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IN THE SUPERIOR COURT OF THE STATE OF ARIZONA
IN AND FOR THE COUNTY OF MARICOPA

IN RE THE GENERAL ADJUDICATION OF ALL RIGHTS TO USE WATER IN THE GILA RIVER SYSTEM AND SOURCE	W-1 (Salt) W-2(Verde) W-3 (Upper Gila) W-4 (San Pedro) (Consolidated) Contested Case No. W1-103 **ARIZONA DEPARTMENT OF WATER RESOURCES' INITIAL PROGRESS REPORT CONCERNING IMPLEMENTATION OF CONE OF DEPRESSION TESTS** (Assigned to the Hon. Mark H. Brain)

DESCRIPTIVE SUMMARY: This progress report describes the Arizona Department of Water Resources' initial steps for implementing cone of depression tests in the San Pedro River watershed.

NUMBER OF PAGES: Four plus attachments

DATE OF FILING: April 23, 2015.

As discussed during the status conference of November 6, 2014, the Arizona Department of Water Resources ("ADWR") is filing this report regarding initial steps taken by ADWR to implement cone of depression tests for wells located outside the subflow zone in the San Pedro River watershed. See Minute Entry dated March 4, 2015. Although cone of depression tests cannot be implemented until the delineation of the subflow zone is approved by final court order, ADWR has undertaken some preliminary work.

In a report filed on October 1, 2014, ADWR summarized prior decisions of the Arizona Supreme Court, and orders of the Trial Court and the Special Master concerning subflow issues in the San Pedro River watershed, including cone of depression tests. These decisions and orders culminated in a 2005 Order of the Trial Court, which set forth in detail requirements that ADWR must follow in its implementation of cone of depression tests. Petitions for interlocutory review of the 2005 Order were denied by the Arizona Supreme Court in May 2007.

By order dated September 28, 2005, the Trial Court approved and adopted the Special Master's recommendations concerning a report filed by ADWR on March 29, 2002 ("2002 Subflow Report"), which included certain procedures related to cone of depression tests. The Trial Court entered a ruling on the Special Master's recommendations by reference to the recommendation numbers, which are cross-referenced below. The Trial Court's ruling requires ADWR to proceed as follows:

- Use a drawdown of greater than or equal to 0.1 foot where a well's cone of depression has reached the edge of the subflow zone [Rec. 20];
- Obtain and use reliable data and information on an ongoing basis to safeguard the reliability of the cone of depression test [Rec. 21, 27];

- Do not adopt a condition that requires the water level in the well to be below the water level in the subflow zone [Rec. 22];
- Do not adopt as a condition that the hydraulic gradient be continuously inclined from the subflow zone to the well [Rec. 23];
- Use both analytical and numerical models for the cone of depression tests, implement any newer versions, and calibrate the models [Rec. 24-26];
- Do not recommend a methodology to evaluate the impact of wells perforated below an impervious formation within the subflow zone [Rec. 30];
- Analyze a well's drawdown at the subflow zone for each well [Rec. 31];
- Ascertain whether significant withdrawals of subflow occur as the result of pumping by one well or a group of wells [Rec. 32 rejected, Rec. 33 modified];
- Utilize a reasonably reliable steady state model in evaluating the effect of cones of depression [Rec. 28 rejected, Rec. 29 modified]; and
- Follow the procedures set forth in Chapter 3 of the 2002 Subflow Report to the extent consistent with the trial court's 2005 Order [Rec. 34 modified].

Solving for the steady-state depth of drawdown induced by pumping wells begins with the collection of data that can be used to establish model parameters. ADWR has reviewed various data sources for this purpose, and has assessed the extent to which they provide useful and reliable information. This assessment is presented in **Attachment 1** hereto. Also, ADWR has reviewed three groundwater models for potential use in the cone of depression analyses, and has identified major assumptions, limitations, and data requirements for each of these models. This information is presented in **Attachment 2** hereto.

DATED this 23rd day of April, 2015.

ARIZONA DEPARTMENT OF WATER RESOURCES

Janet L. Miller, Deputy Counsel
Nicole D. Klobas, Deputy Counsel

ORIGINAL of the foregoing sent by first-class mail this 23rd day of April, 2015, to:

Clerk of the Superior Court
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COPIES of the foregoing sent by first-class mail this 23rd day of April, 2015, to:

Honorable Mark H. Brain
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All parties on the court-approved mailing list for contested case no. W1-103

Attachment 1

DATA AVAILABLE FOR CONE OF DEPRESSION TESTS

In order to conduct cone of depression tests, ADWR will need to assemble accurate information describing both the pumping well and the aquifer in which it is located. The well's location and depth must be known relative to the subflow zone, aquifer boundaries, and other pumping wells. A constant pumping rate producing an equivalent volume of water as that withdrawn for supplying the water uses served by the well must also be determined in order to calculate the steady-state drawdown required by the adjudication court.

