/INFO, Arc View or MapInfo GIS. For example, groundwater data can be read in directly from ESRI shape files or can be interactively created using a mouse by simply pointing and clicking. Scanned TIFF aerial maps, ortho photos, and/or DXF maps of streets, parcels, and buildings can be displayed as a background image, which allows to quickly digitize the region to be modeled.

FEFLOW includes several 2D and 3D geostatistical interpolation methods (e.g., IDW, Akima, Kriging, etc.) for transforming measured field data (e.g., hydraulic conductivity, porosity, etc.) as input data for the model. In addition, FEFLOW also provides tools for calculating and graphically displaying flow volumes, mass, and heat fluxes (either steady state or transient) across boundary sections, along a user specified line, and within model subregions.

FEFLOW groundwater model has complete GIS support and provides integrated GIS functionality (attribute handling, overlay and join functions) for spatial information and assigning automatic parameter values. FEFLOW can exchange groundwater data with any ARC/INFO, Arc View, or MapInfo GIS database, which allows the program to become integrated into regional groundwater management and environmental impact assessment tasks.

A GIS database is an ideal platform for generating; updating, storing and displaying both measured data and computed results. FEFLOW can easily link to any GIS database structure to represent geographical, hydrogeologic, physical and computational data. FEFLOW can import the revised data from GIS to update the numerical model. It can export the computational analysis results, after re-running the simulations. The GIS can be used as a tool for technical planners and decision makers in long-term groundwater and environmental planning and assessment.

Boundary Conditions

Dirichlet (1st kind), Neumann (2nd kind) and Cauchy-type (3rd kind) boundary conditions can be specified for flow, mass and heat. A so-called 4th kind boundary condition exists for singular (pumping or injection) wells. These boundary conditions can be arbitrarily placed at nodal points of a 3D and 2D mesh. All boundary conditions (from 1st to 4th kind) can be specified either as steady state or as transient conditions.

The core of mathematical modeling in FEFLOW is formed by the fundamental physical principals of mass conservation of fluid flow and solid continua, mass conservation of contaminants and chemical constituents, momentum conservation of fluid and solid continua and energy conservation (first law of thermodynamics). However, we are not concerned with the transportation of contaminants for this project.

Mass, motion and energy related quantities can be defined in a microscopic (local) volume element (continuum) for which balance laws are postulated. Mass, linear momentum and energy represent extensive properties (i.e., quantities are additive over volumes), which are dependent on the volume of the continuum. On the other hand, intensive properties concert densities of the extensive properties being independent of balance volume in form of mass densities, momentum densities and energy densities.

The transformation of the local microscopic balance equations to a porous or fractured medium is performed by spatial averaging procedures referred to the representative elementary volume (REV) as a heterogeneous medium domain. The REV has to be sufficiently large to disappear fluctuations of microscopic properties. On the other hand, it has to be appropriately small to possess local variability of particular macroscopic quantities.

The discrete feature approach in FEFLOW provides the crucial link between the complex geometries for subsurface and surface continua in modeling flow process. In this approach a three-dimensional geometry of the subsurface domain (aquifer system, rock masses) can be combined by interconnected one-dimensional or two dimensional features. FEFLOW provides 1D and 2 D discrete feature elements, which can be mixed with porous matrix elements in two and three dimensions. Different laws of fluid motion can be defined within such discrete features, e.g., Darcy, Hagen-Poiseuille or Manning-Strickler laws. Both the geometric and physical characteristics of the discrete feature elements provide a large flexibility in modeling complex situations

CHAPTER V

MODEL APPLICATION & METHODOLOGY

Three different conceptual approaches, Equivalent-continuum approach, discrete fracture, and dual fracture model approach were applied for modeling groundwater flow in fractured medium in Arbuckle-Simpson Aquifer. If fracture densities are high and matrix units are small, the medium can be considered as, one continuum and hydraulic properties represent the values accounting for fractures and matrix (NRC, 1996). Arbuckle-Simpson Aquifer is highly fractured aquifer and matrix contains small fractures along with larger faults, which are spread over entire aquifer. In the equivalent-continuum approach, the rock mass was treated as a homogenous continuum with representative hydraulic characteristics where as in the discrete fracture approach, the medium was assumed to consist of fractures with flowing water and the matrix blocks with stagnant water. In dual fracture approach, the fractures were modeled as in discrete model approach, and for considering the minor fractures in the rock blocks the fractured rock matrix blocks were assumed to behave as one continuum. A site-specific simulation model for groundwater flow was

developed on the basis of data available from USGS reports, USGS website and OWRB for the Arbuckle-Simpson Aquifer.

In this investigation the FEFLOW 5.1 model was used to simulate groundwater flow in Arbuckle-Simpson Aquifer. This model used the finite element method to numerically solve the flow equation (Diersch et. al., 2002)

$$\underbrace{S_o B}_{\bar{S}_o}\frac{\partial h}{\partial t} + \frac{\partial \bar{q}_i^{\,f}}{\partial x_i} \qquad \text{(V-1)}$$

$$\bar{q}_i^{\,f} = -T_{ij}\frac{\partial h}{\partial x_j}$$

where

So= specific storage coefficient (compressibility),

B= aquifer Thickness, L

h= hydraulic head, L

$\bar{Q}_p = B.Q_p$, depth integrated specific sink/source rate of fluid, LT^{-1}

$\bar{q}_i^{\,f}$ = depth integrated Darcy Velocity of fluid phase, L^2T^{-1}

T_{ij} = Tensor of transmissivity of fluid, L^2T^{-1}

This equation is solved for One continuum approach where the rock mass was treated as a homogenous continuum with representative hydraulic characteristics. The above equation is essentially horizontal model equation for confined conditions in 2D.

The general equation (Diersch et. al., 2002), which the model solves for discrete fracture network approach, is

$$L(h) = S\frac{\partial h}{\partial t} - \nabla.(K\, f_{\mu}\, B.(\nabla h + \Theta e)) - Q = 0 \qquad \text{(V-2)}$$

where,

$S = bB\gamma$, Storage term for Poiseuille law, (1)

γ = fluid compressibility, (L^{-1})

K=tensor function for Poiseuille law of motion, (LT^{-1}) = $\frac{r_{hydr}^{2}\rho_{o}g}{3\mu_{o}} I$

f_{μ}= Viscosity relation function,

$\Theta = (\rho - \rho_{o}) / \rho_{o}$, density ratio or buoyancy coefficient, (1)

e = gravitational unit vector, (1)

μ_{o} = Reference dynamic viscosity of fluid, ($ML^{-1}T^{-1}$)

ρ_{o} = Reference fluid density, (ML^{-3})

I = unit (identity) tensor, (1)

r_{hydr} = Hydraulic radius, (L)

$Q = bBQ_{\rho}$, discharge

b = hydraulic aperture, (L)

B = thickness or depth, (L)

Q_{ρ} = fluid mass sink/source, (T^{-1})

which is basically based on the cubic law of Hagen-Poiseuille flow. The cubic law equation (Diersch et. al., 2002) of Hagen-Poiseuille flow is

$$Q = \bar{u}b = -\frac{b^3}{12\mu}\left(\frac{dp}{dx} - \rho g_x\right) \qquad \text{(V-3)}$$

where

$$\bar{u} = -\frac{r_{hydr}^2}{3\mu}\left(\frac{dp}{dx} - \rho g_x\right) \qquad \text{(V-4)}$$

$\bar{u}$ = Average velocity in aperture b

Q = Discharge in aperture b

μ = Dynamic viscosity of fluid, ($ML^{-1}T^{-1}$)

ρ = Fluid density, (ML^{-3})

Hagen-Poiseuille's law of laminar fluid motion for 1D and 2D and for axisymmetric flow represent linear relationship with respect to pressure gradient and gravity $(\nabla p - \rho g)$. Generalized form (Diersch et. al., 2002) is

$$v = -K f_\mu (\nabla h + \Theta e) \qquad \text{(V-5)}$$

where

$$K = \frac{r_{hydr}^2 \rho_o g}{a\mu_o} I \quad with \begin{cases} r_{hydr} = b/2, a = 3 \; for \quad 1D/2D \; plane \\ r_{hydr} = R/2, a = 2 \; for \quad axisymmetry \end{cases} \qquad \text{(V-6)}$$

v = velocity vector of fluid, (LT^{-1})

a = coefficient to specify boundary conditions

FEFLOW 5.1 model uses combination of both sets of equations for solving flow through the fractures as well as the matrix.

The aquifer was subjected to initial and boundary conditions of different types. The equations given above will produce the results that will be referred as a simulation or model. The aquifer was assumed as confined aquifer as most of the area of Arbuckle-Simpson Aquifer was confined. It was found that Arbuckle-Simpson Aquifer behaves as a confined aquifer below Vanoss Conglomerate, and as an unconfined aquifer where the Arbuckle-Simpson Aquifer is exposed at the surface or where the faults penetrate the overlying Vanoss Conglomerate (Fairchild et. al., 1990).

Potentiometric Surface Map

Groundwater level measurements can provide important information about the local groundwater resources. For example, groundwater availability and estimates of aquifer yield are determined by analyzing changes in water levels related to pumpage. Also, because differences in water-level elevation provide potential for flow, spatial mapping of water-level elevations can permit identification of regional groundwater flow direction, as well as areas of recharge and discharge.

A potentiometric surface map showing the water elevation in different wells in the Arbuckle-Simpson Aquifer was generated using ArcView 3.2. The potentiometric map generated was used to determine the groundwater flow direction in the Arbuckle-Simpson Aquifer. The water elevation in different wells has been calculated from data given in shape file of USGS wells downloaded from USGS website. The water elevation data in all the wells were calculated using the land surface elevation data given at the top of the well and depth of water from the top. The calculated values for water elevation in different wells were used to generate the contour map of water elevation in different wells using ArcView 3.2. The map was created using the spatial data of the wells from which water elevation was calculated. The contours were generated using water surface elevation information and interpolation method in ArcView 3.2. Static water levels used to develop the potentiometric surface map were from

wells completed in aquifer systems at various depths and under confined and unconfined conditions.

As we know, water flow from higher elevation to lower elevation. In general, the composite potentiometric surface follows the overlying land-surface topography and intersects the land surface at major streams. The expected flow path is down slope or perpendicular to the potentiometric surface contours. Natural groundwater flow is from areas of recharge toward areas of discharge.

Since the source of water in different USGS wells was from Arbuckle-Simpson Aquifer, the map generated provided roughly the direction of groundwater flow in the region. Most of the flow in Arbuckle-Simpson Aquifer was in the South East direction as shown in Figure V-1. Some of the flow is in the opposite direction to South East direction in the upper side of the Arbuckle Mountain that is obvious due to decrease in surface elevation in that direction from the top of the Arbuckle Mountain.

The groundwater table in the Arbuckle-Simpson Aquifer was constructed using the data available from the wells in the region. The potentiometric map provided the groundwater flow direction in the Arbuckle-Simpson Aquifer.

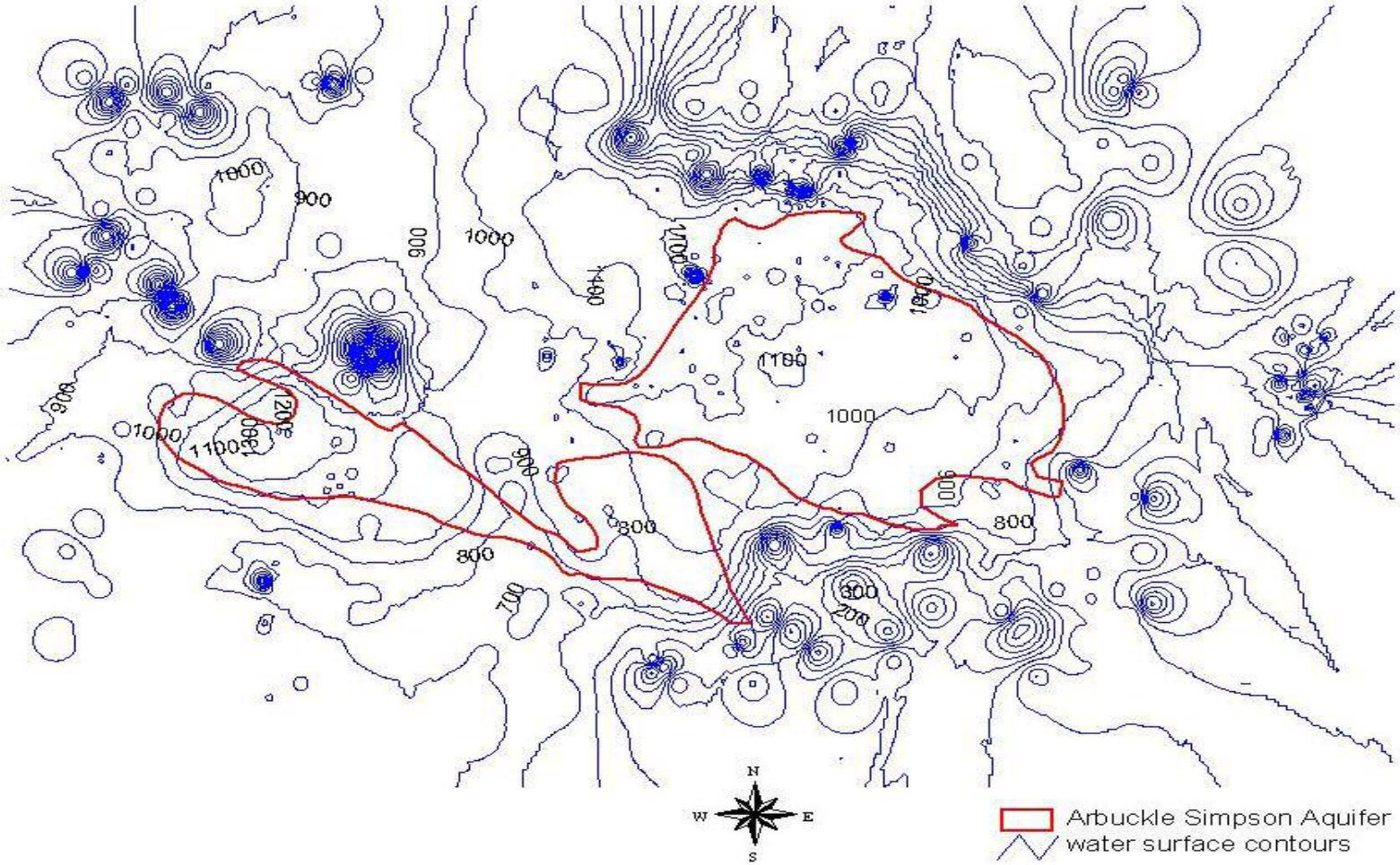

Figure V-1: Potentiometric Surface generated for the wells data collected in Arbuckle-Simpson Aquifer

Modeling of groundwater flow

Three conceptual approaches, Equivalent-continuum approach, discrete fracture, and dual fracture model approach were applied for modeling groundwater flow in fractured medium in Arbuckle-Simpson. In Equivalent-continuum approach, the aquifer medium was assumed to act as one continuum because of high fracture densities. The hydraulic properties accounting for fractures and matrix were entered in the model. However, in discrete fracture model, flow was assumed to occur only through the fractures and in dual fracture model, the dominant fractures were modeled as in discrete model approach, and for considering the minor fractures in the rock blocks, the matrix blocks were assumed to behave as one continuum. The fractures in the model were aligned using the map showing the faults in the Arbuckle-Simpson Aquifer as shown in figure 5.5.

To simulate groundwater flow, a mesh around the outcrop area of Arbuckle-Simpson Aquifer was created in the model for both approaches. In Equivalent-continuum model, the mesh was discretized into 12777 two-dimensional triangular elements with 6547 nodes having finer discretization around the river and pumping wells. As there were number of creeks flowing in the area, locating a node along each of the creeks, resulted in a mesh fine enough to represent the spatial variability within the area. Nodes were also located wherever observation wells were available for the water level recorded in

the wells. Different head boundary conditions were assigned in the model to represent pumping wells, creeks, springs and no flow at the boundaries. Initial head boundary condition was applied to assign the groundwater level in the model using different observation wells in Arbuckle-Simpson Aquifer.

In discrete fracture and dual fracture model approach, the mesh was more refined due to the introduction and alignment of node elements along the fractures in addition to the finer discretization around the rivers. In discrete fracture model and dual fracture approach, the mesh was discretized into 15588 two-dimensional triangular elements with 7963 nodes having finer discretization around the river and pumping wells as wells as along the fractures.

Input Data

The input data for the model is discussed consecutively as it appears in the model. The simulations were carried out for saturated groundwater unsteady flow in an artesian, anisotropic and nonhomogeneous aquifer. Initial head was applied in the model throughout the aquifer using water surface elevation calculated in various observation wells in the region. The water surface elevation in different wells in Arbuckle-Simpson Aquifer was calculated from the data available from USGS through a GIS shape file. The water surface elevation calculated was combined with other data of wells and a new shape file was generated using ArcView 3.2. The shape file containing water surface elevation values was used to generate potentiometric surface using ArcView 3.2. The coordinates of all the observation wells and the corresponding water surface elevation were put together in an ASCII format file (.trp file). The initial hydraulic head in the model was applied through this ASCII format file. The initial hydraulic head was interpolated by data regionalization technique called Inverse Distance Weighting method of regionalization in FEFLOW 5.1 model.

Three types of boundary conditions, the head boundary condition, transfer boundary condition and well boundary condition were applied to Arbuckle-Simpson Aquifer. The water in the Arbuckle-Simpson Aquifer was assumed to be stagnant at the boundaries i.e. no head (no flow) boundary condition was applied at the entire boundary of aquifer. Rivers and creeks were subjected to a third kind (Cauchy) boundary condition, Transfer. For this kind of

boundary condition a spatially variable "Reference Hydraulic Head" was defined to describe the water table in the river and creeks (Diersch et. al., 2002). The transfer boundary condition for rivers takes care of interaction of groundwater with surface water in rivers or creeks. The flow between this surface water and the groundwater was modeled by assigning a transfer rate in the model. For describing the water table in the river and creeks, an approximate water surface elevation values were generated on certain points along the rivers/creeks using ArcView 3.2 as shown in Figure V-4. This was necessary due to no availability of data on water surface elevation along the river/creek. There was only one stream gauge station on Blue River near the outcrop area of Arbuckle-Simpson Aquifer to get the water surface elevation. The water surface elevation values along the river/creek were approximated using elevation map and point files generated for rivers/creeks using ET GeoWizards 9.1 software, which can be used in Arc Map. Only those points along the rivers/creeks were selected which intersected with contour lines to get approximate values for water surface elevation values. The water surface elevation values on the points, which coincided with stream gauge stations, were verified to check the water elevation recorded at stream gauge stations and water elevation values approximated using above method.

The interaction of groundwater and surface water is an important component in groundwater flow hydrology of Arbuckle-Simpson Aquifer. The Arbuckle-Simpson provides base flow to the Blue River, Pennington Creek, Mill

Creek, Rock Creek and Oil Creek (Savoca et. al., 1994). These streams discharge into the Washita and Red Rivers. The aquifer also discharges to numerous springs and seeps. Also, the Arbuckle-Simpson Aquifer receives water from losing streams (Blue river and tributary channels) that cross the outcrop area. The exchange of water between aquifer system and streams was achieved in the model through the reference of leakage coefficient or colmation coefficient. The bed leakage coefficients were specified for each branch of the river system and describe the hydraulic contact between the river and the aquifer.

The formulation of 3rd kind boundary conditions is based on a general transfer relation between the reference value of hydraulic head, h_2^R on the boundary portion and the hydraulic head *h* to be computed at the same place as shown in Figure V-2. For flow problems, the transfer coefficient Φ_h can be identified as a specific colmation (or leakage) coefficient. For inflowing (infiltration) conditions $(\Phi_h \rightarrow \Phi_h^{in}\ (h_2^R > h)$. An adjacent river bed is sealed ('colmated') by a layer of thickness *d* and a conductivity of K_o^{in} as shown in Figure V-2. Normally, the layer conductivity K_o^{in} is much smaller than the conductivity K_1 of the aquifer to be modeled. Thereby the model boundary Γ represents the inner boundary of the 'colmation' layer Γ_3, where the model domain Ω ends as.

The exchange of flow is described by a Darcy approximation as a function of the head gradient and the leakage coefficient and flux through such colmation layer is expressed as (Diersch et. al., 2002)

$$q_n = -K_o^{in} \frac{\Delta h}{\Delta l} = -K_o^{in} \frac{h_2^R - h}{d} \qquad \text{(V-7)}$$

The above equation calculates the volumetric flow between the aquifer and the stream. K_o^{in} is hydraulic conductivity of the stream bottom sediments and d is the stream bed thickness. The streambed leakage coefficient, which is ratio of hydraulic conductivity and streambed thickness but for horizontal confined flow problems, an inherent vertical averaging becomes necessary (in the aquifer all fluxes are integrated over the depth) resulting in a depth-integrated transfer coefficient Φ_h^{-in} as (Diersch et. al., 2002):

$$\Phi_h^{-in} = B\Phi_h^{in} \approx B\frac{K_o^{in}}{d} \quad in \left[md^{-1} \right] \qquad \text{(V-8)}$$

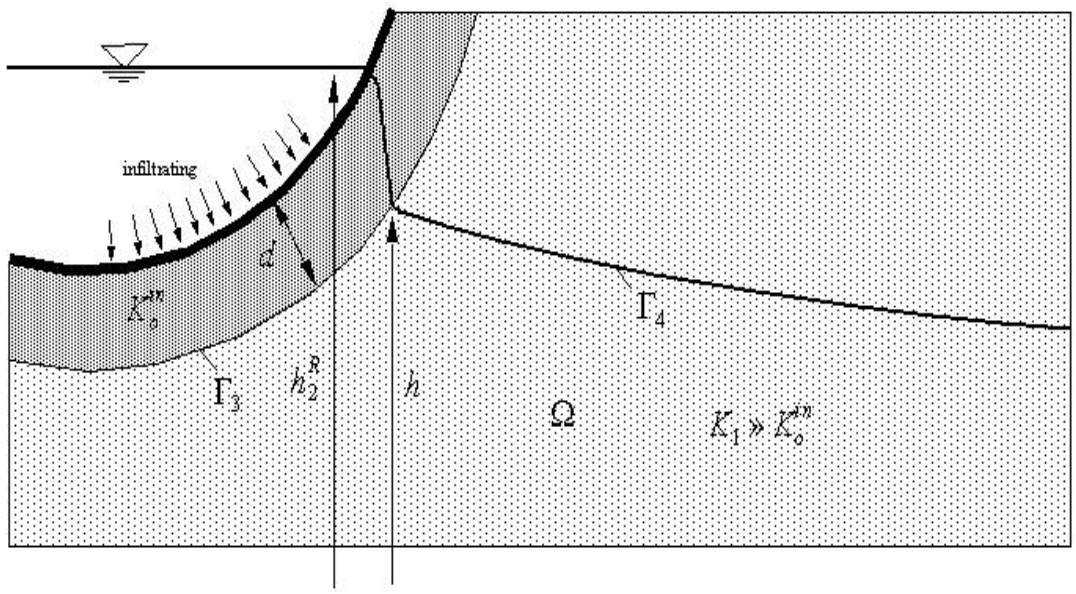

Figure V-2: Transfer coefficient as 'colmation parameter' of a river bed (Diersch et. al., 2002)

The head difference between the aquifer and water level (stage) in the stream may change sign and thereby direction of water flow in different seasons.