Because the cone of depression testing is being conducted assuming steady-state conditions, where aquifer discharge (the well's pumping) and recharge are in balance and the well's cone of depression is constant over time, the relevant aquifer characteristics that must be determined are hydraulic conductivity (a measure of the volume of water that can be transmitted through the aquifer materials in a unit of time), the aquifer thickness and appropriate aquifer boundary conditions. When the hydraulic conductivity is multiplied by the aquifer thickness, the resulting characteristic is called the aquifer's transmissivity. An aquifer's transmissivity can best be estimated by analyzing long-term aquifer pumping tests approaching steady-state conditions.

Aquifer transmissivity can also be estimated from driller's lithology logs[1] and from specific capacity data[2]. Specific capacity is a well's yield per unit of drawdown at a given pumping rate and is calculated by dividing the pumping rate by the drawdown at that rate.

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[1] Kisser, K.G., and Haimson, 1981. Estimates of Aquifer Characteristics Using Driller's Logs: Hydrology and Water Resources of the Southwest Arizona-Nevada Academy of Science Volume 11.

[2] Driscoll, F., 1986. Groundwater and Wells, 2nd Edition. Johnson Division.

The sections below describe the data sources that ADWR has determined would be useful for conducting cone of depression tests. These sections also describe the quality and reliability of this data.

San Pedro River Hydrographic Survey Report

ADWR is required to prepare and publish comprehensive Hydrographic Survey Reports (HSRs) for each watershed being adjudicated. HSRs involve intensive data collection and field inspection efforts by ADWR, including detailed information regarding land ownership, hydrology, and the factual basis for each Statement of Claimant (SOC) that is filed by water users in the watershed.

For each HSR, ADWR prepares a preliminary and a final draft. In February 1987, ADWR published a draft preliminary HSR for the San Pedro River Watershed. A total of 640 comments were received. ADWR incorporated information generated by these comments into a preliminary HSR that was published in August 1990. The final HSR, consisting of nine volumes, was filed with the court on November 20, 1991.

The San Pedro River watershed HSR included certain information concerning wells completed in the watershed. The extent of ADWR's investigation of wells was directly related to the location of the wells within zones described in the HSR.

Zone 1 included the alluvial aquifer immediately adjacent to the San Pedro River. It appears that the vast majority of the Zone 1 wells may fall within the proposed Subflow Zone and thus not be subject to cone of depression testing.

Zone 2 included tributary alluvial aquifers not immediately adjacent to the San Pedro River. Those wells in Zone 2 which supplied solely domestic and stockwatering uses, or irrigation of less than two acres were described in Volume 8 of the HSR. The remaining Zone 2 wells were described in Volume 7 of the HSR entitled "Zone 2 Well

Reports". Volume 7 contains Watershed File Reports (WFRs) which provide apparent annual volumes used. Some of the Zone 2 wells were also accurately mapped by ADWR investigators on the maps contained in Volume 9 of the HSR.

Zone 3 included non-tributary alluvial aquifers, crystalline and consolidated sedimentary rocks, and consolidated to semi-consolidated sedimentary rocks as mapped on Plate 1 of Volume 1A of the HSR. These wells were listed in Volume 8 of the HSR. The well locations and claimed quantities contained in Volume 8 were obtained through ADWR investigations, the SOCs, and the WELLS 55 database. The WELLS 55 and SOC databases are described below.

The WFRs and maps in the San Pedro HSR provide accurate locations for some wells and can also provide information useful for estimating steady-state pumping rates.

ADWR Well Registry Database (WELLS 55)

When the Groundwater Management Act was passed by the Arizona Legislature in 1980, it contained a provision requiring all existing wells within the state to be registered with ADWR. A process for registering all new wells was also created. Any person intending to drill a well in Arizona must first file a Notice of Intent (NOI) to Drill a Well with ADWR. Upon receipt and processing of the NOI, ADWR issues a unique eight-digit well registration number that begins with the number 55. The well registration data for those wells existing prior to the Groundwater Management Act and new wells drilled since the Act are stored in an ADWR database commonly referred to as the WELLS 55 database. Information is added to the WELLS 55 database daily.