The streambed leakage coefficient for the Blue River was calculated by approximating the streambed thickness at various points along the Blue River in ArcMap 8.2. The streambed thickness can vary several orders of magnitude within short distances along streams. The water surface elevation was approximated at certain points generated along the river using ET GeoWizards 9.1 software in ArcMap 8.2 wells near the river. The water elevation for the wells, which were very near to those points along the river, was observed. The difference between the water level in wells that were near the certain points selected along the river and the river water level at those points provided an

indication of streambed thickness for the aquifer. The values of streambed thickness for the Blue River were approximated in the range of 7ft to 40 ft by analyzing the river water elevation at selected points along the river and water elevation in wells near those river points. A streambed thickness of 10 ft was assumed for the Blue River, which was in the range of values approximated. The same value of streambed thickness was assumed for other rivers and creeks for calculation of leakage coefficient values.

The values of hydraulic conductivity for the streambed sediments for fractured igneous and metamorphic rocks are in the range of 10e-4 m/s to 10e-8 m/s as shown in Figure V-3 (Freeze and Cherry, 1979). A mean value of 10e-6 for hydraulic conductivity was taken for calculating the leakage coefficient for rivers and creeks in the region. A value of 25.92 m/day was calculated for leakage coefficient by using equation V-8. The Arbuckle-Simpson provides base flow to the Blue River, Pennington Creek, Mill Creek, Rock Creek and Oil Creek as well as receives water from losing streams (Blue river and tributary channels) that cross the outcrop area (Fairchild et. al., 1990). Since the interaction of groundwater in aquifer is both ways with the surface water in the rivers/creeks. The value of leakage coefficient was assumed to be same for transfer in and transfer out variables which describe the transfer of water from aquifer to rivers and from rivers to aquifer.

Byrds Mill Spring and Antelope spring were assigned first kind boundary condition with a value of 312.5 m and 329.5 m respectively for hydraulic head in combination with a constraint condition of zero maximum flux in the model. This was a seepage boundary condition where all water exceeding the elevation of the node (where the boundary condition was assigned for spring) flows out, but no influx was possible (this is insured by an iterative process in the model). Only Byrds Mill Spring and Antelope Spring were assigned boundary condition because of no availability of data for hydraulic head for other springs. The average discharge from Byrds Mill Spring and Antelope Spring was 30 cfs and 6cfs respectively (USGS, 2003).

The pumping well data was obtained from the Oklahoma Water Resource Board (OWRB) for the four counties in which the Arbuckle-Simpson Aquifer is spread. The data was integrated together to generate the shape file for pumping wells using GIS in ArcView 3.2. Most of pumping wells that were applied in the model were public water supply wells; industrial wells and irrigation wells and some of them were domestic wells. The location of pumping wells is shown in Figure V-3. The location of the wells and pumping rates were put together in an ASCII format file (.trp file) and was imported using Database option of the Assign tool as 4th-kind boundary condition, well. The model interpolated the pumping rate values by performing the data regionalization technique in the model.

Table V-1: Material Parameters for horizontal 2D flow in confined aquifer for Equivalent-continuum approach

Item	**Unit**	**Value**
Transmissivity	10^{-4} m^2s^{-1}	161.29
Anisotropy Factor	1	1
Angle from +x axis to Tmax	0	0
Storage Compressibility	1	0.008
Source(+)/Sink (-)	10^{-4} md^{-1}	3.27
In-transfer rate	10^{-4} md^{-1}	259200
Out-transfer rate	10^{-4} md^{-1}	259200

Material conditions for horizontal 2D flow for a confined aquifer were assigned on the basis of the previous findings mentioned in various published USGS reports. According to a report by Fairchild, Hanson, and Davis (1990), average transmissivity of the aquifer was estimated to be 15,000 feet squared per day and the average storage coefficient was estimated to be .008 for the confined aquifer. The transmissivity and storage coefficient values were assumed to be constant over the entire aquifer in the model. A constant value of 16.129 E-03 m^2/s and .008 for transmissivity and storage coefficient respectively was specified for each node in the model for equivalent continuum model approach. Anisotropy factor [Tmin/Tmax] and angle from +x-axis to Tmax were assigned a value of 1 and 0 respectively. Source(+)/Sink(-) value

describes the area recharge/discharge (groundwater recharge, evaporation etc.) in the model. Equations for flow and transport for each system are linked by a source/sink term that describes the fluid or solute mass exchanged between the systems (Sudicky and Mclaren, 1992). Fairchild et. al. (1983) reported the average recharge of the Arbuckle-Simpson Aquifer as 4.7 inches/year. The same recharge value was applied in the model for each node.

Table V-2: Material Parameters for horizontal 2D flow in confined aquifer for Discrete Fracture Model.

Item	**Unit**	**Value**
Transmissivity	10^{-4} m^2s^{-1}	10
Anisotropy Factor	1	1
Angle from +x axis to Tmax	0	0
Storage Compressibility	1	0.008
Source(+)/Sink (-)	10^{-4} md^{-1}	3.27
In-transfer rate	10^{-4} md^{-1}	259200
Out-transfer rate	10^{-4} md^{-1}	259200
Fracture width	m	.0254
Cross-section Area	m^2	23.23
Compressibility of water	1/m	4.3 E-06

In second approach, a discrete fracture model was used in which the fractures are discretized as 1D entities to account for fracture thickness by an integral form of the flow equations. Discrete fracture approach is implemented

using a Galerkin finite-element method. In discrete fracture element approach, nodes in the model were aligned along the fractures using the map of faults in Arbuckle-Simpson Aquifer area in the background in GIS format. To make flow through fracture and faults only, a very low value of .01 m^2s^{-1} for fractured rock matrix was assigned in the model. The fracture thickness in different parts of the aquifer varied from .25 inches to 3.0 inches as shown in Appendix C, however for the simulation purpose the fracture thickness was assumed to be 1 inch for the entire aquifer. Compressibility in fractures equals the compressibility of water, as in hard rocks there is usually no compressibility of the matrix. The value of compressibility of water is taken as 4.4 E-06 1/m (Freeze and Cherry, 1979).

Table V-3: Material Parameters for horizontal 2D flow in confined aquifer for Dual Fracture Model.

Item	**Unit**	**Value**
Transmissivity	10^{-4} m^2s^{-1}	26.88
Anisotropy Factor	1	1
Angle from +x axis to Tmax	0	0
Storage Compressibility	1	0.008
Source(+)/Sink (-)	10^{-4} md^{-1}	3.27
In-transfer rate	10^{-4} md^{-1}	259200
Out-transfer rate	10^{-4} md^{-1}	259200
Fracture width	m	.0254
Cross-section Area	m^2	23.23
Compressibility of water	1/m	4.3 E-06

In dual fracture model approach, the groundwater flow was assumed to occur through dominant fracture network and the fractured rock matrix. In discrete fracture model, it was assumed that all the flow occurred through the fractures and matrix (rock) blocks do not contribute to the groundwater flow. However, in dual fracture model approach the rock blocks also contribute some groundwater flow in the aquifer. The dominant fractures were modeled as in discrete model approach, and for considering the minor fractures in the rock blocks the fractured rock matrix blocks were assumed to behave as one continuum. The dominant fractures were assigned the same hydraulic properties as in discrete fracture approach, however to take into account the large number of minor fractures in rock matrix a transmissivity value of 2500 ft^2/day was assigned in the model. The transmissivity value applied for fractured rock matrix was very less as compared to average transmissivity of 15,000 ft^2/day for Arbuckle-Simpson Aquifer. The value of transmissivity value for rack matrix was reasonable considering the fact that most of groundwater flow was controlled by dominant fractures. The values of transmissivity for Arbuckle-Simpson Aquifer vary in a wide range of values. The transmissivity of the Arbuckle-Simpson Aquifer ranged from 40 to 49,600 ft^2/day and averaged an estimated 15,000 ft^2/day (Fairchild et. al., 1990). The material parameter details for dual fracture model are displayed in Table III.

The FEFLOW 5.1 model was also run with the same hydraulic parameters for higher pumping for all the approaches to analyze the effect of higher pumping on the aquifer and to analyze if sufficient groundwater flow was available to supply to other parts of the state without reducing the natural flow of springs and hydraulic head in the aquifer. The simulations were carried out to determine the feasibility to transfer as much as 80,000 acre-feet per year of Arbuckle-Simpson water to central Oklahoma (OWRB, 2003). The total pumpage for all the wells applied in the model was approximately 42,466 m^3/day. However, the total demand of water that included the water needed to be transferred to central Oklahoma was approximately 8 times more than the normal pumping rate. By considering future demand, the pumping was increased by a factor of 10 and 20 for all pumping wells. Higher pumping was applied by assigning different input files of ASCII format (.trp files) for pumping wells with increase pumping rate in each approach.

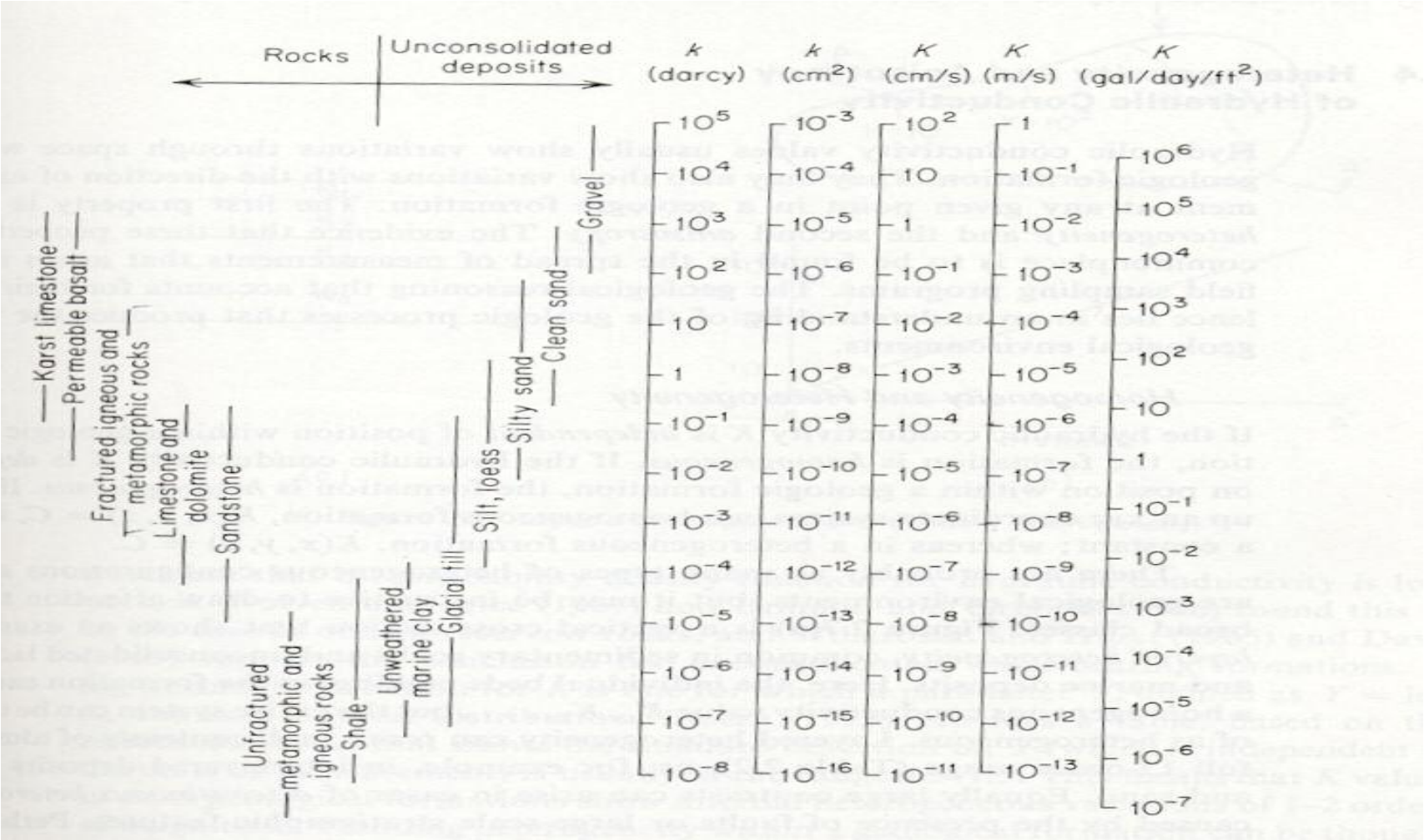

Figure V-3: Range of hydraulic conductivity values for different types of rocks and media (Freeze and Cherry, 1979).

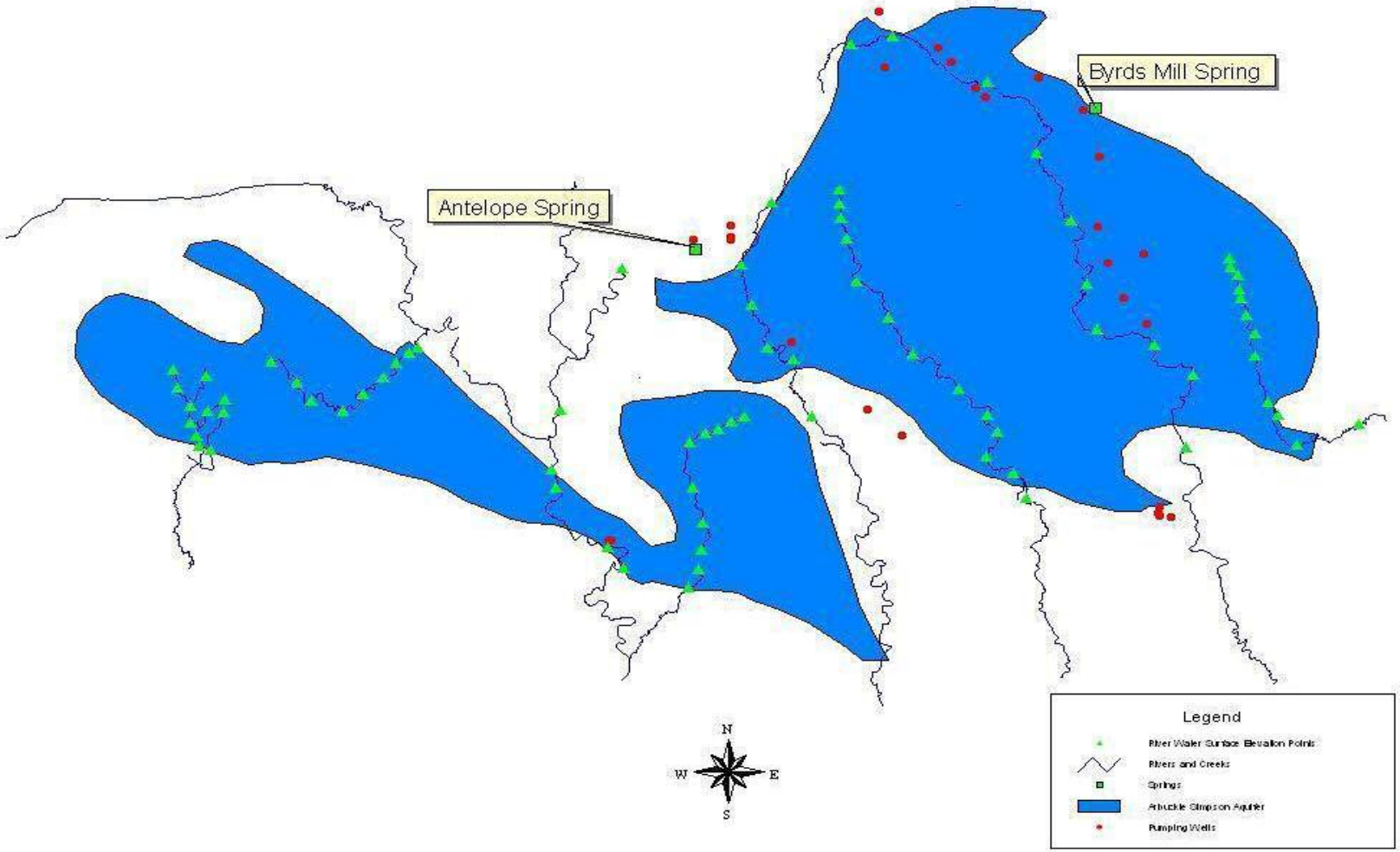

Figure V-4: Input data points for different boundary conditions in Model.

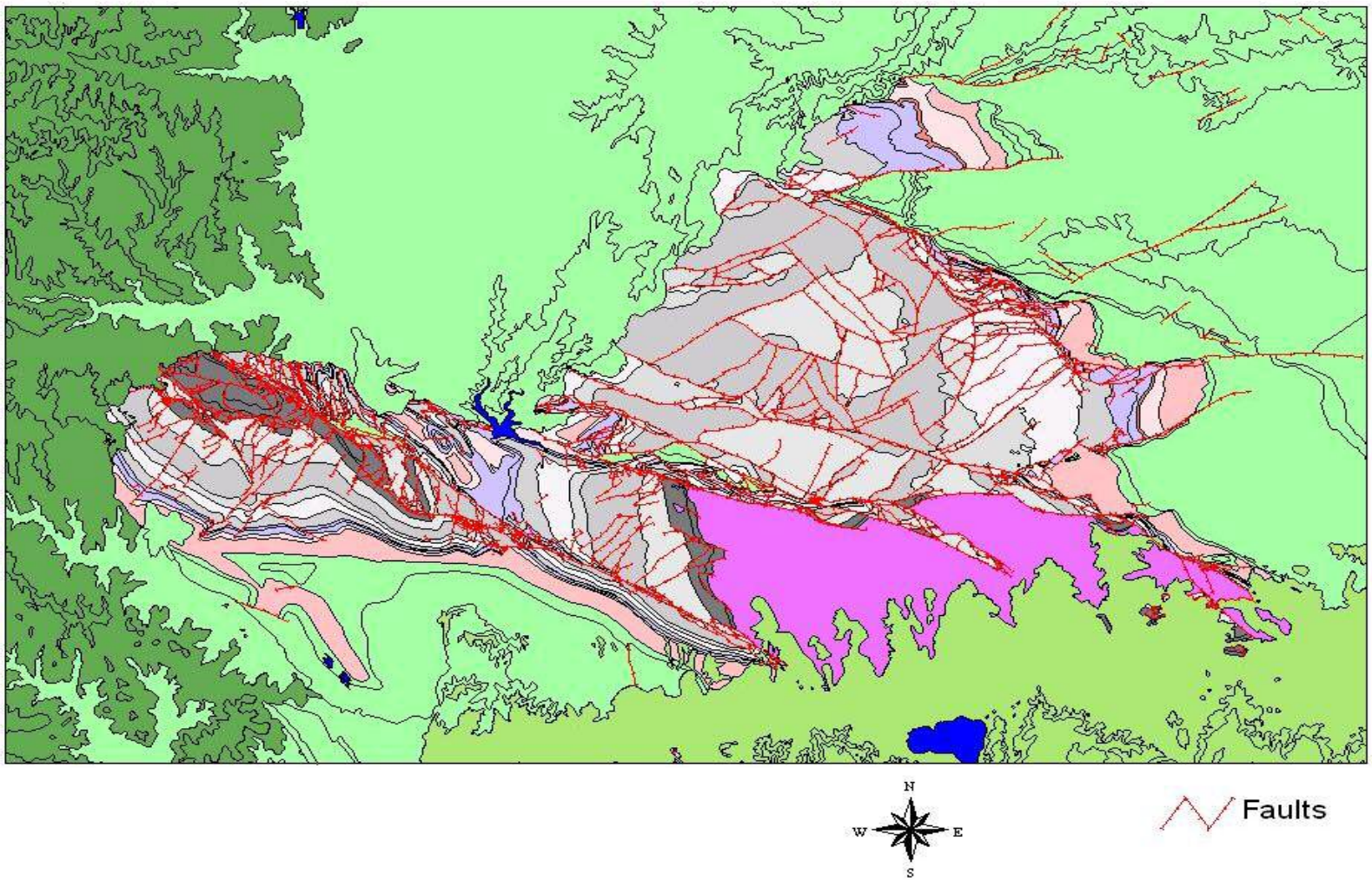

Figure V-5: Geologic Faults in Arbuckle-Simpson Aquifer Region (USGS)

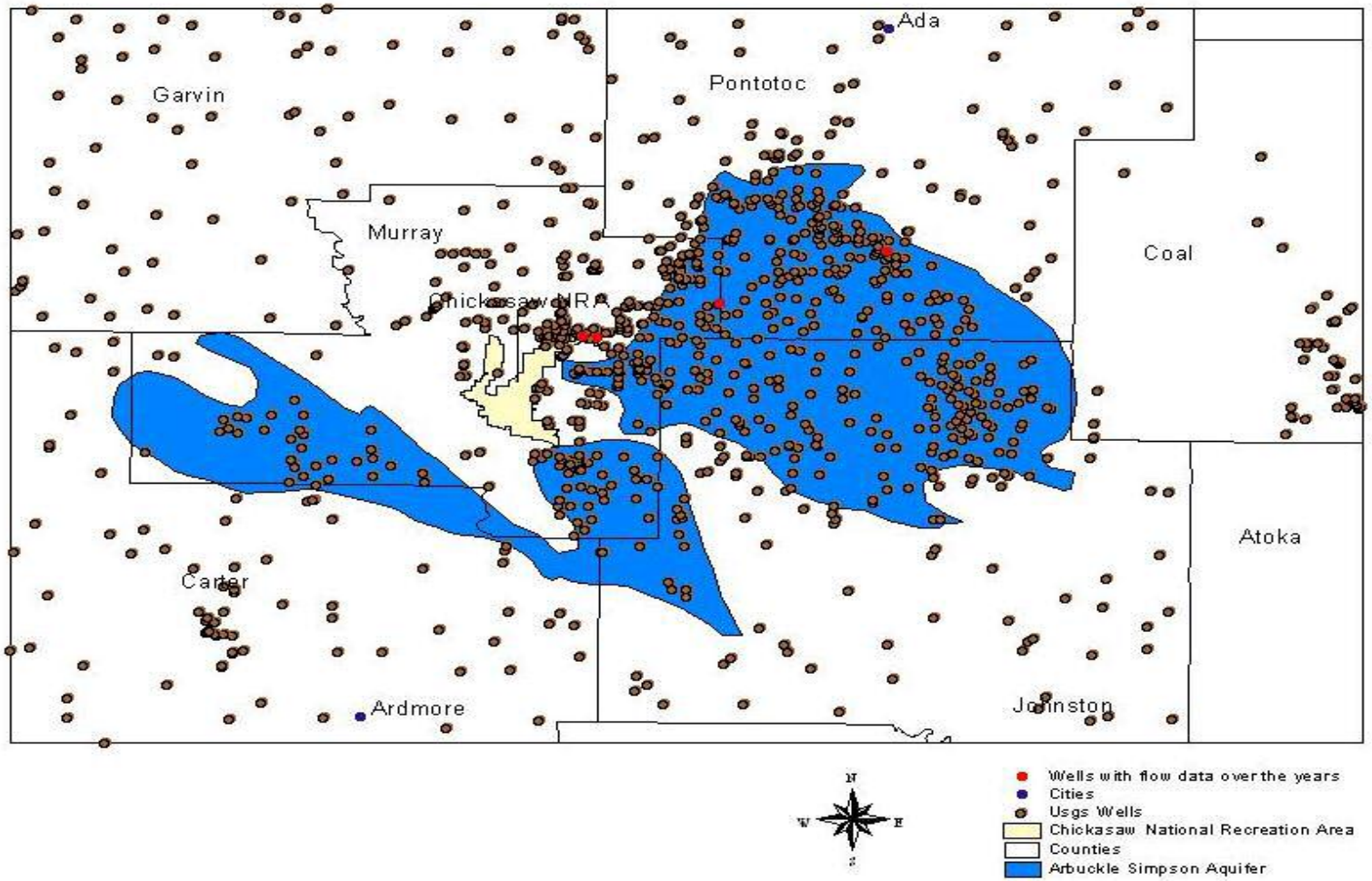

Figure V-6: USGS wells in the Region

CHAPTER VI

RESULTS AND DISCUSSION

The groundwater model FEFLOW 5.1 was used in this study to simulate the flow in groundwater aquifer. The GIS software ArcView (3.2) and ArcMap 8.2 were used to work on the base maps to assemble various types of spatial data inputs for modeling purpose and finally for displaying the post simulation graphics. A 2D transient flow model was used to simulate fluid flow through the fractured rock mass. The fractured rock mass was considered as a confined aquifer. The groundwater model was applied to Arbuckle-Simpson Aquifer in response to increasing demand of water from the aquifer for the surrounding areas. The model was used to evaluate the impact of different possible irrigation, agricultural or public water supply options on the aquifer system under consideration to study groundwater behavior as a result of different stresses on the aquifer. The simulations were carried out for a period of 30 years for equivalent continuum, discrete fracture model and dual fracture model approach in FEFLOW 5.1 model. The FEFLOW 5.1 model was also run with the same hydraulic parameters for higher pumping for all the approaches to analyze the effect of higher pumping on the aquifer and to analyze if sufficient groundwater flow was available to supply to other parts of the state without reducing the natural flow of springs and hydraulic head in the aquifer. The

simulations were carried out to determine the feasibility to transfer as much as 80,000 acre-feet per year of Arbuckle-Simpson water to central Oklahoma (OWRB, 2003). The proposed demand of water was approximately 8 times more than the normal pumping rate. By considering future demand, the pumping was increased by a factor of 10 and 20 for all pumping wells. Higher pumping was applied by assigning different input files of ASCII format (.trp files) for pumping wells with increase pumping rate in each approach.