The WELLS 55 database contains owner-provided information derived from the submitted well registrations for wells existing when the Groundwater Management Act was enacted, and from the submitted NOIs for new wells. Information supplied by the applicant on an NOI includes the following:

- Owner name and address;
- Type of well (Exempt or Non-Exempt);[3]
- Design pump capacity;
- Uses of water such as irrigation, domestic or industrial ;
- Proposed well construction design including casing depth and diameter, perforated casing zones;
- County Assessor's parcel number;
- Cadastral location of well and place of use; and
- Well location site plan or map.

When a new well is completed, the well driller is required to submit a Well Driller's Report and Well Log including "as-built" data detailing the actual construction and that information is also entered into the WELLS 55 database. The Well Driller Report and Well Log should contain the following information:

- Location of the well, including latitude and longitude;
- Construction dates;
- As-built construction data including casing depth and diameter, and perforated casing zones;
- Water level information at time of drilling;
- Geologic log describing the materials encountered during drilling; and
- Well location site plan or map.

[3] An exempt well has a maximum pump capacity of 35 gallons per minute. Most exempt wells are used for residences and are more than adequate for household use. A non-exempt well has a pump capacity exceeding 35 gallons per minute. This type of well is generally used for irrigation, municipal, or industrial purposes.

Within 30 days after a pump is installed in a well, the owner is required to file a Pump Installation Completion Report. Information from that report is incorporated into the WELLS 55 database. The Pump Installation Completion Report includes the following information:

- The static water level in the well. This is the water level in the well immediately prior to the pumping test, as measured in feet below the land surface.
- The pumping water level. This is the water level in the well immediately after the pump was operated for at least four hours, as measured in feet below the land surface.
- Drawdown. This is the difference between the static water level and the pumping water level.
- The pumping rate during the test, as measured in gallons per minute.
- The duration of the pumping test, which must be at least four hours of continuous operation.

A properly completed and reported pumping test can provide information that can be used to estimate aquifer transmissivity at the well. Unfortunately, the number of Pump Installation Completion Reports filed with ADWR is small compared to the overall number of registered wells. ADWR requests the submittal of missing Pump Installation Completion Reports when well records are reviewed in response to a complaint or compliance investigation.

The WELLS 55 database is the largest repository of well information at ADWR. There are WELLS 55 records for approximately 11,800 registered wells within the San Pedro River watershed through December 31, 2014. Below is a table that displays well counts based on the registered well type.

Well Type	# of Wells
Exempt	8,480
Non-Exempt	1,943
Environmental - Monitor/Piezometer	918
Exploration, Geotechnical, Other	475
Total	**11,816**

Approximately 1,800 of these wells are reported as "cancelled". Wells are classified as cancelled as a result of: (1) ADWR being informed that the well was not drilled; (2) ADWR being notified that the well was properly abandoned or (3) ADWR assuming that the well was not drilled because the Well Driller Report was never filed with ADWR. However, some well owners may be using a well that ADWR identifies as cancelled. In addition, there may be duplicate records that may reduce the total number of active wells within the watershed.

The WELLS 55 database contains information on every registered well in the state; however, not all wells have been registered, and the data is based on information provided by the well owner or the well driller. The well data supplied to ADWR are generally not field verified by ADWR staff, and the accuracy of the information generally is not confirmed.

Another limitation of the WELLS 55 database, is that the locations of most of the wells are described by cadastral location or legal description to the nearest 10-acre parcel of land, at best. The terms "cadastral location" or "legal description" refer to a method of locating land according to a rectangular coordinate system commonly known as the Public Lands Survey. Most of the land in Arizona has been mapped according to this system. The survey subdivided lands into townships, typically 6 miles on each side or 36 square miles in total. Each township is divided into 36 equal parts called sections or approximately one square mile or 640 acres. Each section is further subdivided into four 160-acre quarters. Each 160-acre quarter is subdivided into four 40-acre quarters, and each 40-acre quarter is subdivided into four 10-acre quarters. The 10-acre quarter represents the smallest division of land by this system and is approximately 650 feet in length on each side.

The locations of wells in the WELLS 55 database generally are based on the cadastral system. Each NOI applicant is supposed to provide the township, section, 160-acre quarter, 40-acre quarter, and 10-acre quarter for the planned well. This narrows the location of the well to within 10 acres. For mapping purposes, ADWR places the well location in the center of the 10-acre area. This often leads to more than one well having the same cadastral location. Also, in some cases, the applicant does not provide all of the 160, 40, and 10-acre quarters. In those cases, ADWR places the well location in the center of the smallest quarter provided in the NOI. Further well location limitations occur when applicants provide inaccurate cadastral locations.