The results provide the variation of hydraulic head with time (30 years) for all pumping wells, the variation of hydraulic head over the entire aquifer, and the hydraulic head variation in each observation well (pumping well) for a simulated period of 30 years.

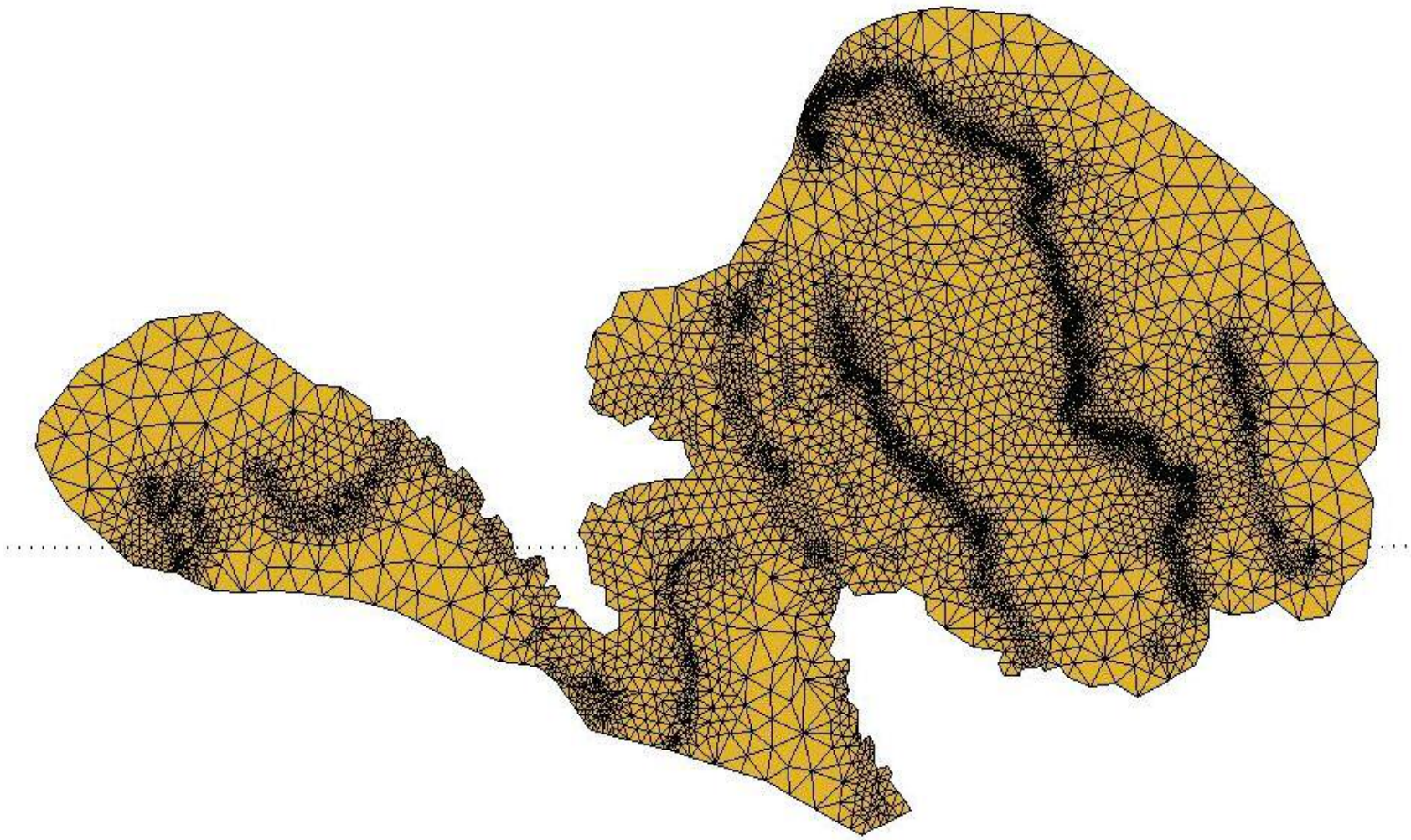

Figure VI-1: Mesh generated in FEFLOW Model for Equivalent Continuum Model

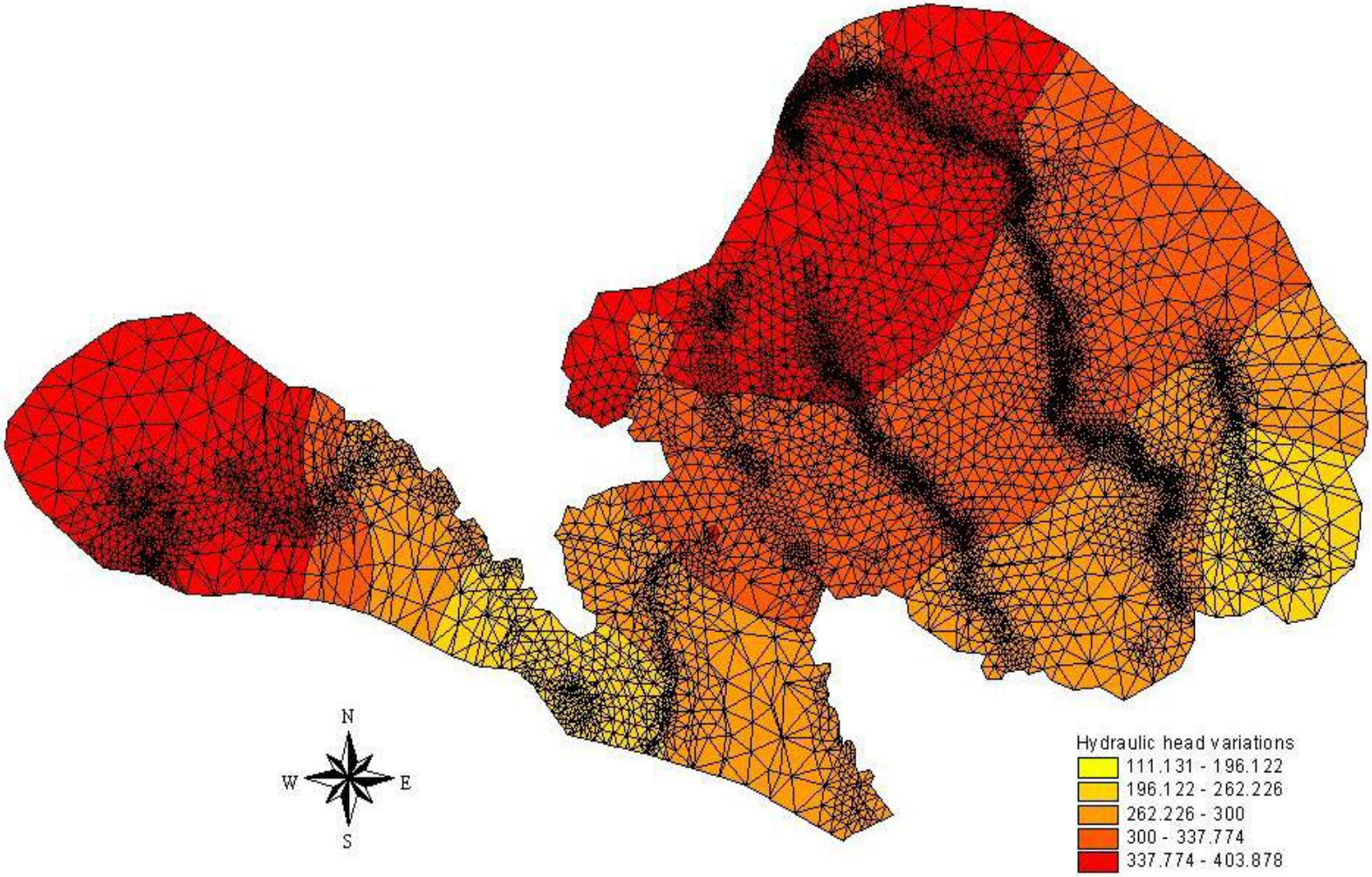

Figure VI-2: Hydraulic head generated in FEFLOW Model for Equivalent Continuum Approach

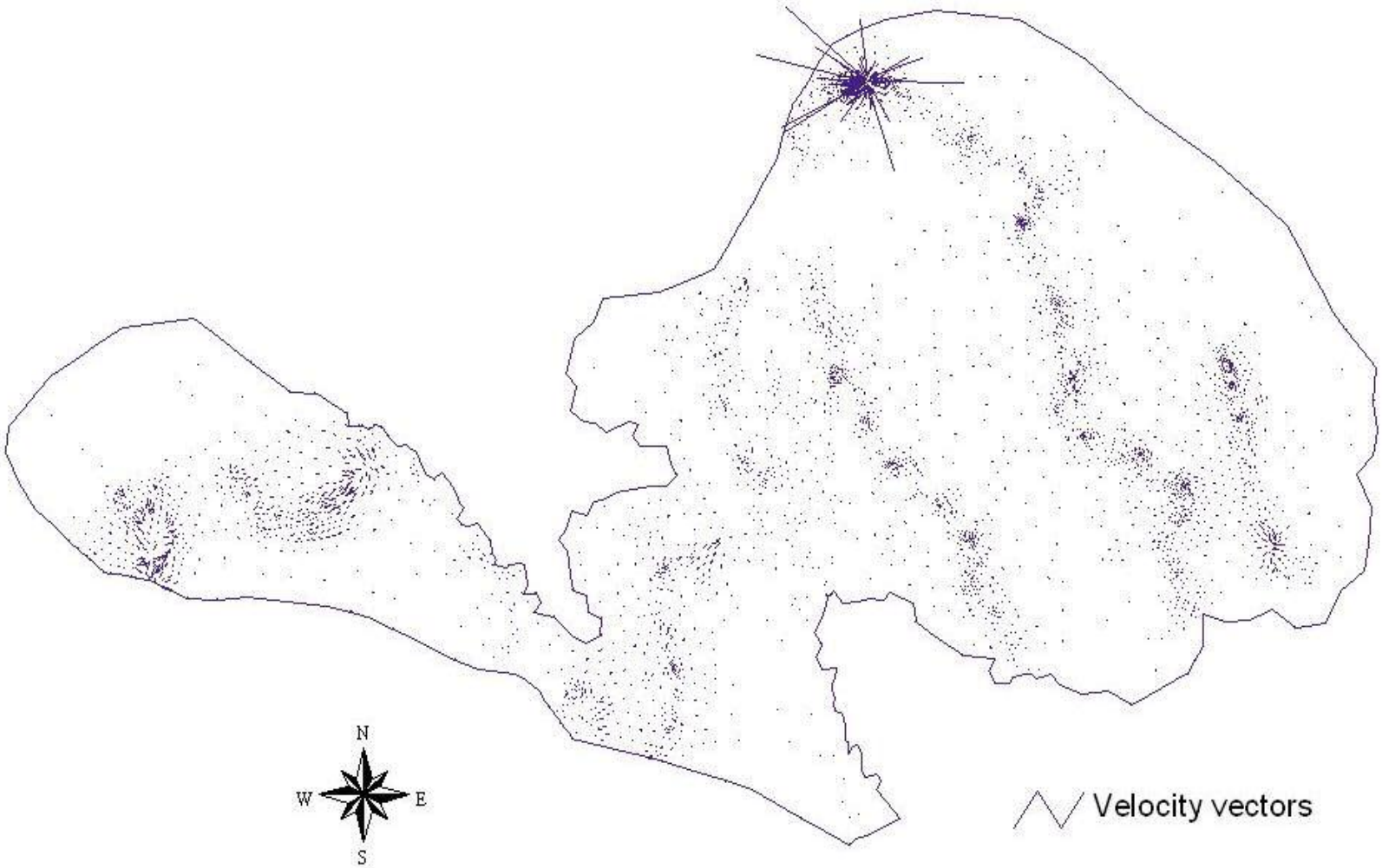

Figure VI-3: Velocity Vectors generated in FEFLOW Model for Equivalent Continuum Model

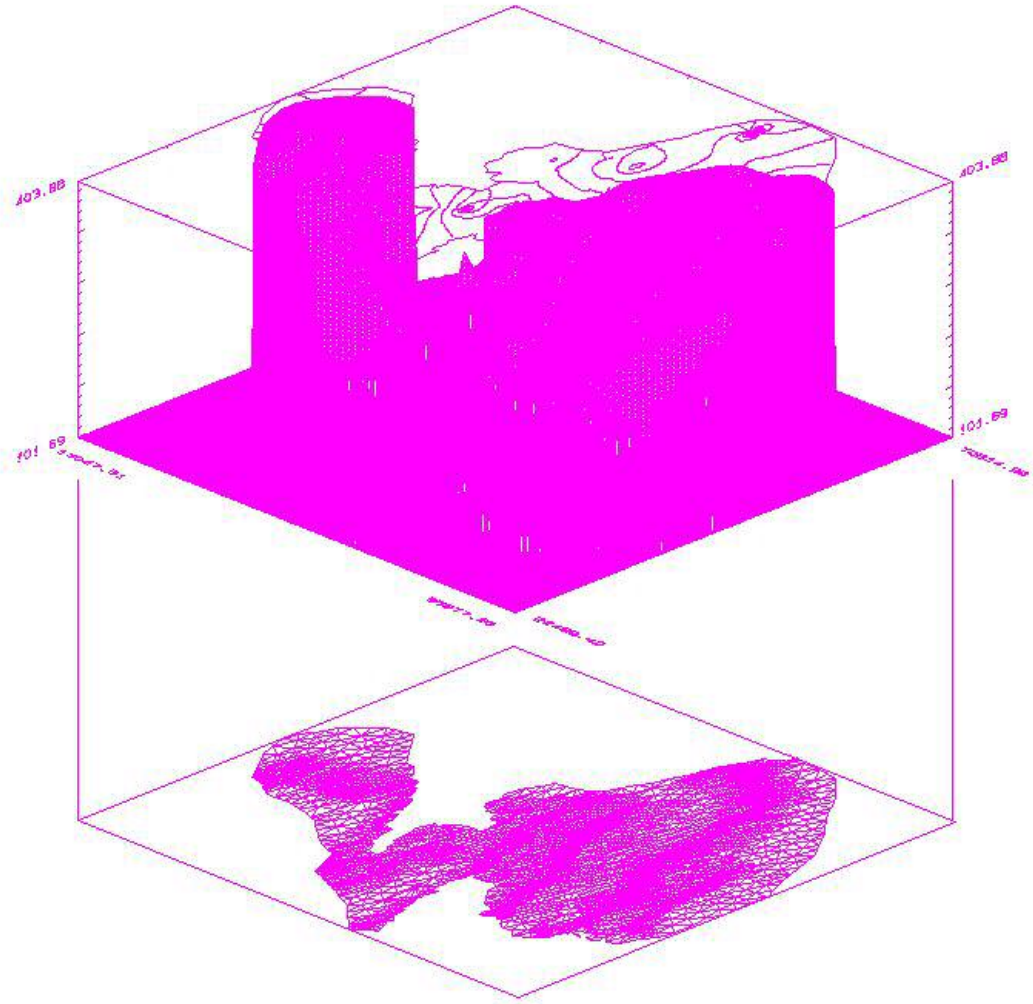

Figure VI-4: 3d plot generated in FEFLOW Model for Equivalent Continuum Model

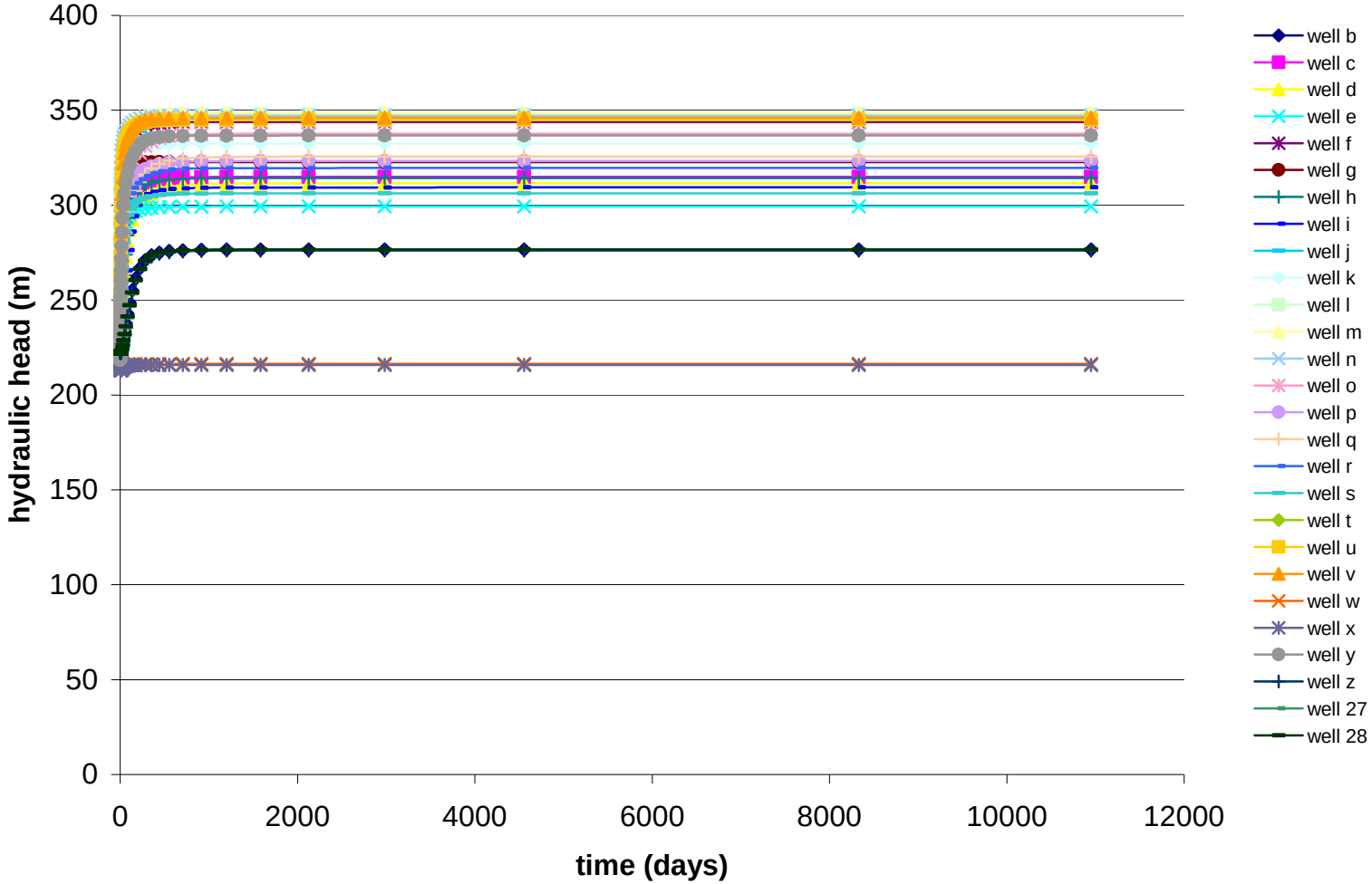

Figure VI-5: Hydraulic head curve for equivalent continuum approach

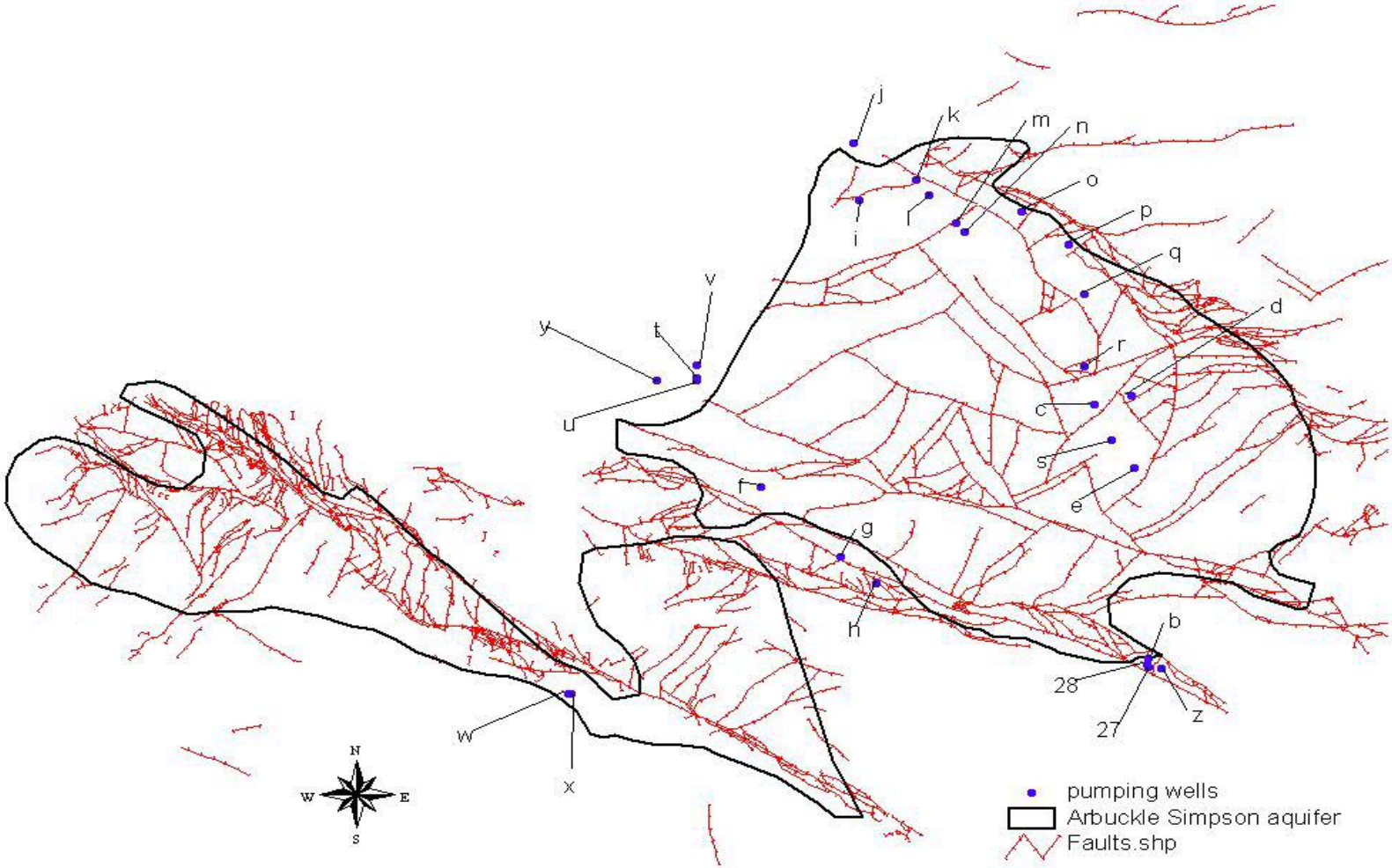

Figure VI-6: Location of pumping wells with their respective names generated by FEFLOW 5.1 Model

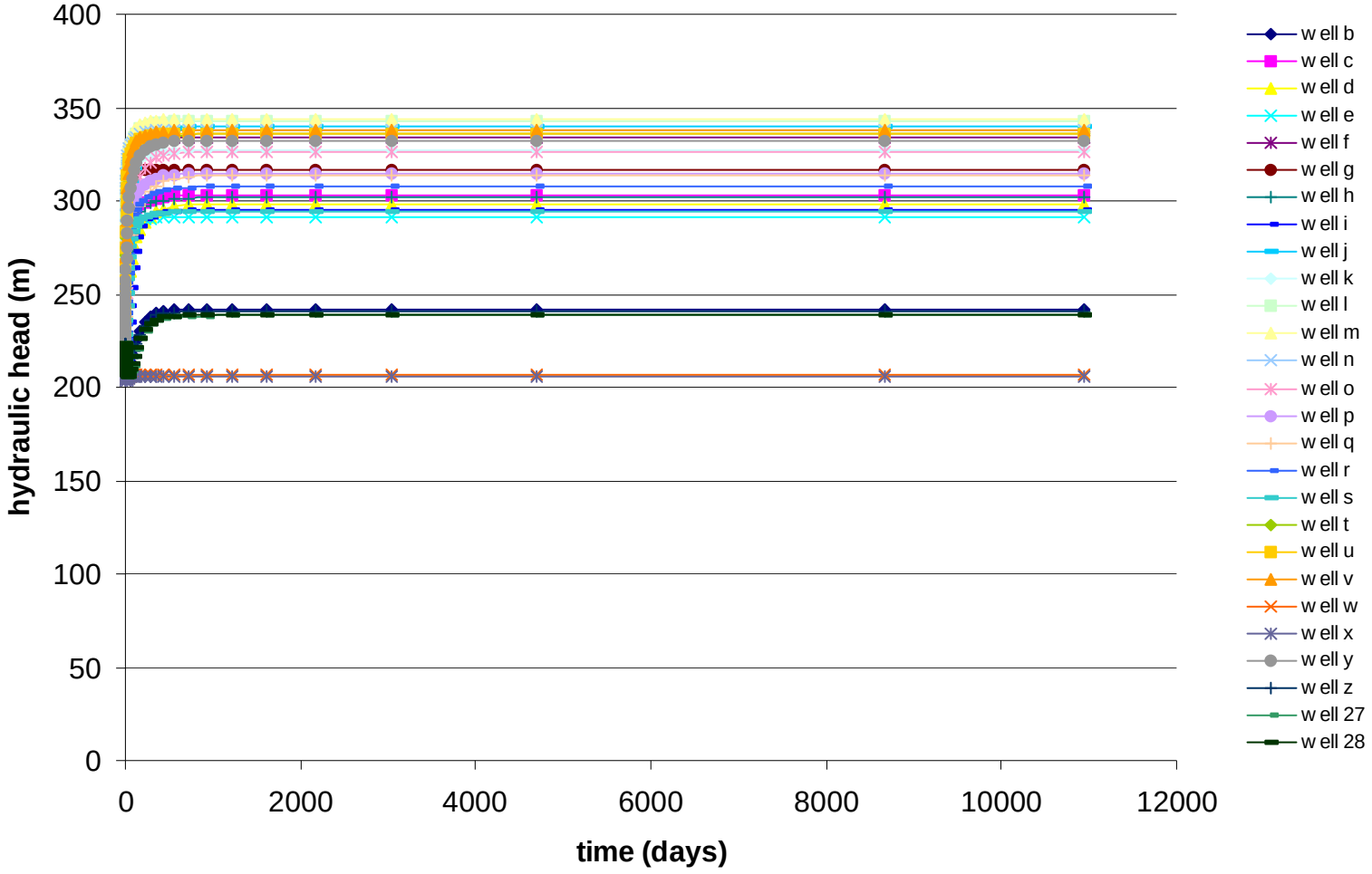

Figure VI-7: Hydraulic head curve for 10x pumping for Equivalent continuum approach

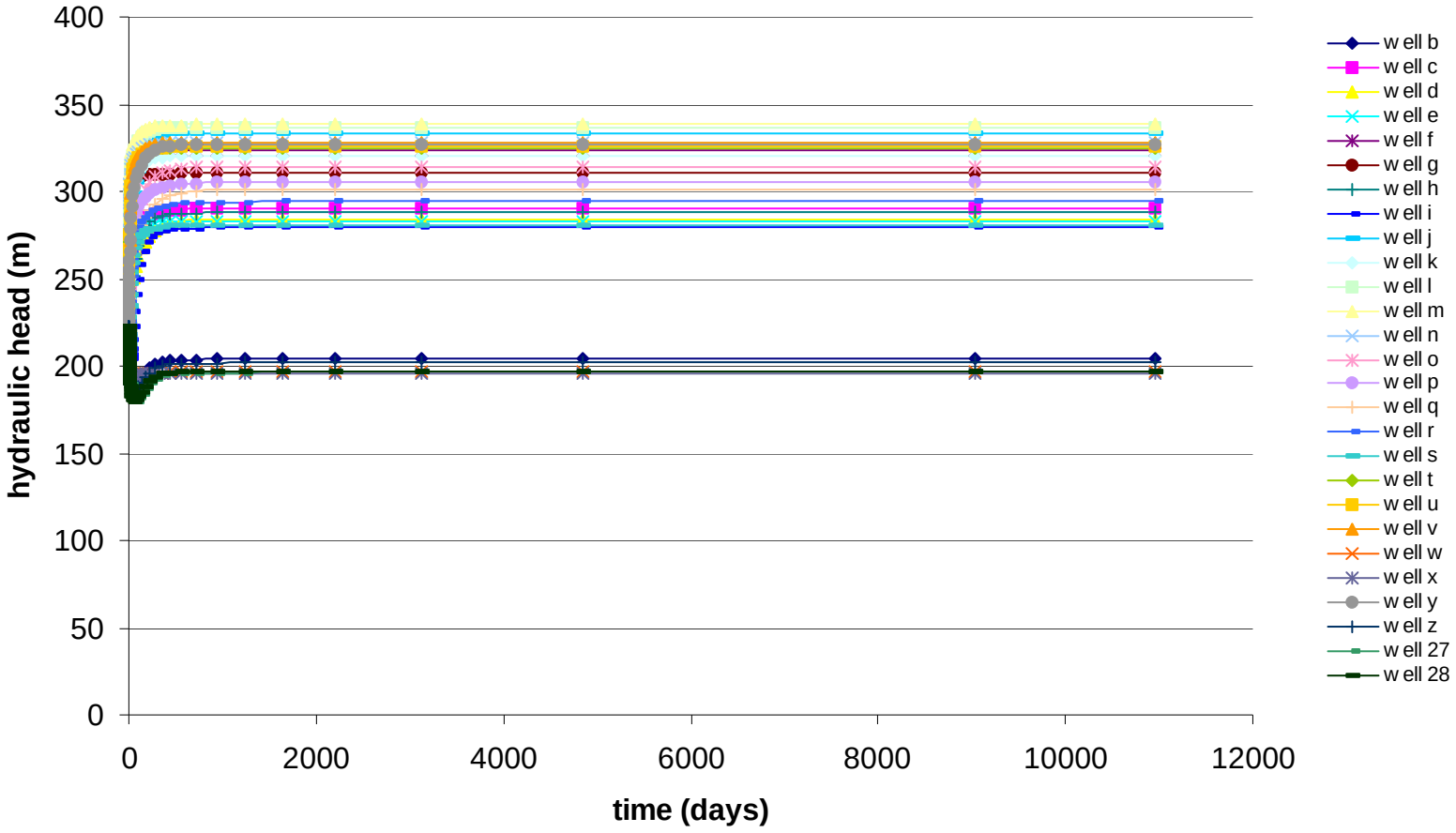

Figure VI-8: Hydraulic head curve for 20x pumping for Equivalent continuum approach

Equivalent Continuum Approach

In the equivalent continuum approach, the fractured medium was treated as a homogenous continuum with representative average hydraulic characteristics found from previous hydrogeologic investigations. In other words, the fractures were assumed to be numerous enough and distributed evenly enough for the effects of individual fractures to be ignored. Thus, transmissivity was modeled as a bulk property of the aquifer and no account was taken of individual fracture contributions or fracture properties such as aperture, roughness, or length. This assumption appears to be a reasonable assumption because of large area and numerous, widely distributed fractures in the aquifer. The conceptual model was based on unsteady state, transient groundwater flow. Based on previous hydrogeologic investigations, a uniform average transmissivity value of 15,000 ft^2/day was applied to the entire aquifer for hydraulic head simulations for the equivalent continuum approach.

The finite element mesh developed was denser around the rivers to represent the river boundary conditions for the groundwater-surface water interaction and around pumping wells as shown in Figure VI-1. The average recharge rate value of 4.7 inches/year was applied to the simulations. The pumping rate for wells was applied through a GIS shape file developed for different wells in the Arbuckle-Simpson Aquifer and .trp file (ASCII format file) containing pumping rates for different wells. Figure VI-1, VI-2, VI-3, & VI-4

shows the finite element mesh, hydraulic head variation plot, velocity vectors and 3D plot respectively generated by FEFLOW 5.1 model for equivalent continuum approach.

The value of hydraulic head for all pumping wells initially increased rapidly and then became constant for all pumping wells for a simulation period of 30 years as shown in Figure VI-5. The value of hydraulic head varied in a range of 300-350 m for most of wells which can be seen in Figure VI-5. Such variation of hydraulic head with time shows that there has been an equilibrium established between the pumpage and recharge in the aquifer.

Figures VI-1 to VI-4 display the output of simulations for equivalent continuum approach. Hydraulic head variations over the entire aquifer as shown in Figure VI-2 for this approach were analyzed to determine the effects of pumping on the hydraulic head over the years. Hydraulic head simulations were compared with potentiometric surface generated for Arbuckle-Simpson Aquifer as shown in Figure V-1. The trend of variation in hydraulic head in the simulations remained same as potentiometric surface. The high hydraulic head for few pumping wells was in the range of 335-345 m. These wells were found to be in the region of high initial head. The wells for which hydraulic head was very less were located in the region of low initial head. The locations of pumping wells with their respective names generated by the model are displayed in Figure VI-6.

The well w and well x were located in the western part of the Arbuckle-Simpson Aquifer. The initial hydraulic head in region surrounding these wells was very less as can be seen in potentiometric surface (Figure V-1). The hydraulic head in the eastern portion of Arbuckle-Simpson Aquifer decreased generally northwest to southeast. The values of hydraulic head in the simulations were comparable with the initial head in the Arbuckle-Simpson Aquifer for normal pumping rate. Thus, it can be deduced that water level in the aquifer remains the same with applied pumping rate except at few places where hydraulic head decreased rapidly due to pumping wells. The hydraulic head decreased rapidly in the western part of the aquifer where the pumping wells were located in the model and down side of eastern part of Arbuckle-Simpson Aquifer. The initial head in the west part of Arbuckle-Simpson Aquifer was high and then decreased rapidly towards the southeastern side. The highest hydraulic head was in the small western part of the aquifer. It should to be noted that there were no pumping wells in the western part of the aquifer.

The equivalent continuum model was run with higher pumping values for all pumping wells to predict the hydraulic head over the entire aquifer. The simulations were carried out with increasing pumping by a factor of 10 and 20. The graphical representation of hydraulic head for simulations of 10 times pumping and 20 times pumping are shown in Figure VI-7 and VI-8 respectively. It can be easily inferred from the figure VI-7 that the hydraulic head for all pumping wells decreased insignificantly with increased pumping by a factor of

10. The decrease in hydraulic head for most of the wells with 20 times pumping was noticeable, which gave an indication of the aquifer behavior with higher pumping. The overall hydraulic head in the aquifer with higher pumping in all wells would decrease.

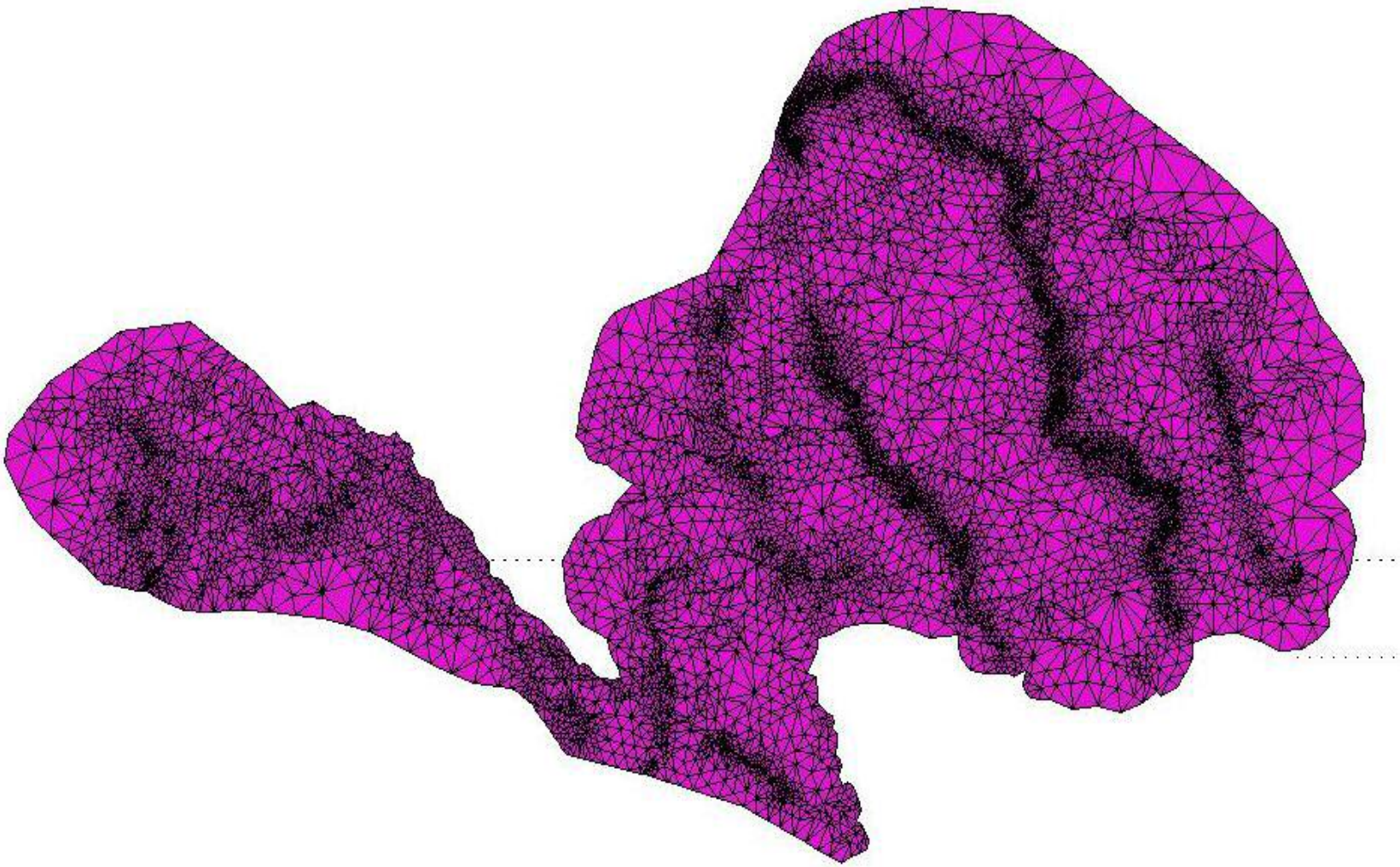

Figure VI-9: Mesh generated in FEFLOW Model for Discrete Fracture Approach

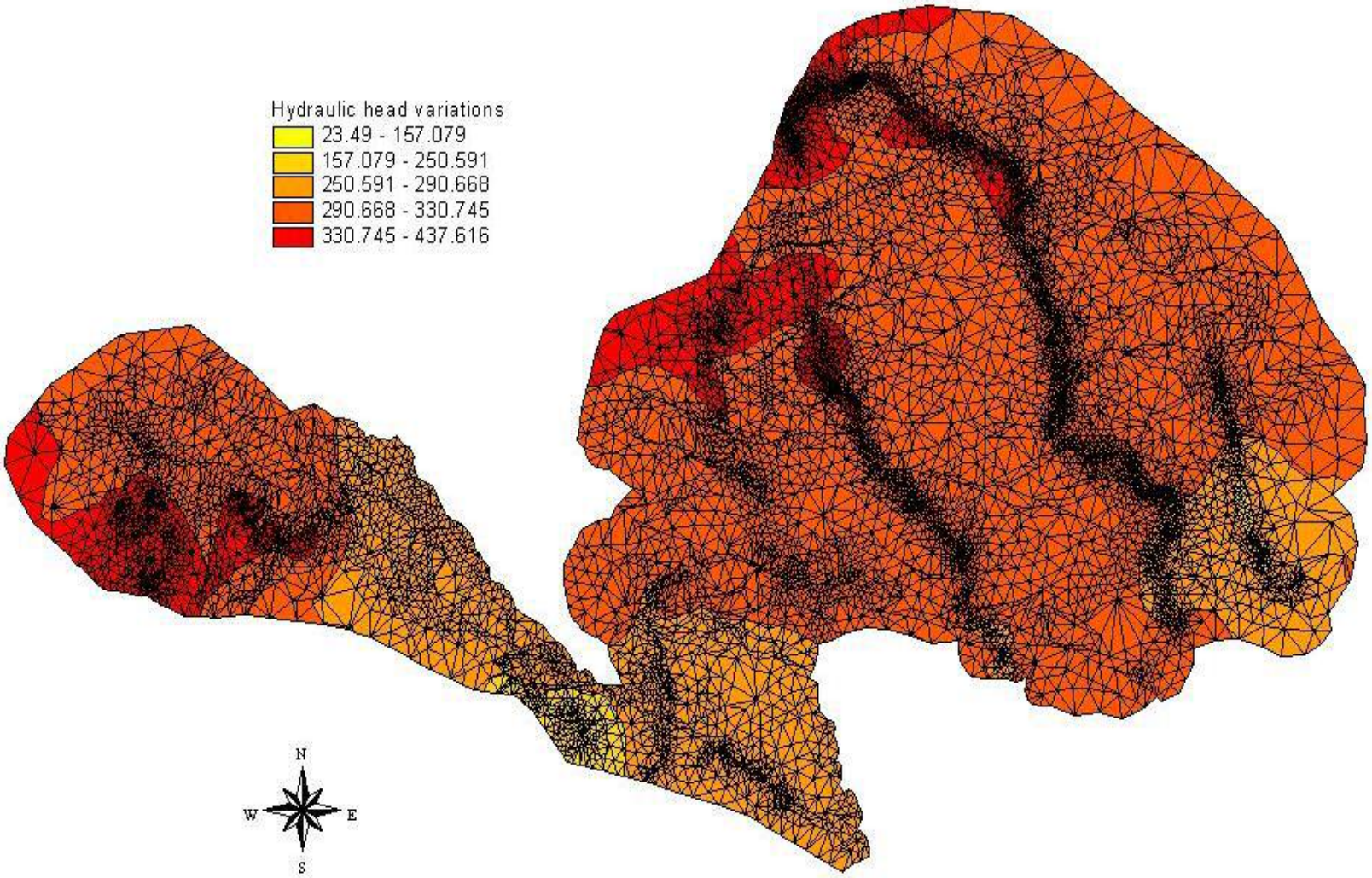

Figure VI-10: Hydraulic head generated in FEFLOW Model for Discrete Fracture Approach

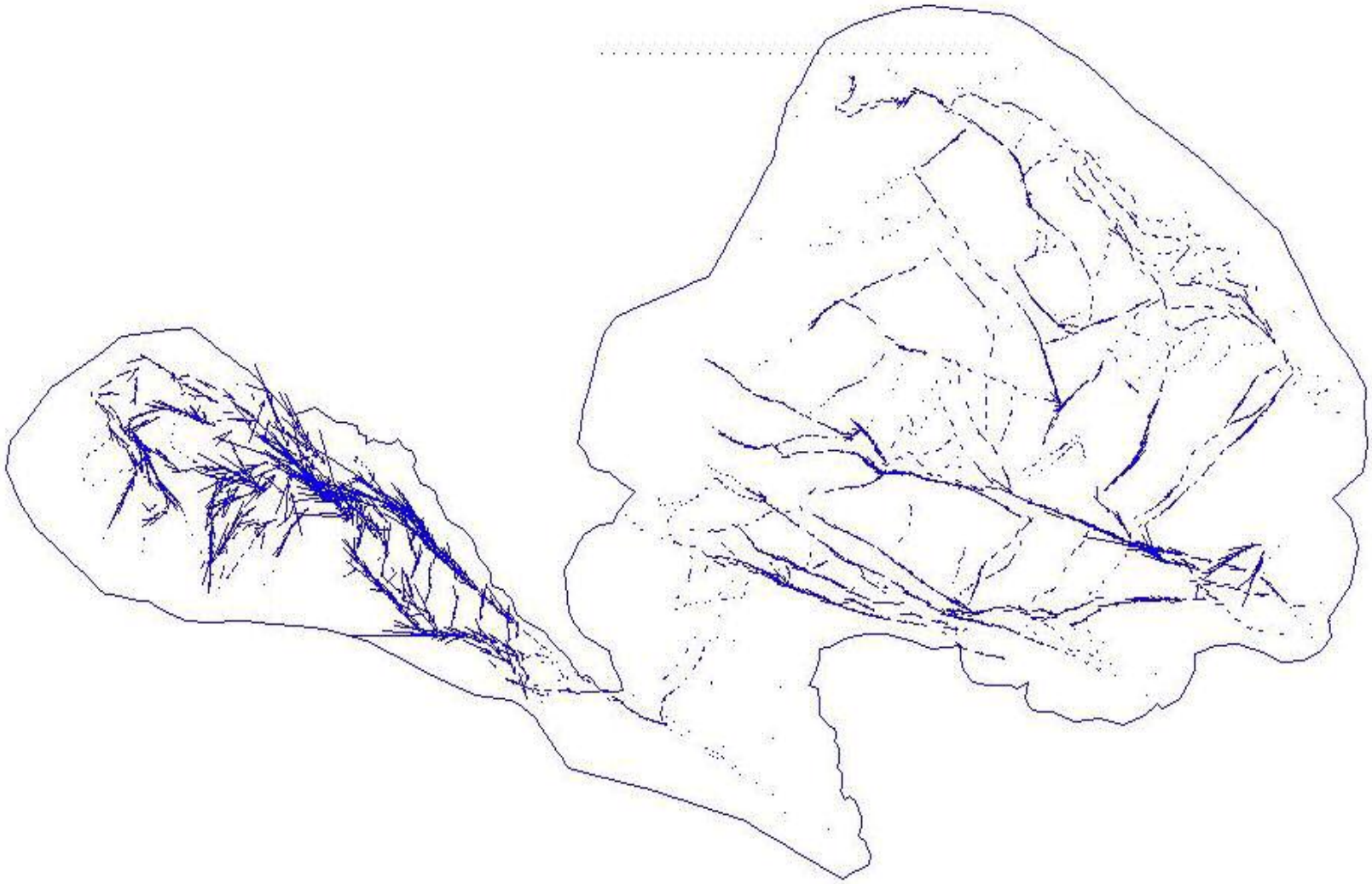

Figure VI-11: Velocity Vectors generated in FEFLOW Model for Discrete Fracture Approach