The WELLS 55 database is the most comprehensive database at ADWR related to well, pump, and lithology information. This database is utilized by ADWR staff in managing Arizona's water supplies. It is also available to the general public, and information and data can be easily obtained from ADWR's website. It is anticipated that information from the WELLS 55 database will be relied upon extensively in cone of depression testing.

Ground Water Site Inventory (GWSI) Database

The Ground Water Site Inventory (GWSI) database is ADWR's main repository for reliable and accurate, state-wide groundwater and well data. The GWSI, acquired from the USGS in 1983, consists of field data collected and verified by ADWR or the United States Geologic Survey (USGS). The City of Tucson, Salt River Project, and United States Bureau of Reclamation also contribute data to the database and that data is attributed to the source. Field services staff measure water levels in wells and may collect water quality samples, measure discharge from pumping wells, and inventory wells throughout the state.

The information in GWSI is constantly updated and expanded by ongoing field investigations. ADWR conducts a state-wide water level monitoring program that annually measures water levels in approximately 1,700-1,800 “Index Wells”, which are located throughout the state. In approximately 113 of these wells, ADWR has installed automated groundwater monitoring devices that record water levels at a predefined frequency on a continuous basis. In addition, ADWR periodically conducts groundwater basin sweeps to measure water levels for a large number of accessible wells distributed within a specific basin.

The GWSI database contains well records for 2,851 wells within the San Pedro River watershed. Of this total, 87 wells are Index wells and five of those wells have automated measuring devices.

GWSI wells are assigned and identified by a unique 15- digit “Site Identification Number.” Although the Site Identification Number is derived initially from the latitude and longitude of the site, the number is a unique identifier and not a locator. Many of the GWSI wells have been linked to a specific WELLS 55 registry number. Review of the GWSI database indicates that 1,384 out of the 2,851 total GWSI wells (approximately 49%) located in the San Pedro River watershed have been linked to a specific WELLS 55 registry number.

The GWSI database includes the following:

- Site Identification Number;
- Cadastral location;
- Owner name;
- 55 registration number (if known);
- Date(s) of water level measurement(s);
- Depth to water measurement and corresponding water elevation;

- Well depth, casing diameter, and perforated interval; and
- Discharge measurements and drawdown.

Because the information in the GWSI is verified before it is entered into the data tables, GWSI contains the most accurate well data that is available. GWSI well locations are significantly more accurate than the 10-acre parcel cadastral locations contained in the Wells 55 data base. However, the GWSI database contains information on only a relatively small subset of existing wells across the state.

Arizona State Land Department Database (WELLS 35)

The first statewide registration of wells began in 1945, when all irrigation wells that pumped greater than 100 gallons per minute in Critical Groundwater Areas had to be registered with the Arizona State Land Department (ASLD). This database is referred to as the WELLS 35 database because the ASLD began attaching 35-prefix identification numbers to wells sometime during the 1970s. The ASLD well records were transferred to ADWR in 1980. Many wells with the 35 prefix were subsequently registered with ADWR and assigned a 55-prefix registration number in response to the well registration requirements of the 1980 Groundwater Management Code. As a result, there is overlap and duplication of records between the WELLS 35 and WELLS 55 databases. Well records in the WELLS 35 database are represented by a paper file and a digital record not currently available on-line. The WELLS 35 database is static so no records are added to this database.

The WELLS 35 database includes:

- Owner name;
- Cadastral location;
- Well depth, casing diameter, and perforated interval;
- Discharge measurements and drawdown; and

- Well logs.

There are WELLS 35 records for approximately 2,900 wells within the San Pedro River watershed. The WELLS 35 database includes information that is not necessarily included in the WELLS 55 database.

Statement of Claimant (SOC) Database

ADWR maintains and updates Statement of Claimant (SOC) information, including names and addresses of the parties to the adjudications, the location and nature of claims, property records and payment of filing fees. The information is maintained in a database that is updated as new SOCs are filed, and as existing SOCs are amended or assigned due to changes in property ownership or other changes. The SOC database contains information related to four types of water use. There is an SOC form for each of the following uses: (1) domestic, (2) irrigation, (3) stockpond, and (4) other uses. There are records for approximately 10,800 filed SOC claims within the San Pedro River Watershed.

Pertinent well information contained in the SOC database includes:

- Cadastral location;
- Water source;
- Claimed volume; and
- Well registration (WELLS 55) number (if provided).

The information provided on SOC forms is collected and submitted by the claimant and are generally not verified, except during HSR investigations. As such, well information is not always accurate or complete. The result is that not all of the SOC data described above is available for all claims and the accuracy of the information is generally not confirmed.

Community Water System (CWS) Database

A community water system (CWS) is one that serves at least 15 connections used by year-round residents of the area served, or that regularly serves at least 25 year-round residents. The Arizona Department of Environmental Quality determines whether a water provider is a CWS. CWSs are required by statute to submit Annual Water Use Reports by June 1. The Annual Water Use Report includes such information as water pumped or diverted, water received from other suppliers, water delivered to customers, and effluent used or received. System Water Plan Updates are due every five years after the initial System Water Plan is submitted. The System Water Plan consists of three components: Water Supply Plan, Drought Preparedness Plan, and Water Conservation Plan.

ADWR maintains a database for CWSs across the state. The CWS database contains records for 43 CWSs within the San Pedro River Watershed.

The CWS database includes the following information:

- Well registration (WELLS 55) number, and
- Annual pumping quantities by well.

Annual pumping volumes reported for CWS's provide data for calculation of steady-state well pumping rates.

Assured and Adequate Water Supply (AAWS) Database

ADWR's Assured and Adequate Water Supply Programs (AAWS) were created to address the problem of limited groundwater supplies in Arizona. ADWR maintains an AAWS database of previously issued determinations of Assured and Adequate Water Supply.

The AAWS database contains 256 determinations within the San Pedro River Watershed. The majority of determinations, 230 in total, are Water Adequacy Reports. In addition, there are 19 Analysis of Adequate Water Supply, five Designation of Adequate Water Supply or Modification, and two PADs in the database.

Well data in the AAWS database includes the following:

- Well locations and information derived from the WELLS 55 database with a link to GWSI where available, and
- Annual pumping quantities by well derived from the CWS database.

One of the requirements of the Adequate Water Supply Program is a demonstration of physical availability of the proposed water supply. Physical availability of the water supply is typically demonstrated through a hydrologic study. There are approximately 30 hydrologic studies on file at ADWR for developments or water providers within the San Pedro River Watershed.

One important component of hydrologic studies related to cone of depression testing is aquifer characterization. AAWS applicants must present a complete aquifer characterization that includes using existing data if sufficient, or collecting additional data, if necessary. Pertinent aquifer characterization data in hydrologic studies generally includes:

- Description of well(s) to be used in serving lots including current or estimated pumping capacity of each well;
- Data collected during aquifer testing, if testing is deemed necessary;
- Aquifer parameters including hydraulic conductivity, transmissivity, specific yield, storage coefficient and other data and how these parameters were determined; and
- Depth to groundwater impact analysis of the proposed project using analytical or numeric models.

Availability of Hydrogeologic Data and Reports

As noted above, the modeling of the steady-state drawdown caused by a well's pumping requires, among other data, information concerning aquifer boundary conditions and transmissivity. In areas where numerical models exist, transmissivity and boundary conditions should be reviewed for appropriateness. In areas where no models exist, data will need to be compiled from sources such as those described above. Table 1 lists selected hydrologic and modeling reports for the San Pedro Watershed that may be useful in providing the hydrogeologic information necessary to conduct cone of depression tests.

Table 1 Selected Hydrologic and Groundwater Modeling Reports for the San Pedro River Watershed