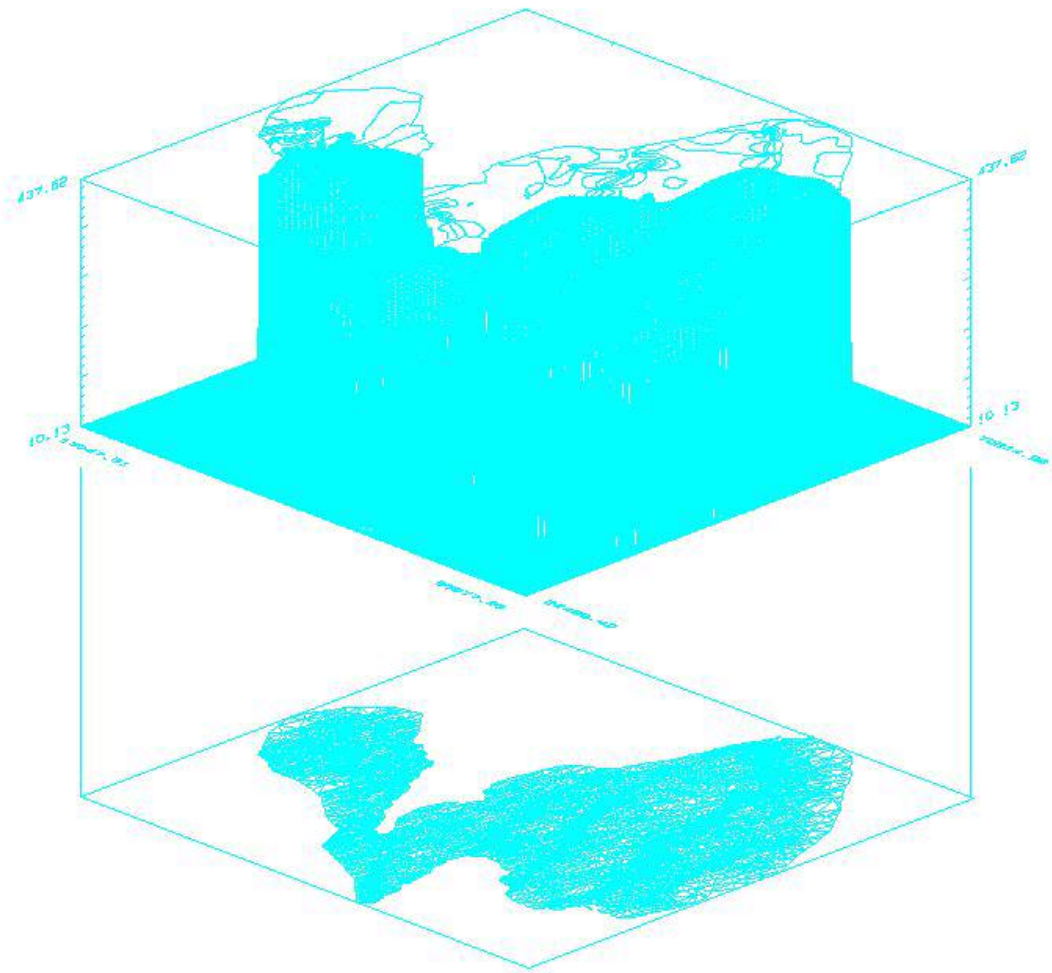

Figure VI-12: 3d plot generated in FEFLOW Model for Discrete Fracture Approach

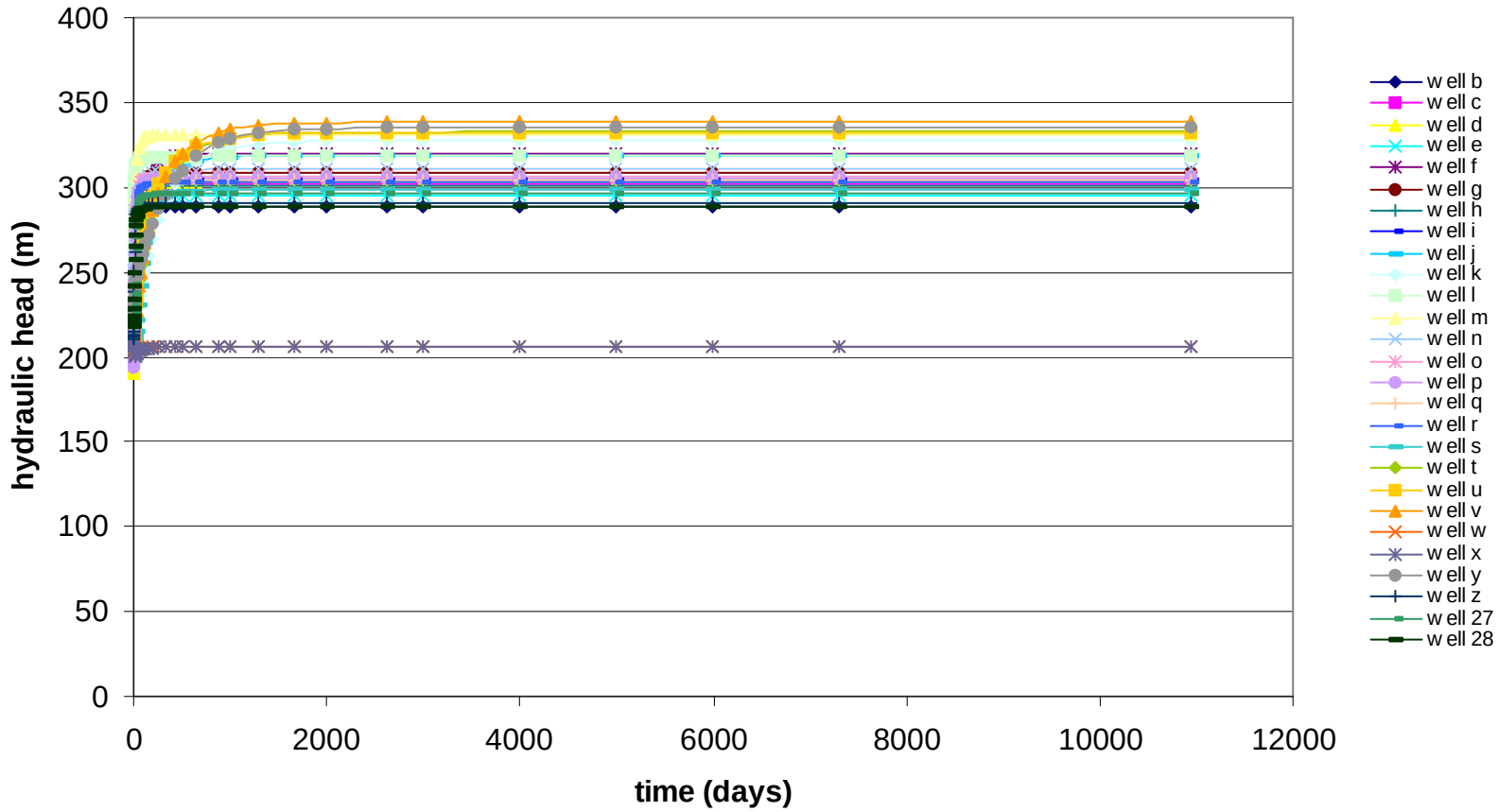

Figure VI-13: Hydraulic head curve for Discrete Fracture Model approach

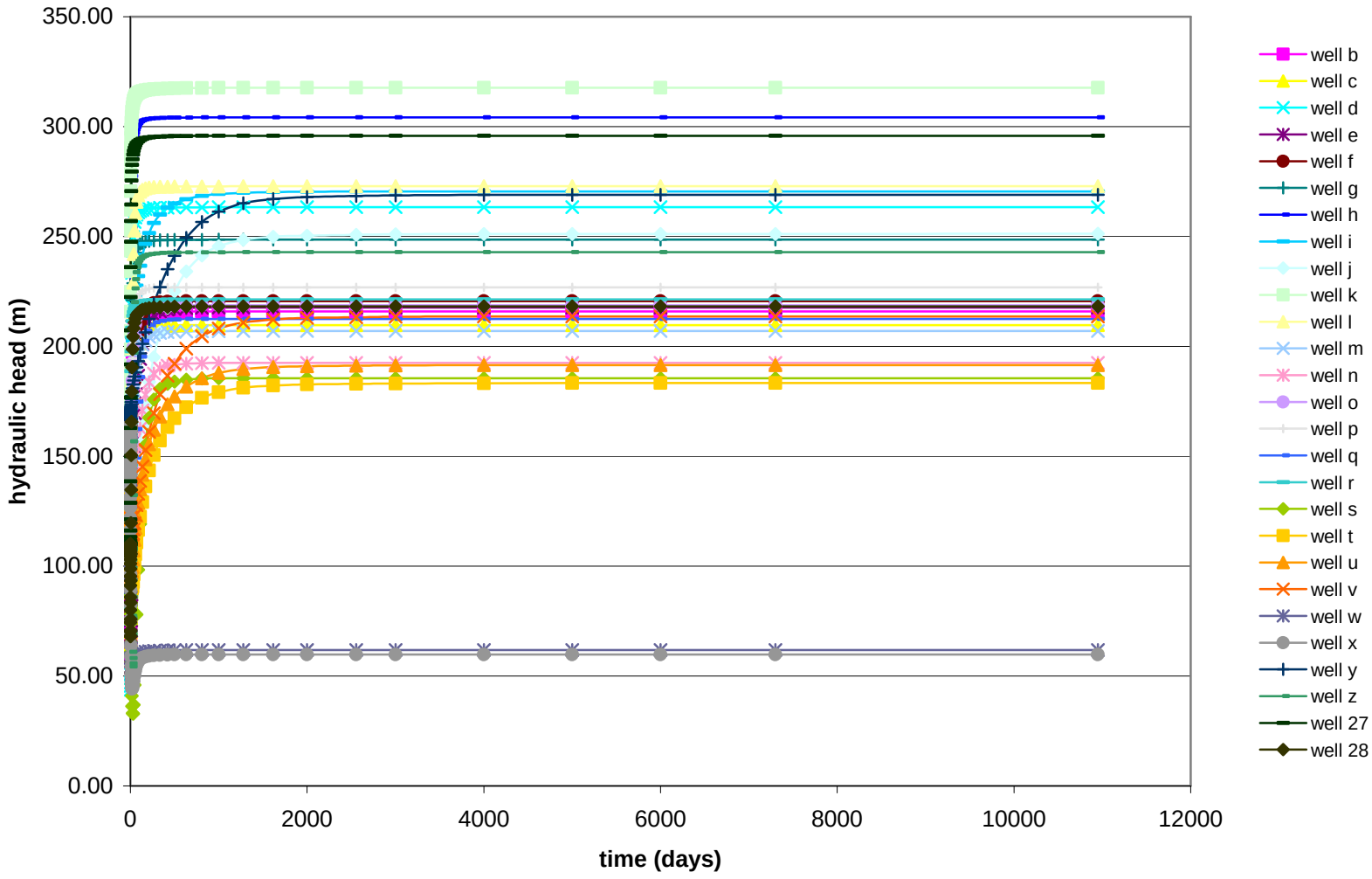

Figure VI-14: Hydraulic head curve for 10x pumping for Discrete Fracture Model approach

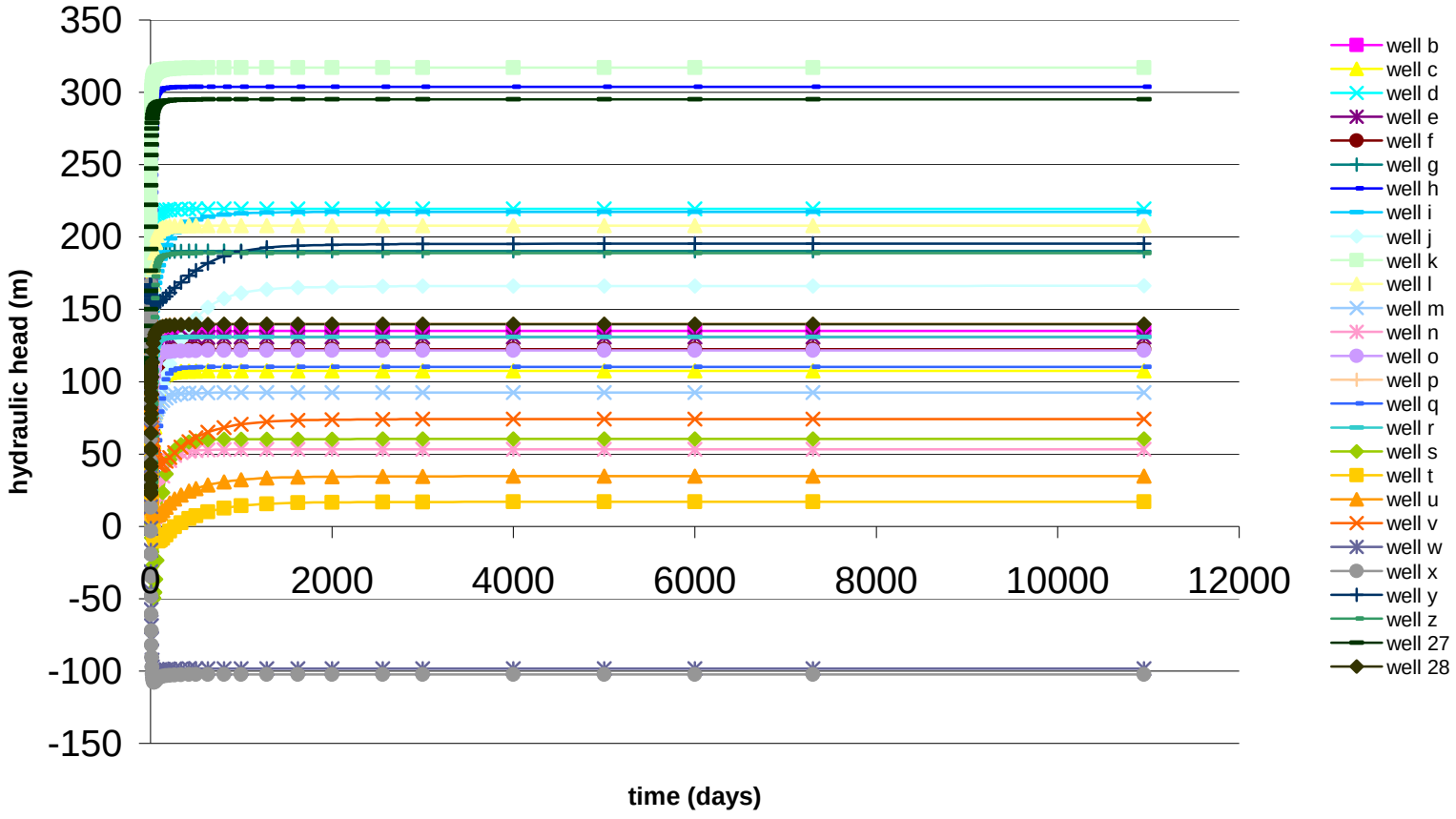

Figure VI-15: Hydraulic head curve for 20x pumping for Discrete Fracture Model approach

Discrete Fracture Model Approach

In discrete fracture model approach, the medium was assumed to consist of fractures with flowing water and matrix blocks with essentially stagnant water. This approach assumes that all groundwater flow occurs in fractures. Thus, transmissivity is based upon width of the fractures and fracture density in this approach. The equation solved for this model calculated the hydraulic conductivity of the fractures based on the width of the fracture. In discrete fracture model, the fractures were discretized as 1D entities to account for fracture thickness by an integral form of the flow equations. The fracture thickness in different parts of the aquifer varied from .25 inches to 3.0 inches as shown in Appendix C, however for the simulation purpose the fracture thickness was assumed to be 1 inch for the entire aquifer. The fractures were aligned in the model by using the fault map of the Arbuckle-Simpson Aquifer with the help of a shape file (GIS file) for faults provided by USGS. The finite element mesh developed was more refined around the fractures in comparison to the grid developed for equivalent continuum approach. A finite element mesh generated for discrete fracture model is shown in Figure VI-7.

Figures VI-10, VI-11, & VI-12 show hydraulic head variation plot, velocity vectors and 3D plot respectively generated by FEFLOW 5.1 model for discrete fracture approach. The graphical representation of hydraulic head as shown in figure VI-13 for the discrete fracture model approach shows how hydraulic head

varied for all pumping wells over a simulation period of 30 years. The hydraulic head variation plot (Figure VI-10) predicts the hydraulic head to be in the range of 290 to 330 m for most part of the aquifer which was comparable with the potentiometric surface generated for the Arbuckle-Simpson Aquifer shown in Figure V-1. In some parts of the aquifer, the hydraulic head was higher in the range of 330 m to 437 m. The hydraulic head was higher in a part of the west of the aquifer and in some parts of eastern portion of the Arbuckle-Simpson Aquifer to the North West as shown in figure VI-10. The hydraulic head decreased very rapidly near the location of pumping wells well w and well x, which can be seen by looking at Figure VI-6 and Figure VI-10. The locations of pumping wells with their respective names generated by the model are displayed in Figure VI-6.

The discrete fracture model like the equivalent continuum model was also run with higher pumping values for all pumping wells to predict the hydraulic head over the entire aquifer for the next 30 years. The simulations were carried out with increasing pumping 10 times and 20 times as in equivalent continuum model approach. The graphical representation of hydraulic head for simulations of 10 times pumping and 20 times pumping is shown in Figure VI-14 and VI-15 respectively. The hydraulic head for all pumping wells for 10 times pumpage had significant change for most of wells over the 30 years. The peak hydraulic head in most of the wells over the 30 years decreased by a significant amount as shown in Figure VI-14. The decrease in hydraulic head in most of the wells

with high pumping was due to very low value of transmissivity applied in the model over the entire aquifer for the rock masses. The low value of transmissivity was applied to the rock masses because of the assumption that all flow occurs through the faults as the dominant fracture network consists of large fractures and faults, which control the groundwater flow in rock masses (Wang et. al., 2002).

The hydraulic head for three different wells in the aquifer did not decrease. The locations of these wells were analyzed with the mesh in the model. It was found that, all these three wells, well k, well h, and well 27 lie on the nodes of the elements which are discretized as fractured elements. The location of these wells can also be analyzed by looking at Figure VI-6. Thus, the hydraulic head remained the same over a simulation period of 30 years for the wells that lie exactly on the faults. This was obvious, since the discrete fracture model assumes the flow is only through the fractures. There is always water flowing in the fractures and the wells. The pumping wells, which were lying exactly on the fractures, might take water from other parts of the aquifer through the connectivity of the fractures.

The hydraulic head for all pumping wells for 20 times pumpage further decreased for most of wells over the 30 years. The hydraulic head for same three wells, which lied on fractured elements, remained the same.