Upper San Pedro Basin		Lower San Pedro Basin		San Pedro Watershed						Title	Author	Date	Reported Range of Transmissivity (T) or Hydraulic Conductivity (K) or Specific Capacity (SC)
Sierra Vista	Allen Flat	Mammoth	Camp Grant Wash	Mexico	Sierra Vista	Benson	Redington	Winkelman	Aravaipa				
X					x					USGS - Water Resources of Fort Huachucha Military Reservation, southeastern Arizona. USGS WSP - 1819-D	Brown, S.G., and others	1966	Valley-fill T= 20,000 ft^3/d/ft to 31,000 ft^3/d/ft (aquifer test results as reported in Roeske and Werrell)
X					X	X				USGS - Maps Showing Groundwater Conditions in the Upper San Pedro Basin Area, Pima, Santa Cruz, and Cochise Counties, Arizona - 1978. USGS OFR 80-1192	Konieczki, A.D.	1980	
X					X					USGS - Hydrologic Analysis of the Upper San Pedro Basin from the Mexico - US International Boundary to Fairbank, Arizona. USGS OFR 82-752.	Freethey, G.W.	1982	<2,000 Ft^2/D to >8,000 FT^2/D
X					x					USGS - Hydrogeologic Investigations of the Sierra Vista Subwatershed of the Upper San Pedro Basin Cochise County, Southeast Arizona. USGS WRI 99-4197	Pool, D.R., and Coes, A.L.	1999	
X				X	X					USGS - Ground-Water flow Model of the Sierra Vista Subwatershed and Sonoran Portions of the Upper San Pedro Basin, Southeastern Arizona, US, and Northern Sonora, Mexico. USGS SIR 2006 - 5228	Pool, D.R., and Dickinson, J.E.	2007	Sedimentary rocks = 0.3 to 0.0001 m/d Basin-fill Undifferentiated Sand & Gravel = 10 to 0.0003 m/d Undifferentiated Silt & Clay = 1.25 to 0.0013 m/d Stream Alluvium Undifferentiated = 12.5 to 2.5 m/d
X				X	X					USGS - Simulated Effects of Ground-water Withdrawals and Artificial Recharge on Discharge to Streams, Springs, and Riparian Vegetation in the Sierra Vista Subwatershed of the Upper San Pedro basin, Southeastern Arizona. USGS SIR 2008-5207	Leake, S.A., Pool, D.R., Leenhouts, J.M.	2008	
X		X			X	X	X	X		USGS - Predevelopment Hydrologic Conditions in the Alluvial Basins of Arizona and Adjacent Parts of California and New Mexico. USGS HA - 664	Freethey, G.W., and Anderson, T.W.	1986	USP - Upper aquifer =0.1 to 18.3 FT/D, Ave= 4.1 Ft/D: Lower Aquifer= 9 to 2,307 FT^2/D, Ave=684 Ft^2/D Benson - Upper aquifer = 2 to 45 FT/D, Ave= 17.1 FT/D: Lower Aquifer = 11 to 4,445 FT^2/D, Ave = 832 FT^2/D LSP= Upper aquifer = 16 to 32 Ft/D, Ave=31.6 FT/D: Lower Aquifer = 67 to 5,346 FT^2/D Ave.=947 FT^2/D
X	X	X	X		X	X	X	X	X	USGS - Simulation of Groundwater Flow in Alluvial Basins in South-Central Arizona and Parts of Adjacent States. USGS PP 1406-D	Anderson, T.W., and Freethey, G.W.	1995	
X	X	X				X	X			USGS - Hydrogeologic Framework of the Middle San Pedro Watershed, Southeastern Arizona USGS 2010-5126	Dickinson, J.E., and others	2010	T range = 24 to 1,600 m^2/d aquifer tests SC range = 25 to 840 m^3/d/m
		X	X				X	X		USGS - Maps Showing Ground-water Conditions in the Lower San Pedro Basin Area, Pinal, Cochise, Pima, and Graham Counties, Arizona -1979. USGS OFR 80-964	Jones, S.C.	1980	

Table 1 continued Selected Hydrologic and Groundwater Modeling Reports for the San Pedro River Watershed

Upper San Pedro Basin		Lower San Pedro Basin		San Pedro Watershed						Title	Author	Date	Reported Range of Transmissivity (T) or Hydraulic Conductivity (K) or Specific Capacity (SC)
Sierra Vista	Allen Flat	Mammoth	Camp Grant Wash	Mexico	Sierra Vista	Benson	Redington	Winkelman	Aravaipa				
X	X	X	X		X	X	X	X	X	ADWR - Preliminary Hydrographic Survey Report for the San Pedro Watershed Volume 1		1990	See Table E-1 for Specific Values T Values in Various Parts of Model Area
X	X				X	X				ADWR - Water Resources of the Upper San Pedro Basin	Putman, F., Mitchell, K., and Bushner, G.	1988	4,000 - 8,000 ft^2/d
X	X				X	X				ADWR - Maps Showing Groundwater conditions in the Upper San Pedro Basin, Cochise, Graham, and Santa Cruz Counties -- 1990 ADWR HMS 31	Barnes, R.L.	1997	
X					X					ADWR - A Groundwater Flow Model of the Upper San Pedro Basin, Southeastern Arizona Modeling Report #10	Correll et al	1996	20 - 14,000 ft^2/d
X	X				X	X				ADWR - Maps Showing Groundwater conditions in the Upper San Pedro Basin, Cochise, Graham, and Santa Cruz Counties -- Dec. 2001-Jan. 2002 ADWR HMS 34	Barnes, R.L., and Putman, F.	2002	
									X	ADWR - Maps Showing Groundwater Conditions in Aravaipa Canyon Basin, Pinal and Graham Counties, Arizona, 1996 ADWR HMS 36	Holmes, M.A.	2003	
X	X	X	X		X	X	X	X		Arizona Water Commission - Hydrologic Conditions in the San Pedro River Valley Arizona, 1971 AWC Bulletin 4	Roske, R.H., Werrell, W.L.	1973	USP Basin Average Flood Plain Alluvium = 40 gpm/ft Average Valley-fill deposits = 13 gpm/ft LSP Basin Average Flood Plain Alluvium = 100 gpm/ft Average Valley-Fill Deposits = 16 gpm/ft
X					X					UofA - Modeling of Groundwater Flow and Surface Water/Groundwater Interactions in the San Pedro River Basin - Part I - Cananea, Mexico to Fairbank, Arizona: Tucson: UofA Dept. of Hydrology and Water Resources, HWR No. 92-010	Vionnet, L.B. and Maddock, T.	1992	500 - 15,000 ft^2/d
										Groundwater Capture Processes under a Seasonal Variation in Natural Recharge Discharge. Hydrogeology Journal 6: 24-32	Maddock, T., and Vionett, L.	1988	
X	X	X	X		X	X	X	X	X	Preliminary Report: Hydrologic Investigation of the San Pedro River Basin, Southeastern Arizona	Rovey, C.K.	1987	Used for Analytical Modeling: Late T =4,000 FT^2/D Early T=8,000 ft^2/d (as per Putman, et al, 1988)
X					X					Harshbarger and Associates, Appendix 1 - Consultant's Report on Water Development, in Report on Water Supply, Fort Huachuca and Vicinity, by US Army Corps of Engineers, Los Angeles Area	Harshbarger & Assoc.	1974	500 to 15,000 ft^2/d

Attachment 2

PRELIMINARY ANALYSIS OF MODELS FOR CONE OF DEPRESSION TESTS

ADWR has been tasked with evaluating both analytical and numerical models for use in steady-state cone of depression testing. Analytical models present a simplistic evaluation of an aquifer (single geologic unit, simplified aquifer parameters). Typically analytical groundwater models utilize mathematical equations that treat the aquifer as a uniform porous media, and solve for induced drawdown at varying distances from a pumping well based on assumed aquifer parameters, boundary conditions and projected pumping rates.

Numerical models have the ability to account for complexity in aquifer parameters and boundary conditions. Numerical models solve groundwater flow equations by dividing an aquifer system into discrete model cells having assigned characteristic aquifer parameters and pumpage. The ADWR Groundwater Modeling Unit uses the USGS 3D numeric groundwater flow model code (MODFLOW) to evaluate regional aquifer behavior throughout Arizona.

ADWR has examined three modeling approaches (two analytical and one numerical) summarized in the table below.

Model Approach	Implementation	Able to Readily Account for Multiple Wells?	Able to Account for Stream-Aquifer Interaction?	Able to Account for Aquifer Heterogeneity?
Closed-Form Analytical Solution (Thiem Equation)	Single Equation	No	No*	No
Analytical Element Method (Winflow©)	Computer Groundwater Flow Model	Yes	Yes	No
Finite Difference Numerical Method (MODFLOW)	Computer Groundwater Flow Model	Yes	Yes	Yes

* Stream-aquifer interaction can be emulated with image wells.

Each of these modeling approaches are described in the following sections.

Thiem Equation

The Thiem (1906) equation (Equation 1), as described in Bouwer (1978), is an analytical equation based on Darcy's Law that can be used to calculate the steady-state drawdown of a well in confined and unconfined aquifers (Equations 1 and 2, Figures 1 and 2).

$H_2 - H_1 = (Q * \ln(R_2/R_1))/(2*\pi*T)$ (confined version of Thiem Equation 1)

Q = Well Pumping Rate (L^3/T)

R_2 and R_1 Distances From Well (L)

K= Hydraulic Conductivity (L/T)

D= Aquifer Thickness (L)

T = Transmissivity = KD (L^2/T)

$H^2{}_2 - H^2{}_1 = (Q * \ln (R_2/R_1))/(\pi*K)$

$H_2 - H_1 = (Q * \ln (R_2/R_1))/(\pi*K*(H_2+H_1))$ (unconfined Version of Thiem Equation 2)

Q = Well Pumping Rate (L^3/T)

R_2 and R_1 Distances From Well (L)

K= Hydraulic Conductivity (L/T)

$(H_2 + H_1)/2$ =average height of aquifer between R_2 and R_1

T = Average Aquifer Transmissivity = K $(H_2 + H_1)/2$

The unconfined and confined versions of the Thiem equation yield essentially equivalent results when the drawdown in the aquifer is only a small percentage of the total aquifer thickness.

Major assumptions and data requirements of the Thiem equation, as developed for confined aquifers, include:

- The well is fully penetrating
- The aquifer is infinite and homogeneous
- Pump rate and aquifer transmissivity are constant
- Steady horizontal flow exists
- At some distance from the well (the radius of influence) the drawdown from its pumping is negligible.