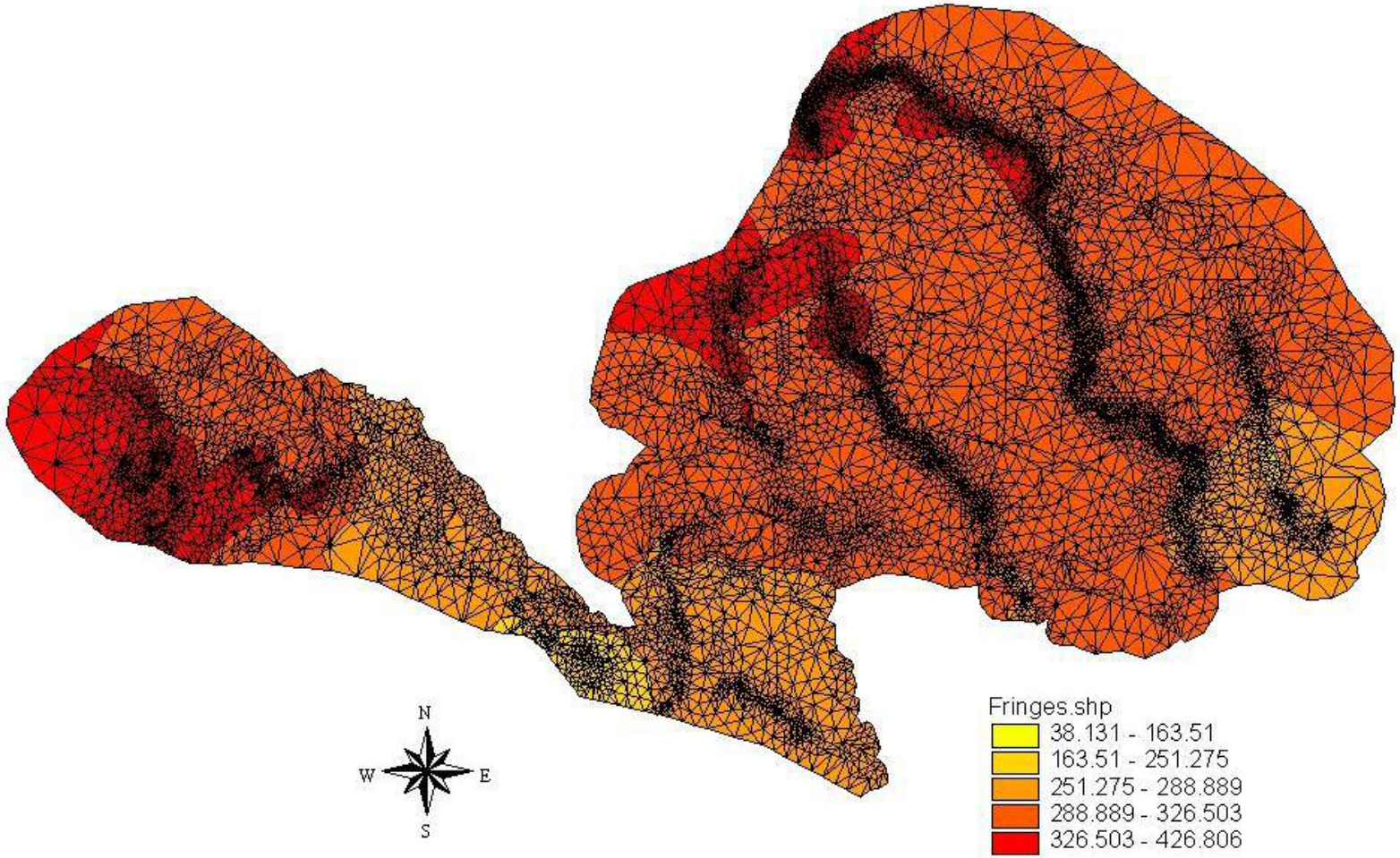

Figure VI-16 Hydraulic head generated in FEFLOW Model for Dual Fracture Approach

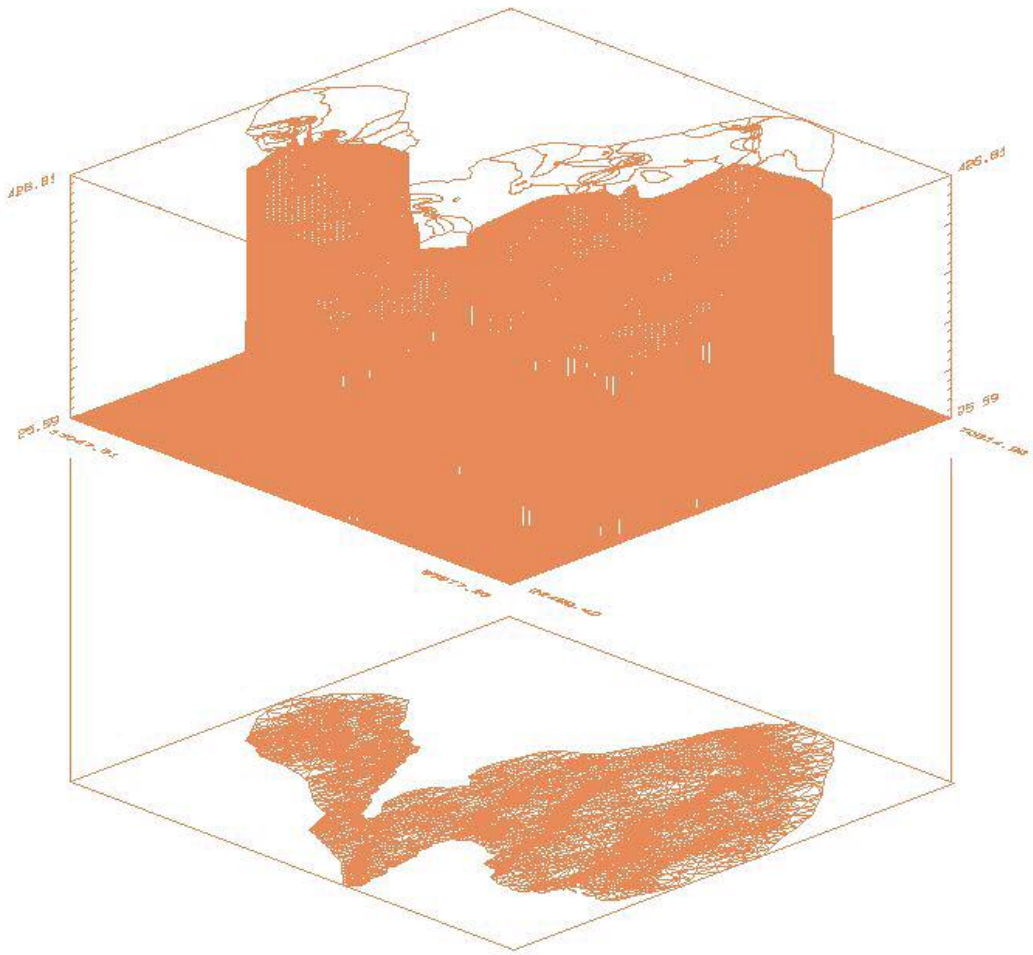

Figure VI-17: 3d plot generated in FEFLOW Model for Dual Fracture Approach

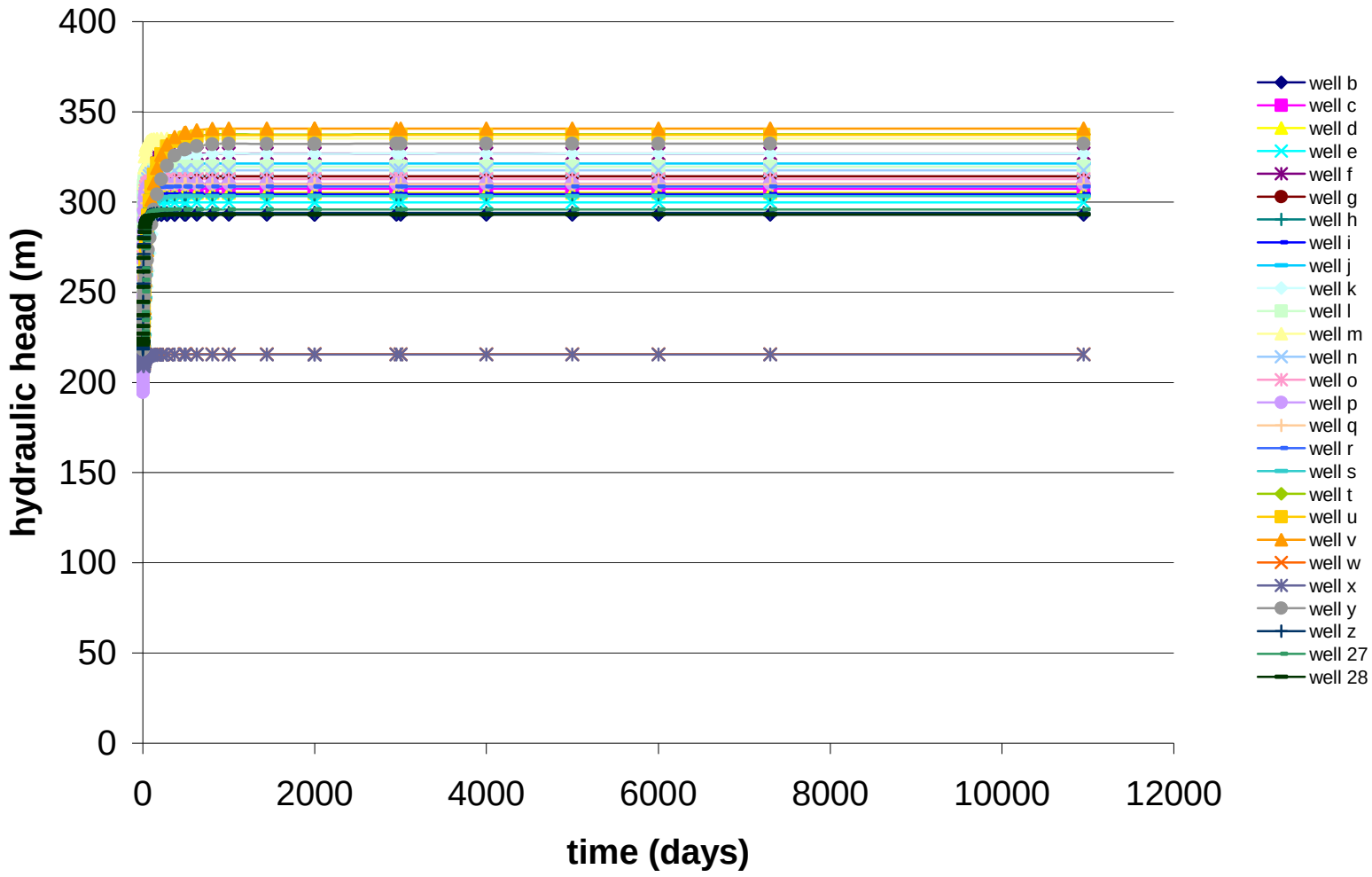

Figure VI-18: Hydraulic head curve for Dual Fracture Model approach

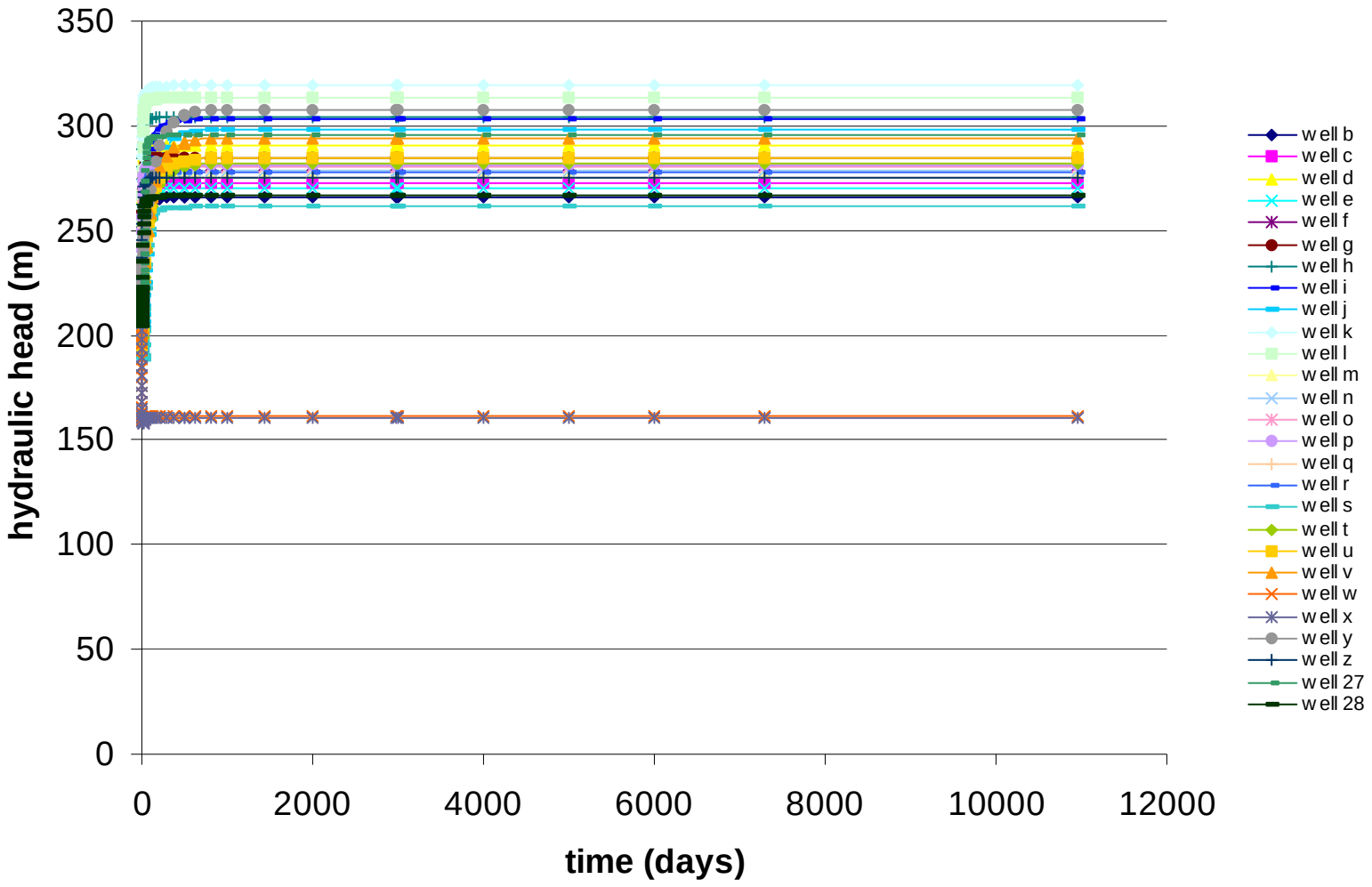

Figure VI-19: Hydraulic head curve for 10x pumping for Dual Fracture Model approach

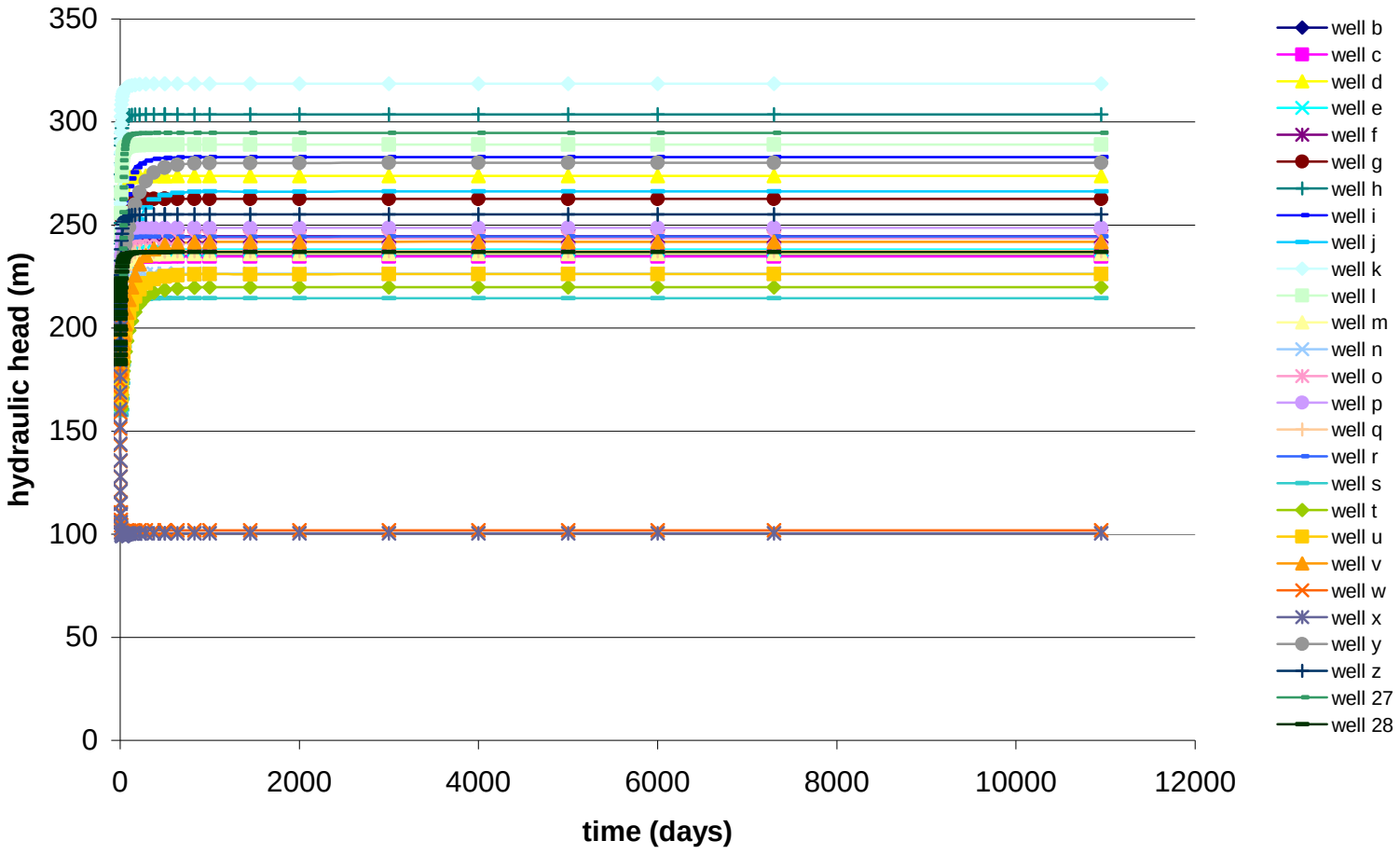

Figure VI-20: Hydraulic head curve for 20x pumping for Dual Fracture Model approach

Dual Fracture Model Approach

Dual fracture model approach consists of dominant fracture network and the fractured rock matrix. In discrete fracture model, it was assumed that all the flow occurred through the fractures, and matrix (rock) blocks do not contribute to the groundwater flow. However, in dual fracture model approach the rock blocks also contribute some groundwater flow in the aquifer. The dominant fractures were modeled as in discrete model approach, and for considering the minor fractures in the rock blocks the fractured rock matrix blocks were assumed to behave as one continuum. The dominant fractures were assigned the same hydraulic properties as given in the discrete approach, however to take into account the large number of minor fractures a transmissivity value of 2500 ft^2/day was assigned for fractured rock matrix blocks.

Figures VI-16 & VI-17 show hydraulic head variation plot, and 3D plot respectively generated by FEFLOW V-1 model for dual fracture approach. The groundwater flow simulations for dual fracture model approach for normal pumping are very similar to the discrete fracture model approach. The graphical representation of hydraulic head as shown in Figure VI-16 for the dual fracture model approach shows how hydraulic head varies for all pumping wells over a simulation period of 30 years. The hydraulic head variation plot (Figure VI-16)

predicted the hydraulic head to be in the range of 290 to 330 m for most part of the aquifer, which was similar to the discrete fracture model approach results. The dual fracture model like the equivalent continuum model, and discrete fracture model approach was also run with higher pumping values for all pumping wells to predict the hydraulic head over the entire aquifer for the next 30 years. The simulations were carried out with increasing pumping by a factor of 10 and 20 times as in other two approaches. The graphical representation of hydraulic head for simulations of 10 times pumping and 20 times pumping is shown in Figure VI-19 and VI-20 respectively. The decrease in hydraulic head for most of the pumping wells for 10 times and 20 times pumpage in dual fracture approach was higher than equivalent continuum model but lesser than discrete fracture approach.

A value of transmissivity greater than 2500 ft2/day for the rock blocks simulated less decrease in hydraulic head in all the pumping wells and a value of transmissivity less than 2500 ft2 day simulated in more decrease in hydraulic head in all the pumping wells. However, the rate of variation in hydraulic head by assuming different transmissivity values was very low.

Table VI-1: Comparison of final hydraulic head simulated for pumping wells in all the approaches for normal pumping

Pumping well	Pumping yield (gpm)	Equivalent continuum	Discrete Fracture Model	Dual Fracture model
well b	200	276.61	288.67	292.986
well c	150	314.99	301.72	307.358
well d	100	311.49	302.74	305.228
well e	150	299.32	295.73	299.735
well f	200	343.84	319.86	326.792
well g	135	322.73	308.9	314.345
well h	200	314.34	300.88	304.181
well I	276	309.36	304.48	304.295
well j	200	344.99	318.81	321.35
well k	900	332.55	327.7	326.78
well l	125	347.78	318.16	319.55
well m	600	348.56	331.26	335.15
well n	100	347.08	310.38	317.57
well o	150	337.72	306.142	312.66
well p	150	323.33	305.02	310.11
well q	500	325.6	304.53	309.86
well r	200	319.6	302.67	308.6
well s	116	306.24	298.23	303.31
well t	800	345.033	332.67	337.53
well u	600	344.94	332.5	337.2
well v	600	346.02	338.58	340.71
well w	350	216.34	205.91	215.57
well x	300	215.88	205.71	215.42
well y	150	336.7	335.35	332.39
well z	115	276.17	291.31	293.96
well 27	100	276.47	293.38	295.85
well 28	100	276.56	291.68	293.05

Comparison of Equivalent Continuum Approach, Discrete Fracture Model and Dual Fracture Model Approach

The discrete fracture model and dual fracture model results were compared to identical simulations from equivalent continuum approach, which assume no fracture influence. The continuum approach represents the fracture network as an equivalent porous medium, whereas the discrete-fracture approach considers flow through each individual fracture and dual fracture approach considers flow through both fractures and rock blocks. The different approaches predicted the hydraulic head in all the pumping wells for a simulation period of 30 years. The results of all the approaches were comparable to each other for normal pumping despite slight differences in hydraulic head for pumping wells. Table VI-1 shows the hydraulic head simulated for pumping wells in three different approaches for normal pumping. The variation of hydraulic head over the entire aquifer in dual fracture model was comparable with discrete fracture approach and equivalent continuum model for a simulation period of 30 years, which can be seen by comparing the Figures VI-2, VI-10 and VI-16.

However, the simulations for all the approaches with increased pumping had lot more variation of hydraulic head in all pumping wells. The hydraulic head in almost all of the wells decreased with 10 times pumping and the decrease was more in 20 times pumping in all the approaches, however, the decrease in hydraulic head was less in equivalent continuum model (Figure VI-7

& Figure VI-8) and dual fracture model (Figure VI-14 & Figure VI-15) than discrete fracture approach (Figure VI-19 & Figure VI-20). The decrease in hydraulic head in all the wells with increase of pumping by a factor of 10 and 20 was much higher in discrete fracture approach. The larger decrease in hydraulic head for discrete model approach with increase in pumping by a factor of 10 and 20 might be due to the fact that only dominant fracture network consisting of large fractures and faults were modeled as discrete fractures which were assumed to control the groundwater flow in rock masses. However, fractured rock matrix includes small fractures and rock blocks that possess low permeability, but their numbers are very large in fractured rocks. These small fractures provide large volume for groundwater storage and might contribute secondary role in groundwater flow in such medium (Wang et. al., 2002). Nevertheless, in discrete fracture model these small fractures were not accounted for groundwater flow contribution. This could be one of the reasons of such a higher decrease of hydraulic head in wells with higher pumping. Higher pumping put great stresses on wells in the aquifer, which are not connected with fracture networks. There was no significant change in simulations for hydraulic head for three wells when the pumping was increased 10 times and 20 times in discrete fracture model approach. The locations of these wells were exactly on the elements, which were discretized as fractures.

The limitation of discrete fracture model was overcome by dual fracture model. The dual fracture model considered flow through the dominant fracture

network as wells as minor fractures in the rock blocks. This could be the reason of very less decrease in the hydraulic head as compared to discrete fracture approach with increase of pumping in dual fracture model approach. However, the decrease in hydraulic head for all the pumping wells in dual fracture model approach with increase of pumping by a factor of 10 and 20 was significant and higher than the equivalent continuum approach.

The hydraulic head in all the wells was near to each other even after increased pumping for equivalent continuum model and dual fracture model even though the decrease in hydraulic head for higher pumping in dual fracture approach was more.

The initial head was changed to see the effect on flow simulations in all the approaches. It was found that the peak hydraulic head achieved for all pumping wells over a simulation period of 30 years in all the approach remains the same even with the change in initial head. Thus, final hydraulic head values achieved in different pumping wells were not depending upon the initial head applied in the model significantly.

CHAPTER VII

SUMMARY AND CONCLUSIONS

Fractures play an important role in groundwater flow in the Arbuckle-Simpson aquifer. In some aquifers, virtually all groundwater flow occurs in fractures. Thus, a detailed knowledge of fracture geometry and hydraulics is essential for determining the groundwater flow rates and directions. However, little is known quantitatively about the regional hydrogeological implications of fractures. The purpose of this study was to predict the hydraulic head in Arbuckle-Simpson Aquifer and impact of pumping on Arbuckle-Simpson Aquifer using the groundwater flow model.

In this investigation, the equivalent continuum, discrete fracture model and dual fracture model approaches were used to simulate the future hydraulic head and impact of higher pumping in the aquifer. All the three conceptual approaches simulated the hydraulic head values which were comparable to each other. The higher pumping scenarios in each approach for all wells demonstrated that hydraulic head in all the wells would decrease significantly. This study has determined that pumping was not safe in some areas of western

part of the aquifer because of drastic decrease of hydraulic head. To determine the hydraulic head in the aquifer for water management purposes, either of these approaches can be used.

The simulation results indicated that hydraulic head would not change significantly from present level over the entire aquifer for the next 30 years if the pumping rate were not increased. However, higher pumping may cause decrease of water level over the entire aquifer depending upon the assumed variations in actual transmissivity and other important parameters governing water level in the aquifer.

The study showed that equivalent porous media models could be used to simulate regional groundwater flow in this fractured karst aquifer. The main limitation of equivalent porous media models is that the major explicit conduits are not represented in the model and turbulent flow is not included. However, the simulations for the fracture model did not differ much from equivalent continuum approach. Results of this study show the ability of equivalent continuum model and fracture models to simulate regional groundwater flow which is critical for managing water resources in fractured aquifers and predicting the impact of future pumping on the aquifer.

Recommendations for Future Research

Results from any modeling effort may be interpreted in a variety of ways. Not all of these may be proper given the situation. The utility of a model is increased when sufficient observed data are available to support the modeling effort. The model used for this approach will be more accurate and contain lower uncertainty when required observed data is available for use. Due to high level of uncertainty without calibration, model results should be compared only on a relative basis. Identification and compilation of these guidelines for the proper use of a model for a variety of scenarios will be quite useful to new users.

Future research should consider a variety of improvements to the existing model, including additional data collection, different conceptual model design, and other factors. Further study as recommended below will provide clarification of several important parameters that govern the aquifer water level in response to pumping at different wells. The following list gives some insight into the data used for the model and scope for improvements.

1. All the conceptual approaches used in this study assume that the recharge and transmissivity are distributed uniformly all over the aquifer, however this is unrealistic. Future modeling should consider focusing recharge and transmissivity at different points on the basis of field data.

Faults exist side by side in different rock types that may have different hydraulic conductivity values. The transmissivity values should be measured in the field for different rock types that might give an idea about the variation in values of transmissivity for different rock types. Also transmissivity value might be affected by density of small fractures and dominant fractures in the area.

2. Future modeling should consider representing the aquifer having multiple layers that would allow vertical variation in hydraulic properties and use of different specific storage values to reduce water level fluctuations.
3. Data available from different kind of wells such as irrigation wells, public supply wells etc. from OWRB provides safe yield of wells not actual pumping. Actual pumping data would certainly lower the uncertainty associated with the model simulations.
4. There was only one stream gauge station on Blue River near the outcrop area of Arbuckle-Simpson Aquifer to get the water surface elevation. More field data should be collected at various points along the rivers/creek.
5. There are number of springs in Chickasaw National Recreation Area, that are of main concern. Data for water surface elevation for these springs was not available. Only Byrds Mill Spring and Antelope spring were applied in the model.

6. Fracture data was not available in detail. All the fractures were assumed to be of 1-inch width. Fractures were aligned along the faults in the model provided by USGS in the form of a shape file. More data about dominant fractures or faults responsible for groundwater flow in Arbuckle-Simpson Aquifer would help in getting accurate simulations.

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APPENDICES

Appendix A: Location of observation wells and corresponding water elevation (m) for initial head applied in FEFLOW 5.1 model

x-coord.	Y-coord.	Water elevation (m)
34.1503	-97.3700	265.176
34.1658	-97.0656	268.224
34.1717	-97.2597	275.2344
34.1722	-97.4036	271.272
34.1739	-96.9839	236.8296
34.1739	-97.1758	245.0592
34.1864	-97.2306	278.5872
34.1881	-97.4039	246.888
34.2008	-97.3156	243.84
34.2156	-97.0536	251.46
34.2172	-97.0100	223.7232
34.2172	-97.3897	260.2992
34.2175	-97.2656	260.2992
34.2186	-97.2661	267.3096
34.2189	-97.2658	262.4328
34.2297	-96.9489	199.644
34.2297	-97.2572	247.8024
34.2300	-97.2567	247.1928
34.2300	-97.4553	223.7232
34.2317	-97.1236	234.0864
34.2317	-97.1628	232.2576
34.2317	-97.2469	248.1072
34.2317	-97.4378	254.8128
34.2417	-97.0250	206.0448
34.2439	-97.2711	229.8192
34.2442	-97.2569	263.3472
34.2456	-97.2653	180.7464
34.2458	-97.2733	257.8608
34.2461	-97.2728	258.1656
34.2475	-97.2814	264.2616
34.2481	-97.2792	258.1656
34.2489	-97.2772	259.3848
34.2517	-97.0733	231.9528
34.2558	-97.2783	268.5288
34.2561	-97.2739	260.9088
34.2572	-96.9528	215.7984
34.2572	-97.2808	260.2992
34.2583	-96.9750	238.9632
34.2597	-97.2789	270.0528
34.2608	-97.1694	259.9944
34.2653	-97.2881	252.6792
34.2658	-97.2656	257.556
34.2667	-96.9667	178.308
34.2681	-97.0122	210.0072
34.2717	-97.1694	232.5624
34.2725	-97.2133	217.0176
34.2778	-97.4225	278.892
34.2828	-97.2564	233.7816

34.2853	-97.2561	236.8296
34.2867	-97.2664	-9.7536
34.3025	-97.2931	254.2032
34.3042	-97.2567	249.936
34.3044	-97.0886	259.08
34.3111	-97.0167	213.36
34.3214	-97.0158	213.36
34.3111	-97.0167	208.1784
34.3111	-97.0167	213.36
34.3111	-97.0167	213.36
34.3111	-97.0167	213.36
34.3111	-97.2278	254.8128
34.3147	-97.4531	313.0296
34.3150	-97.3486	249.936
34.3189	-97.3178	261.8232
34.3250	-97.0139	211.2264
34.3317	-97.3681	259.08
34.3353	-97.3375	260.604
34.3403	-97.4353	219.456
34.3442	-97.2653	283.464
34.3461	-97.1694	280.416
34.3622	-97.1917	323.088
34.3633	-97.1856	334.6704
34.3633	-97.1881	321.564
34.3639	-97.2564	320.04
34.3758	-97.1842	334.0608
34.3847	-97.3769	302.6664
34.4058	-97.4225	289.2552
34.4086	-97.4225	228.6
34.4350	-97.4050	310.5912
34.4722	-97.3667	320.04
34.4892	-97.4006	285.9024
34.4931	-97.4203	280.1112
34.4983	-97.3681	281.94
34.6511	-96.4669	213.0552
34.4217	-96.4925	234.696
34.4219	-96.4917	234.696
34.4228	-96.4914	234.696
34.4228	-96.4922	234.696
34.4256	-96.3211	194.4624
34.4339	-96.4917	231.648
34.4406	-96.3150	208.788
34.4408	-96.3158	208.788
34.4478	-96.2561	185.928
34.4486	-96.2675	199.644
34.4486	-96.2756	210.312
34.4492	-96.2547	185.928
34.4494	-96.3161	208.4832
34.4508	-96.2567	185.928
34.4519	-96.2575	187.452
34.4539	-96.2583	188.976
34.4564	-96.2672	213.0552
34.4572	-96.2589	190.8048
34.4633	-96.4894	239.8776
34.4653	-96.2797	216.408
34.4742	-96.2592	194.7672
34.4764	-96.2778	210.0072

34.4769	-96.2833	205.74
34.5006	-96.2883	207.264
34.5006	-96.3019	202.692
34.5042	-96.3017	192.6336
34.5050	-96.2922	184.404
34.5050	-96.3089	193.8528
34.5233	-96.2761	197.2056
34.5244	-96.2761	201.7776
34.5336	-96.2661	201.7776
34.5353	-96.2969	220.3704
34.5467	-96.2847	190.5
34.5350	-96.2992	225.552
34.5364	-96.2625	195.072
34.6667	-96.3433	220.98
34.7764	-97.0564	307.848
34.5147	-97.1689	963.4728
34.5200	-97.2281	288.3408
34.5200	-97.3708	265.7856
34.5200	-97.4322	273.7104
34.6942	-97.0681	311.8104
34.5275	-97.3383	261.2136
34.5353	-97.3883	251.46
34.5411	-97.4550	283.464
34.5447	-97.4508	274.32
34.5494	-97.4500	246.888
34.5500	-97.4492	225.8568
34.5592	-97.3586	610.2096
34.5672	-97.3333	275.2344
34.5708	-97.2369	250.5456
34.5936	-97.4319	316.992
34.6053	-97.2808	291.9984
34.6089	-97.3311	281.3304
34.6167	-97.3972	277.368
34.6217	-97.2106	237.1344
34.6292	-97.1653	263.3472
34.6508	-96.9703	359.664
34.6525	-97.3006	331.9272
34.6525	-97.4278	299.0088
34.6556	-96.9753	351.4344
34.6561	-97.1722	249.0216
34.6583	-96.9917	350.52
34.6667	-97.3861	315.7728
34.6797	-96.9392	351.4344
34.6823	-97.3138	313.6392
34.6828	-97.1856	243.84
34.6869	-96.9650	350.52
34.6925	-97.3356	294.4368
34.6942	-97.2831	320.04
34.6961	-97.0156	316.6872
34.6961	-97.1603	256.9464
34.6961	-97.2128	273.1008
34.7000	-97.2089	254.8128
34.7069	-97.1250	270.3576
34.7086	-97.3686	288.6456
34.7106	-97.4211	306.9336
34.7350	-97.4003	289.56
34.7422	-97.4003	283.464

34.7450	-97.3642	271.8816
34.7469	-97.2808	288.9504
34.7500	-97.2083	256.6416
34.7522	-97.0725	301.752
34.7533	-97.1778	253.5936
34.7542	-97.0178	343.8144
34.7558	-96.9475	325.5264
34.7561	-97.1986	250.8504
34.7578	-97.1228	281.6352
34.7644	-96.9500	336.804
34.7680	-96.9552	358.14
34.7686	-96.9792	345.6432
34.7736	-97.3028	269.748
34.7775	-97.4058	312.1152
34.7778	-97.3281	279.8064
34.7808	-96.9708	341.9856
34.7815	-96.9598	345.6432
34.7831	-96.9707	338.9376
34.7831	-97.2239	293.8272
34.7842	-97.4453	322.4784
34.7889	-97.1819	295.656
34.4481	-96.6375	299.9232
34.1761	-96.4944	199.644
34.1778	-96.4208	192.024
34.1806	-96.4778	188.3664
34.1833	-96.7167	205.1304
34.1864	-96.5389	188.3664
34.1889	-96.8028	216.7128
34.1889	-96.8736	211.836
34.1972	-96.5331	248.1072
34.2125	-96.8975	219.1512
34.2125	-96.6694	195.072
34.2244	-96.8200	199.644
34.2333	-96.4931	202.692
34.2347	-96.7625	221.5896
34.2389	-96.4433	210.0072
34.2417	-96.7667	248.7168
34.2586	-96.4442	205.1304
34.2625	-96.5672	212.1408
34.2653	-96.6339	221.2848
34.2750	-96.4833	217.932
34.2814	-96.8531	281.0256
34.2825	-96.8531	281.0256
34.2833	-96.5161	225.2472
34.2881	-96.8536	286.512
34.2883	-96.8661	281.94
34.2944	-96.8694	283.1592
34.3000	-96.4806	218.2368
34.3083	-96.5819	219.456
34.3200	-96.9297	262.128
34.3206	-96.9294	258.7752
34.3208	-96.4331	236.5248
34.3256	-96.8561	306.324
34.3258	-96.8950	291.084
34.3367	-96.8611	310.896
34.3486	-96.8625	317.6016
34.3500	-96.7222	279.8064

34.3500	-96.8583	324.612
34.3506	-96.6333	268.224
34.3506	-96.6339	268.5288
34.3511	-96.6286	270.0528
34.3514	-96.8028	302.0568
34.3536	-96.8589	325.8312
34.3558	-96.7242	278.892
34.3578	-96.8625	327.0504
34.3597	-96.7500	291.084
34.3622	-96.7233	277.368
34.3647	-96.6886	282.2448
34.3675	-96.6886	281.0256
34.3675	-96.8564	311.5056
34.3739	-96.7658	306.6288
34.3744	-96.7911	332.8416
34.3767	-96.4408	193.548
34.3767	-96.7619	309.0672
34.3769	-96.6750	294.4368
34.3772	-96.8797	330.708
34.3778	-96.6564	296.2656
34.3786	-96.6292	278.5872
34.3792	-96.5750	276.4536
34.3819	-96.6006	273.4056
34.3853	-96.5994	271.272
34.3867	-96.6347	281.6352
34.3869	-96.5828	276.7584
34.3875	-96.6792	302.0568
34.3875	-96.8111	287.7312
34.3881	-96.5483	242.9256
34.3883	-96.5678	271.5768
34.3889	-96.8417	296.8752
34.3894	-96.7356	291.9984
34.3900	-96.8111	299.9232
34.3903	-96.8364	294.4368
34.3906	-96.7597	312.42
34.3908	-96.5714	276.7584
34.3936	-96.6356	286.8168
34.3956	-96.6450	284.3784
34.3997	-96.8258	305.4096
34.4000	-96.8250	310.5912
34.4008	-96.5953	273.1008
34.4031	-96.8800	316.0776
34.4036	-96.7586	313.6392
34.4039	-96.6033	276.7584
34.4039	-96.7889	316.6872
34.4039	-96.8800	315.7728
34.4042	-96.5333	219.7608
34.4042	-96.7975	313.944
34.4042	-96.8008	303.5808
34.4042	-96.8222	309.9816
34.4047	-96.6250	279.5016
34.4047	-96.8006	301.4472
34.4047	-96.8014	302.6664
34.4075	-96.6175	279.8064
34.4078	-96.5653	236.22
34.4094	-96.6367	286.8168
34.4089	-96.7756	313.3344

34.4094	-96.5756	256.6416
34.4119	-96.6825	299.3136
34.4125	-96.6675	287.7312
34.4125	-96.7553	307.5432
34.4125	-96.8250	309.372
34.4128	-96.7633	311.5056
34.4050	-96.7264	311.8104
34.4133	-96.7372	312.42
34.4139	-96.6353	289.2552
34.4150	-96.7397	307.2384
34.4150	-96.7633	309.0672
34.4156	-96.8553	318.2112
34.4189	-96.5639	268.8336
34.4194	-96.6097	283.7688
34.4203	-96.8547	327.9648
34.4211	-96.7381	303.8856
34.4214	-96.6175	295.9608
34.4217	-96.5853	277.0632
34.4228	-96.6006	279.8064
34.4242	-96.6758	262.7376
34.4244	-96.8261	316.992
34.4261	-96.6906	290.4744
34.4264	-96.6033	287.1216
34.4264	-96.8028	316.6872
34.4281	-96.7464	305.7144
34.4292	-96.6103	297.7896
34.4292	-96.7814	310.896
34.4297	-96.6333	304.8
34.4300	-96.6481	299.6184
34.4306	-96.5575	242.9256
34.4306	-96.5825	295.656
34.4314	-96.8083	314.5536
34.4317	-96.6197	288.3408
34.4333	-96.5550	242.316
34.4333	-96.5872	299.9232
34.4333	-96.7500	300.228
34.4333	-96.8083	302.9712
34.4342	-96.7094	322.4784
34.4344	-96.7094	311.8104
34.4342	-96.8375	330.0984
34.4356	-96.6144	283.464
34.4361	-96.6150	287.4264
34.4367	-96.8117	311.8104
34.4369	-96.7900	313.944
34.4381	-96.6047	274.32
34.4383	-96.6864	301.4472
34.4400	-96.7625	316.0776
34.4403	-96.6339	297.7896
34.4408	-96.6119	292.3032
34.4425	-96.8289	318.2112
34.4400	-96.5925	293.5224
34.4444	-96.6019	288.3408
34.4472	-96.5306	254.508
34.4478	-96.5686	263.3472
34.4483	-96.7611	319.7352
34.4486	-96.6028	291.9984
34.4486	-96.8736	319.7352

34.4489	-96.5328	274.9296
34.4492	-96.6075	279.8064
34.4506	-96.5792	299.3136
34.4506	-96.5922	298.704
34.4508	-96.6131	290.7792
34.4519	-96.5592	258.7752
34.4519	-96.5964	308.4576
34.4550	-96.6372	297.18
34.4550	-96.7158	314.2488
34.4550	-96.7953	321.8688
34.4558	-96.6186	292.9128
34.4561	-96.5486	263.652
34.4586	-96.7047	310.2864
34.4592	-96.7442	322.7832
34.4600	-96.5983	308.7624
34.4606	-96.5769	295.0464
34.4594	-96.8183	338.328
34.4619	-96.5547	262.128
34.4625	-96.6036	301.4472
34.4625	-96.8450	338.328
34.4625	-96.8542	331.9272
34.4625	-96.8750	327.3552
34.4631	-96.6228	296.5704
34.4633	-96.5464	288.036
34.4633	-96.7167	309.6768
34.4636	-96.7736	328.8792
34.4639	-96.7958	331.9272
34.4661	-96.6131	305.1048
34.4661	-96.8736	331.0128
34.4664	-96.8719	334.9752
34.4675	-96.6269	304.1904
34.4694	-96.8369	350.2152
34.4697	-96.7819	335.8896
34.4700	-96.5867	284.3784
34.4703	-96.6389	312.7248
34.4714	-96.5978	315.468
34.4714	-96.7739	324.0024
34.4722	-96.8428	353.2632
34.4733	-96.6150	299.0088
34.4750	-96.5842	310.2864
34.4750	-96.6458	312.1152
34.4750	-96.8131	334.3656
34.4764	-96.8367	331.0128
34.4792	-96.8469	342.2904
34.4769	-96.6186	298.3992
34.4769	-96.8700	329.184
34.4778	-96.7400	329.184
34.4781	-96.7103	317.2968
34.4786	-96.8478	341.9856
34.4836	-96.8028	306.324
34.4797	-96.6269	309.372
34.4833	-96.5847	317.9064
34.4853	-96.5539	284.3784
34.4853	-96.6022	306.9336
34.4853	-96.6125	310.2864
34.4856	-96.8042	329.4888
34.4881	-96.6592	315.1632

34.4881	-96.8286	337.4136
34.4883	-96.6269	306.9336
34.4894	-96.5486	301.1424
34.4911	-96.7375	317.2968
34.4917	-96.7822	339.852
34.4917	-96.8450	323.088
34.4922	-96.5936	335.28
34.4936	-96.7050	313.944
34.4950	-96.6489	309.6768
34.4964	-96.7547	320.3448
34.4972	-96.7625	360.8832
34.5003	-96.8436	352.3488
34.5006	-96.6850	313.3344
34.5022	-96.8647	327.66
34.5028	-96.8708	359.664
34.5050	-96.6172	318.2112
34.5050	-96.6172	319.1256
34.5050	-96.8472	337.4136
34.5019	-96.8125	328.2696
34.4917	-96.6264	304.8
34.4481	-96.6397	306.6288
34.4853	-96.6028	317.6016
34.3344	-96.9542	299.3136
34.3397	-96.9444	282.2448
34.3397	-96.9450	276.4536
34.3464	-96.9517	299.6184
34.3481	-96.9394	268.5288
34.3503	-96.8881	313.0296
34.3525	-96.9678	310.5912
34.3603	-96.9575	280.416
34.3603	-96.9689	304.8
34.3608	-96.9425	268.5288
34.3656	-96.9675	306.9336
34.3658	-96.9275	277.9776
34.3672	-96.8986	316.3824
34.3714	-96.9294	277.0632
34.3750	-96.9389	281.0256
34.3761	-96.9614	295.9608
34.3764	-97.0306	222.8088
34.3781	-96.9214	291.3888
34.3786	-97.2086	331.6224
34.3800	-97.0878	335.8896
34.3814	-97.1744	355.092
34.3833	-96.9000	321.8688
34.3836	-97.1967	330.0984
34.3839	-96.8894	316.992
34.3839	-97.1344	323.088
34.3872	-96.9300	294.132
34.3872	-97.0903	322.7832
34.3881	-96.9600	286.512
34.3908	-96.9497	281.0256
34.3911	-96.9483	272.796
34.3911	-97.2047	374.904
34.3922	-96.9011	334.6704
34.3769	-96.9481	279.8064
34.3931	-97.1853	380.6952
34.3939	-97.1181	327.3552

34.4022	-96.9514	290.4744
34.3944	-96.9672	284.0736
34.3972	-96.9422	290.4744
34.3978	-97.1478	341.0712
34.3978	-97.1703	348.6912
34.3978	-97.2067	359.664
34.3981	-96.9911	327.0504
34.3986	-96.9483	279.5016
34.3986	-96.9506	288.6456
34.4000	-97.1342	324.612
34.4008	-96.9594	283.464
34.4008	-96.9658	282.8544
34.4008	-96.9831	312.42
34.4017	-96.9506	287.4264
34.3967	-96.9583	281.6352
34.4022	-96.9675	286.2072
34.4036	-96.9106	315.7728
34.4036	-97.3369	352.3488
34.4039	-97.0514	234.0864
34.4044	-96.9508	296.5704
34.4047	-96.9342	303.276
34.4047	-96.9897	290.4744
34.4058	-96.9786	299.3136
34.4061	-97.0386	240.1824
34.4081	-97.1367	328.2696
34.4089	-97.1978	345.948
34.4161	-97.2072	370.332
34.4164	-96.9500	289.8648
34.4197	-97.1958	382.2192
34.4203	-97.2547	391.668
34.4217	-97.2706	400.812
34.4236	-97.2000	358.7496
34.4236	-97.2311	391.668
34.4244	-97.1358	332.8416
34.4244	-97.2636	399.5928
34.4258	-96.8867	329.7936
34.4294	-96.9508	290.4744
34.4300	-96.9775	270.6624
34.4314	-96.8983	346.5576
34.4328	-97.2686	413.6136
34.4331	-96.9792	281.6352
34.4339	-97.2475	404.4696
34.4339	-96.9578	288.036
34.4353	-97.2547	352.044
34.4361	-97.2256	391.668
34.4367	-97.1964	365.76
34.4467	-96.9308	320.6496
34.4483	-96.9350	316.0776
34.4483	-96.9453	313.6392
34.4494	-96.9500	320.04
34.4333	-96.9511	292.9128
34.4503	-97.2050	361.188
34.4575	-96.9342	313.944
34.4578	-96.8811	326.4408
34.4586	-96.9417	309.9816
34.4594	-96.9803	306.6288
34.4611	-96.9894	287.1216

34.4619	-96.9889	290.1696
34.4619	-96.9864	304.8
34.4644	-96.9172	289.56
34.4658	-96.9850	320.04
34.4644	-96.9161	326.7456
34.4664	-96.9161	322.7832
34.4675	-96.8817	325.8312
34.4694	-96.8958	330.0984
34.4714	-96.9164	331.3176
34.4717	-96.8831	331.9272
34.4717	-97.0533	293.5224
34.4717	-97.0578	299.9232
34.4742	-96.9547	331.3176
34.4744	-97.0242	300.5328
34.4753	-96.8958	337.7184
34.4753	-96.9553	353.2632
34.4756	-96.8975	339.5472
34.4753	-96.9553	351.7392
34.4692	-96.8953	332.232
34.4764	-96.8994	337.7184
34.4764	-96.9153	335.28
34.4767	-96.9306	349.6056
34.4767	-96.9339	331.3176
34.4767	-96.9411	356.3112
34.4769	-96.9258	357.5304
34.4769	-96.9361	336.804
34.4772	-96.9514	350.2152
34.4778	-96.8992	339.852
34.4781	-96.8911	329.184
34.4783	-96.9167	353.568
34.4783	-96.9494	340.4616
34.4794	-96.9511	346.2528
34.4800	-96.8972	340.7664
34.4806	-97.0550	298.0944
34.4828	-97.0544	299.3136
34.4836	-96.8914	336.4992
34.4836	-96.9169	328.5744
34.4842	-96.9014	332.8416
34.4844	-96.8967	336.804
34.4844	-96.8975	332.5368
34.4847	-96.8911	341.0712
34.4847	-96.8986	342.2904
34.4856	-97.3136	329.184
34.4864	-96.8989	342.2904
34.4867	-97.3283	321.564
34.4878	-96.8883	345.948
34.4892	-97.1869	291.084
34.4897	-96.9667	309.6768
34.4911	-96.9122	342.5952
34.4914	-96.9661	307.2384
34.4919	-96.9222	351.7392
34.4925	-96.8989	348.3864
34.4942	-96.9625	326.136
34.4964	-96.9625	319.1256
34.4967	-97.0553	284.6832
34.4975	-97.0558	283.7688
34.4978	-96.9161	350.52

34.4983	-96.9297	331.9272
34.4978	-96.9819	284.988
34.4997	-96.9797	289.56
34.5089	-96.9811	289.56
34.4997	-96.9689	280.416
34.5050	-96.9369	339.5472
34.5056	-96.9731	288.036
34.5056	-96.9858	288.036
34.5053	-96.9419	338.328
34.5061	-96.9492	320.9544
34.5067	-96.8903	337.4136
34.5058	-96.9814	298.704
34.5069	-96.9839	289.56
34.4978	-96.9819	289.56
34.5078	-96.9806	298.704
34.4978	-96.9819	295.656
34.5081	-96.9506	310.896
34.5081	-96.9508	310.896
34.5081	-96.9514	313.944
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34.5083	-96.9519	316.992
34.5083	-96.9678	307.848
34.5053	-96.9644	295.656
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34.5069	-96.9703	303.276
34.5108	-96.9878	291.9984
34.5086	-96.9525	319.1256
34.5086	-96.9531	329.184
34.5089	-96.9500	310.896
34.5108	-96.9878	301.752
34.5083	-96.9675	307.848
34.5100	-96.9081	342.9
34.5069	-96.9681	303.276
34.5108	-96.9878	303.276
34.5103	-96.9244	349.9104
34.5106	-96.9461	327.9648
34.5069	-96.9681	307.848
34.5111	-96.9350	338.6328
34.5111	-96.9889	286.512
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34.5119	-96.9636	316.992
34.5119	-96.9658	307.848
34.5119	-96.9658	309.372
34.5108	-96.9283	335.5848
34.5128	-97.0111	303.276
34.5131	-97.0017	176.784
34.5133	-96.9153	334.3656
34.5136	-96.9528	335.28
34.5125	-96.9725	300.228
34.5139	-96.9389	333.4512
34.5142	-96.9081	336.804
34.5147	-97.1158	249.936
34.5156	-96.8294	341.376
34.5156	-96.9150	336.1944
34.5069	-96.8603	336.804
34.5167	-96.8394	337.4136

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34.5172	-96.8622	346.8624
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34.5183	-96.8953	341.0712
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34.5186	-97.0539	301.1424
34.5189	-96.9150	336.804
34.5192	-97.0364	299.0088
34.5194	-96.8733	333.1464
34.5197	-96.9106	342.9
34.5197	-97.1069	249.3264
34.5161	-96.9639	295.656
34.5208	-96.9653	295.656
34.5208	-96.9681	295.656
34.5208	-97.0431	296.5704
34.5211	-97.0200	294.7416
34.5225	-96.9158	325.2216
34.5231	-97.0886	255.4224
34.5228	-96.9669	294.132
34.5211	-96.9681	294.132
34.5242	-96.8358	340.4616
34.5256	-96.8844	339.2424
34.5272	-96.8439	365.76
34.5264	-96.9692	291.084
34.5281	-96.9192	325.2216
34.5281	-97.0028	309.372
34.5283	-96.9678	296.8752
34.5286	-96.9681	301.752
34.5300	-97.0822	260.604
34.5317	-97.0811	256.9464
34.5322	-97.0794	262.128
34.5328	-96.9086	327.9648
34.5336	-96.8828	352.9584
34.5336	-96.9111	347.472
34.5400	-97.0711	264.5664
34.5344	-96.8383	339.2424
34.5344	-96.8992	352.3488
34.5347	-96.9056	356.9208
34.5350	-96.9933	317.9064
34.5350	-97.0225	284.0736
34.5350	-97.0303	299.0088
34.5361	-96.9658	335.28
34.5356	-96.8281	345.3384
34.5347	-96.8894	338.328
34.5378	-96.8800	337.7184
34.5372	-96.8719	350.2152
34.5361	-96.9725	298.704
34.5378	-96.8625	333.1464
34.5381	-96.9078	353.8728
34.5397	-96.9322	333.4512
34.4528	-96.9914	264.5664
34.5497	-96.8711	364.236
34.5500	-97.0278	292.9128
34.5522	-96.8606	368.5032

34.5533	-97.0806	271.272
34.5536	-96.8439	380.0856
34.5567	-96.8592	366.9792
34.5572	-96.8522	351.4344
34.5572	-96.8567	362.712
34.5572	-96.8567	344.7288
34.5572	-96.8631	365.1504
34.5575	-96.8450	371.5512
34.5594	-96.9664	320.6496
34.5597	-96.9628	312.7248
34.5603	-96.8744	353.2632
34.5625	-96.8628	348.996
34.5631	-97.0033	312.42
34.5633	-97.1592	245.364
34.5639	-96.8214	335.28
34.5642	-96.8753	352.3488
34.5642	-96.9406	323.088
34.5644	-96.8628	339.5472
34.5644	-96.8631	343.8144
34.5644	-96.9358	322.4784
34.5644	-96.9406	322.4784
34.5647	-96.8611	341.0712
34.5656	-96.9378	321.564
34.5658	-96.9394	326.4408
34.5661	-96.8281	342.9
34.5661	-96.8719	371.856
34.5661	-96.8783	366.9792
34.5664	-97.0550	296.5704
34.5683	-96.9375	320.9544
34.5686	-96.8456	377.952
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34.5686	-96.9675	330.4032
34.5689	-96.9675	332.232
34.5689	-97.0325	320.04
34.5689	-97.0325	320.04
34.5692	-96.8469	381
34.5694	-96.9389	316.992
34.5703	-96.8994	357.5304
34.5708	-96.8611	347.472
34.5717	-96.8478	345.948
34.5717	-96.8631	363.6264
34.5731	-96.8742	373.38
34.5736	-96.9678	334.0608
34.5750	-96.9497	327.66
34.5769	-96.8611	348.996
34.5772	-96.9656	361.188
34.5778	-96.8528	359.664
34.5778	-97.0650	301.752
34.5783	-97.0650	307.2384
34.5783	-97.0764	273.4056
34.5786	-97.0372	320.04
34.5786	-97.0450	316.6872
34.5789	-96.8283	379.476
34.5789	-96.8608	339.5472
34.5789	-97.0550	316.6872
34.5792	-96.8542	384.048
34.5806	-96.8458	350.8248

34.5814	-96.8803	377.3424
34.5814	-96.8800	373.38
34.5833	-97.0139	302.9712
34.5861	-96.8719	370.332
34.5889	-96.8489	385.572
34.5922	-96.8908	349.9104
34.5925	-96.8906	362.712
34.5931	-96.8453	340.7664
34.5939	-96.9381	317.2968
34.6053	-96.9789	353.568
34.6056	-96.9792	347.1672
34.6161	-97.0558	291.9984
34.6208	-97.0208	330.0984
34.6217	-96.9417	366.9792
34.6228	-96.9456	347.7768
34.6233	-97.1233	262.4328
34.6353	-96.9597	342.9
34.6361	-96.9667	343.2048
34.5225	-96.6333	318.2112
34.6600	-96.8236	366.3696
34.5086	-96.6789	315.468
34.5100	-96.8217	344.424
34.5106	-96.6333	313.944
34.5117	-96.7033	325.2216
34.5131	-96.6567	313.944
34.5136	-96.7517	331.0128
34.5144	-96.6858	315.1632
34.5147	-96.6131	338.0232
34.5181	-96.6014	311.8104
34.5186	-96.7417	336.4992
34.5200	-96.6317	319.1256
34.5203	-96.6617	321.2592
34.5292	-96.7461	322.4784
34.5222	-96.6472	315.7728
34.5222	-96.7639	340.4616
34.5222	-96.7667	327.3552
34.5222	-96.7661	331.6224
34.5244	-96.6072	327.3552
34.5250	-96.7000	316.3824
34.5253	-96.6347	316.992
34.5292	-96.7794	315.1632
34.5269	-96.6997	318.2112
34.5269	-96.8217	290.1696
34.5319	-96.6944	315.7728
34.5339	-96.6039	344.424
34.5386	-96.7408	327.3552
34.5392	-96.6386	327.66
34.5394	-96.8047	338.6328
34.5403	-96.6306	314.2488
34.5403	-96.6778	325.5264
34.5406	-96.6094	324.612
34.5417	-96.7208	328.5744
34.5417	-96.7575	324.0024
34.5422	-96.7722	330.708
34.5431	-96.6583	316.6872
34.5439	-96.6775	315.7728
34.5444	-96.5531	240.792

34.5439	-96.6225	326.4408
34.5464	-96.6339	323.088
34.5483	-96.7283	324.9168
34.5497	-96.7247	334.6704
34.5514	-96.7986	331.9272
34.5519	-96.5631	263.0424
34.5547	-96.7750	337.4136
34.5553	-96.6872	321.564
34.5564	-96.7561	330.0984
34.5569	-96.6889	321.2592
34.5581	-96.7706	361.188
34.5583	-96.7875	355.092
34.5586	-96.6822	322.4784
34.5589	-96.8633	357.5304
34.5606	-96.5508	314.5536
34.5611	-96.7653	340.7664
34.5656	-96.5453	242.6208
34.5647	-96.7739	347.1672
34.5625	-96.7208	322.4784
34.5633	-96.7172	316.992
34.5633	-96.7303	338.9376
34.5636	-96.6700	318.8208
34.5644	-96.7444	338.9376
34.5644	-96.7542	332.232
34.5644	-96.7594	339.852
34.5647	-96.7594	331.0128
34.5639	-96.6606	318.516
34.5667	-96.6792	314.8584
34.5672	-96.7144	320.6496
34.5672	-96.7228	332.8416
34.5700	-96.6383	291.084
34.5714	-96.6700	321.2592
34.5731	-96.7758	337.7184
34.5756	-96.7300	325.8312
34.5764	-96.6639	310.896
34.5786	-96.6761	328.5744
34.5772	-96.7014	322.7832
34.5775	-96.6617	318.8208
34.5775	-96.7108	322.7832
34.5778	-96.7542	331.3176
34.5778	-96.8044	345.6432
34.5786	-96.6692	320.3448
34.5819	-96.7722	350.52
34.5797	-96.7606	330.4032
34.5922	-96.6764	325.8312
34.5067	-96.7936	342.5952
34.5819	-96.6786	314.8584
34.5789	-96.6881	320.9544
34.5825	-96.6792	320.04
34.5833	-96.6792	308.7624
34.5819	-96.6878	327.0504
34.5847	-96.6861	322.7832
34.5878	-96.7367	340.1568
34.5897	-96.6869	316.3824
34.5914	-96.6964	327.66
34.5903	-96.7028	323.6976
34.5158	-96.7792	336.1944

34.5903	-96.8167	337.4136
34.5906	-96.6617	314.2488
34.5908	-96.7222	336.4992
34.5878	-96.6853	318.8208
34.5944	-96.7194	332.5368
34.5936	-96.7250	331.0128
34.5917	-96.7625	331.3176
34.5917	-96.7833	332.232
34.5917	-96.8208	338.328
34.5928	-96.7603	344.1192
34.5928	-96.7833	329.184
34.5928	-96.8194	346.8624
34.5931	-96.7056	328.5744
34.5931	-96.8139	329.184
34.5933	-96.7392	340.4616
34.5936	-96.7139	333.756
34.5936	-96.7258	356.616
34.5944	-96.6861	347.472
34.5939	-96.7036	324.9168
34.5950	-96.6911	342.2904
34.6000	-96.6608	298.704
34.5969	-96.7383	340.4616
34.6008	-96.7389	339.2424
34.5986	-96.7514	334.9752
34.5986	-96.8125	338.9376
34.5992	-96.7222	337.4136
34.6003	-96.7011	324.3072
34.6000	-96.6583	298.704
34.6017	-96.7231	335.8896
34.6039	-96.7228	341.376
34.6019	-96.7403	333.1464
34.5269	-96.7842	334.9752
34.5286	-96.8103	330.0984
34.6033	-96.8417	360.8832
34.6042	-96.7361	344.424
34.6042	-96.8569	359.664
34.6056	-96.7250	329.184
34.6064	-96.7050	337.4136
34.6078	-96.7392	342.2904
34.6075	-96.8453	357.8352
34.6081	-96.7444	339.2424
34.6097	-96.8431	379.7808
34.6097	-96.7639	333.1464
34.6142	-96.7317	338.9376
34.6111	-96.7403	337.4136
34.6133	-96.7736	350.2152
34.5369	-96.7853	344.424
34.6125	-96.7375	330.0984
34.6125	-96.8625	382.8288
34.6186	-96.8103	335.8896
34.6186	-96.8106	342.2904
34.6203	-96.7417	343.5096
34.6206	-96.7194	349.9104
34.6208	-96.7069	345.0336
34.6208	-96.7583	332.232
34.6208	-96.7742	338.9376
34.6211	-96.7556	346.5576

34.6217	-96.7994	332.8416
34.6222	-96.7250	348.996
34.6222	-96.8500	350.8248
34.6228	-96.7244	332.8416
34.6228	-96.7450	344.7288
34.6231	-96.7806	346.2528
34.6231	-96.7806	356.616
34.6231	-96.8153	334.6704
34.6231	-96.8731	332.8416
34.6236	-96.8144	345.6432
34.6250	-96.7825	334.9752
34.6253	-96.7828	334.9752
34.6261	-96.7406	349.9104
34.6269	-96.7756	350.52
34.6272	-96.8008	368.808
34.6275	-96.7844	335.28
34.6275	-96.7958	340.4616
34.6278	-96.7389	338.9376
34.6278	-96.7583	336.4992
34.6281	-96.8269	366.9792
34.6289	-96.8461	333.756
34.6292	-96.8306	348.996
34.6300	-96.8206	357.8352
34.6314	-96.8222	358.14
34.6324	-96.6123	237.744
34.6307	-96.6131	235.6104
34.6325	-96.7717	334.9752
34.6328	-96.7183	346.2528
34.6350	-96.7397	361.4928
34.6361	-96.7572	357.2256
34.6375	-96.6389	259.08
34.6375	-96.8319	350.52
34.6375	-96.8347	347.472
34.6381	-96.9108	348.3864
34.6431	-96.7953	347.7768
34.6433	-96.7958	335.5848
34.6439	-96.7839	356.9208
34.6486	-96.7958	350.52
34.6500	-96.6833	292.9128
34.6508	-96.7422	364.236
34.6508	-96.7794	372.1608
34.6522	-96.7583	365.1504
34.6583	-96.6500	284.988
34.6625	-96.7750	316.992
34.6656	-96.7778	323.3928
34.6625	-96.7778	316.992
34.6639	-96.7625	389.5344
34.6650	-96.7775	297.7896
34.6650	-96.7867	365.1504
34.6656	-96.7883	340.4616
34.6661	-96.7411	373.6848
34.6672	-96.7753	382.524
34.6675	-96.7597	344.424
34.6792	-96.8958	323.088
34.6792	-96.8972	341.376
34.6825	-96.8017	358.7496
34.6833	-96.7292	311.8104

34.6844	-96.7747	391.668
34.6950	-96.7136	265.176
34.6958	-96.7250	310.896
34.7131	-96.8647	229.5144
34.7278	-96.7094	286.2072
34.7789	-96.4640	227.3808
34.7914	-96.4549	230.4288
34.6800	-96.8867	335.28

Appendix B: Location of pumping wells and pumping rate

X-coord.	Y-coord.	Pumping yield (m^3/day)
34.3217	-96.9979	1907.5
34.3217	-96.9958	1635
34.5107	-96.9422	817.5
34.5125	-96.9160	4360
34.5107	-96.9160	3270
34.5197	-96.9160	3270
34.4602	-96.6281	817.5
34.3894	-96.7967	1090
34.3457	-96.6178	817.5
34.3457	-96.6178	1635
34.4474	-96.8732	1090
34.3457	-96.6178	1635
34.3403	-96.6178	545
34.3421	-96.6194	545
34.3394	-96.6101	626.75
34.4057	-96.8208	735.75
34.6322	-96.7738	4905
34.5647	-96.6621	2725
34.6541	-96.8152	1090
34.6012	-96.7408	545
34.6066	-96.7473	3270
34.6195	-96.8105	1504.2
34.6138	-96.7039	817.5
34.5038	-96.6304	545
34.4602	-96.6282	817.5
34.4983	-96.6547	817.5
34.4765	-96.6437	632.2

Appendix C: Fractures Data (After Barathel, 1985)

Table I: Fracture Measurements of the Pontotoc Group*

STATION	ORIENTATION	DIP (degrees)	FRACTURE WIDTH (inches)	DISTANCE BETWEEN STATIONS (feet)	TOTAL DISTANCE (feet)
		TRAVERSE DIRECTION IS N5E			
1	N70W	UNK	+1.0-2.0	0.	0.
2	N75W	"	"	2.0	2.0
3	N75W	"	"	2.0	4.0
4	S87W	"	"	1.5	5.5
5	N72W	"	"	1.5	7.0
6	N60W	"	"	.5	7.5
7	N60W	"	"	2.0	9.5
8	W	"	"	3.0	12.5
9	N88W	"	"	1.5	14.0
10	N64W	"	2.0	3.0	17.0
11	N75W	"	.5-1.5	6.0	23.0
12	N65W	"	+1.0-2.0	8.0	31.0
13	N50W	"	"	36.0	67.0
14	N75W	"	"	12.0	79.0
15	N80W	"	"	4.0	83.0
16	S89W	"	"	26.0	109.0
17	N88W	"	"	10.0	119.0
18	N87W	"	"	6.0	125.0
19	N72W	"	"	10.0	135.0

* Location - SE¼ NE¼ NE¼ of Sec. 1, T1S, R3E

\+ Fracture is filled with soil and vegetation.

Table II: Fracture measurements of an Indurated Sandstone of Simpson Group Glass Sand Quarry*

STATION	ORIENTATION	DIP (degrees)	FRACTURE WIDTH (inches)	DISTANCE BETWEEN STATIONS (feet)	TOTAL DISTANCE (feet)
		TRAVERSE DIRECTION IS N25W			
1	S55W	UNK	.5-1.0	0.	0.
2	S70W	"	.25	3.5	3.5
3	S60W	"	.25	3.5	7.0
4	S62W	"	.125	3.5	10.5
5	S25W	"	.25	3.0	13.5
5a	S67W	"	.25	0.	13.5
6	S75W	"	.125	4.0	17.5
6a	N70W	"	.125	0.	17.5
7	S70W	"	.125	4.0	21.5
7a	N30W	"	.25	0.	21.5
8	N80W	"	.25	6.0	27.5
8a	S55W	"	.25	0.	27.5
9	N80W	"	.25	3.0	30.5
10	S45W	"	.25	2.0	32.5
11	N75W	"	.125	4.5	37.0
12	S70W	"	.125	4.0	41.0
12a	N40W	"	.125	0.	41.0
13	S50W	"	.25-.5	3.0	44.0
13a	N80W	"	.5	0.	44.0
14	S50W	"	.5	1.5	45.5
15	S35W	"	.125	6.0	51.5
15a	N82W	"	.125	0.	51.5
16	N80W	"	.125	6.0	57.5
17	S55W	"	.25-.5	1.5	59.0
18	N80W	"	.25	1.5	60.5
19	N80W	"	.75	6.0	66.5
19a	N45W	"	.75	0.	66.5
20	S35W	"	.25-.5	15.0	81.5
20a	N82W	"	.125	0.	81.5
21	S50W	"	.25-.5	3.0	84.5
21a	N30W	"	.125	0.	84.5
22	N75W	"	.125	10.0	94.5
22a	S15W	"	.0625	0.	94.5
23	N10W	"	.125	6.0	100.5
24	S40W	"	.25	3.0	103.5

* Location - SW¼ SW¼ NW¼ NE¼ of Sec. 14, T1S, R4E

Table III: Fracture Measurements of the Arbuckle Group, Mill Creek and State Highway 7*

STATION	ORIENTATION	DIP (degrees)	FRACTURE WIDTH (inches)	DISTANCE BETWEEN STATIONS (feet)	TOTAL DISTANCE (feet)
		TRAVERSE DIRECTION IS N70W			
1	S60W	near vertical	1.0	0.	0.
2	S70W	"	1.5	.5	.5
3	S70W	"	1.5	.5	1.0
4	S40W	"	.5	1.0	2.0
5	N5W	"	.5	2.0	4.0
6	N35W	"	1.5	2.0	6.0
7	S60W	"	.5	.5	6.5
8	N50W	"	.5	1.0	7.5
8a	N30W	"	.25	0.	7.5
8b	S70W	"	.25	0.	7.5
9	S5W	"	.75	0.	8.5
9a	S85W	"	.75	0.	8.5
10	S60W	"	.125	.5	9.0
10a	S10W	"	.125	0.	9.0
11	S	"	1.0	.5	9.5
11a	S80W	"	.5	0.	9.5
11b	S10W	"	.25	0.	9.5
12	S45W	"	2.0	2.0	11.5
13	S75W	"	1.0	1.0	12.5
14	N40W	"	1.0	1.0	13.5
14a	W	"	2.0	0.	13.5
15	S45W	"	1.5	.5	14.0
15a	N15W	"	2.0	0.	14.0
16	S80W	"	2.0	1.0	15.0
17	N70W	"	2.0	2.0	17.0
18	N50W	"	1.0	1.0	15.0
19	N70W	"	2.0	2.0	20.0
20	S70W	"	3.0	5.0	25.0
20a	N15W	"	1.0	0.	25.0
21	N15W	"	1.0	1.0	26.0
21a	S60W	"	1.0	0.	26.0
22	S40W	"	2.0	4.0	30.0
22a	N20W	"	2.0	0.	30.0

* Location - SE¼ NE¼ SE¼ SE¼ of Sec. 32, T1N, R4E

Table IV: Fracture Measurements of the Arbuckle Group, Intersection of State Highways 7 and 12*

STATION	ORIENTATION	DIP (degrees)	FRACTURE WIDTH (inches)	DISTANCE BETWEEN STATIONS (feet)	TOTAL DISTANCE (feet)
		TRAVERSE DIRECTION IS S30W			
1	S65W	near vertical	.125	0.	0.
2	N20W	"	.25	.1	.1
3	S65W	"	.125	.1	.2
4	S70W	"	.125	1.0	1.2
5	S75W	"	.125	.1	1.3
6	S60W	"	.25	.1	1.4
7	S65W	"	.0625	.6	2.0
8	S60W	"	.0625	.1	2.1
9	W	"	.0625	.2	2.3
10	S60W	"	.125	.1	2.4
11	S65W	"	.125	.2	2.6
12	S55W	"	.125	.2	2.8
13	S	"	.25	.5	3.3
13a	S65W	"	.125	0.	3.3
14	N25W	"	.5	.2	3.5
		TRAVERSE DIRECTION IS W			
1	N20W	near vertical	.125	0.	0.
2	N40W	"	.25	.3	.3
3	N30W	"	.25	.3	.6
4	N30W	"	.25	.6	1.2
4a	N10W	"	.5	0.	1.2
4b	S40W	"	1.0	0.	1.2

* Location - NE¼ NE¼ NW¼ NW¼ of Sec. 2, T1S, R4E

Table V: Fracture Measurements of the Arbuckle Group, Collins' Ranch*

STATION	ORIENTATION	DIP (degrees)	FRACTURE WIDTH (inches)	DISTANCE BETWEEN STATIONS (feet)	TOTAL DISTANCE (feet)
		TRAVERSE DIRECTION IS WEST			
1	S35	near vertical	.125	0.	0.
1a	N40W	"	.125	0.	0.
2	S40W	"	.25	.25	.25
2a	N	"	.125	0.	.25
3	S30W	"	.125	.25	.50
4	S20W	"	.0625	.1	.60
5	S55W	"	.125	.2	.80
6	N70W	"	.0625	.2	1.0
6a	S45W	"	.125	0.	1.0
		TRAVERSE DIRECTION IS N10W			
1	S80W	near vertical	1.5	0.	0.
1a	S55W	"	1.5	0.	0.
2	S70W	"	1.0	.8	.8
2a	S5W	"	.25	0.	.8
3	S45W	"	.25	.7	1.5

* Location - NW¼ NE¼ NE¼ of Sec. 6, T1S, R4E

VITA

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Pages in Study: 139 Candidate for Degree of Master of Science

Major Field: Environmental Engineering

Scope of Study: This research concerns the decreasing water level in Arbuckle-Simpson Aquifer and low discharge from springs in the aquifer. The purpose of the study was to predict the hydraulic head in the aquifer and impact of pumping on the Aquifer for groundwater management. Three different conceptual approaches were used to simulate the groundwater flow in the aquifer by integrating the data on GIS platform and using FEFLOW groundwater flow model.

Findings and Conclusions: Modeling approaches, equivalent continuum model, discrete fracture model, and dual fracture model simulated the hydraulic head values for pumping wells in the aquifer. The difference in hydraulic head values ranged from 2 to 20 m. The simulated results did not indicate any significant decrease in water level in the aquifer for normal pumping rates for next 30 years with current pumpage in the aquifer. However, higher pumping in the future may cause decline of water level over the entire aquifer. The rate of decrease of hydraulic head would depend upon the assumed variations in actual transmissivity and other parameters governing water level in the aquifer.

ADVISOR'S APPROVAL: Avdhesh K. Tyagi