As indicated, an important requirement of the Thiem equation is the specification of the distance at which a well's pumping has no appreciable impact on the potentiometric surface (for confined aquifers) or water table (for unconfined aquifers). This distance is known as the radius of influence of the well. If the assumed radius of influence is over-estimated then the drawdowns everywhere will also be overestimated, perhaps greatly so. Conversely, if under-estimated, then so will be the calculated drawdowns.

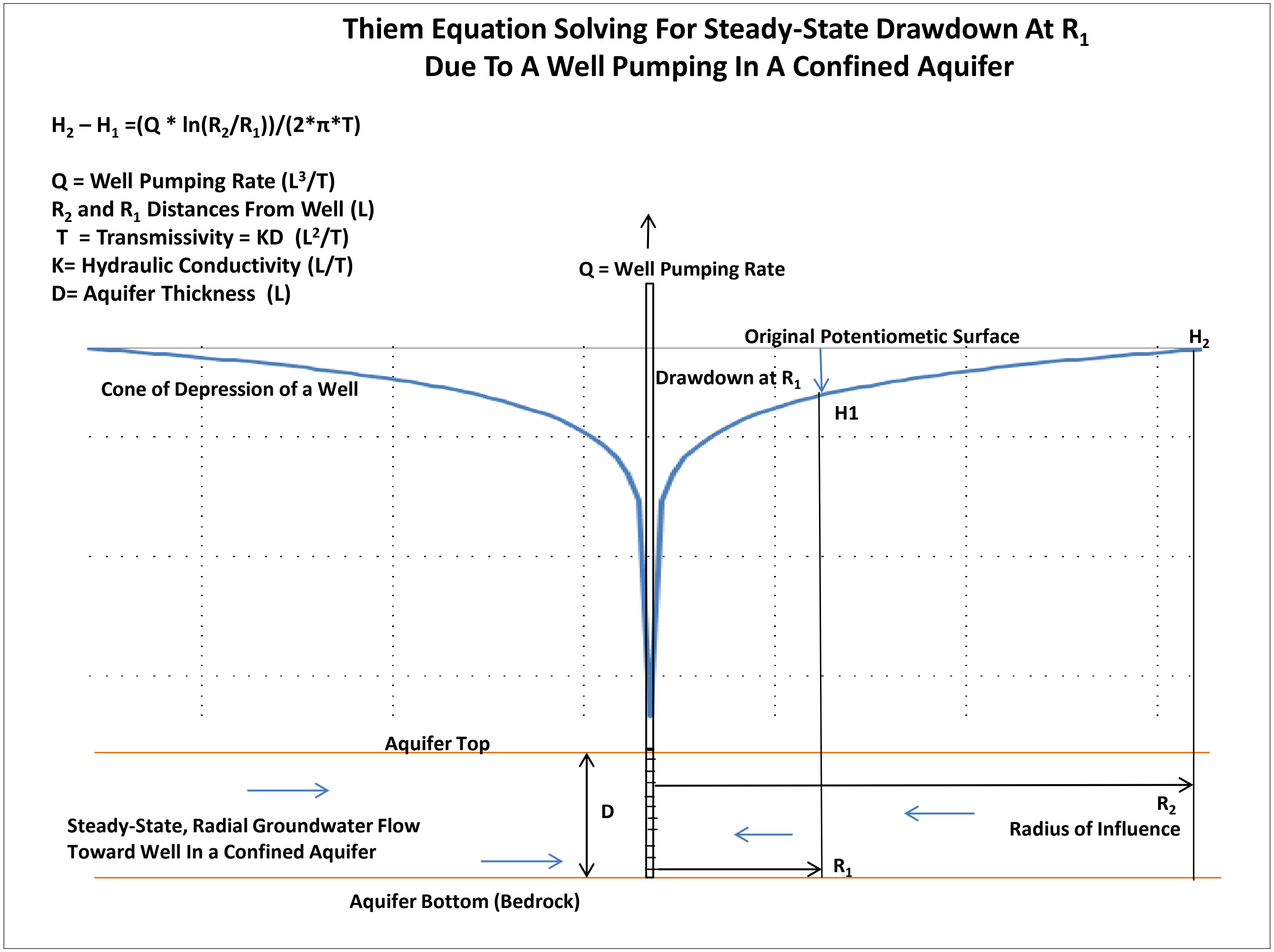

Figure 1 Thiem Equation For Steady-State Radial Flow In A Confined Aquifer

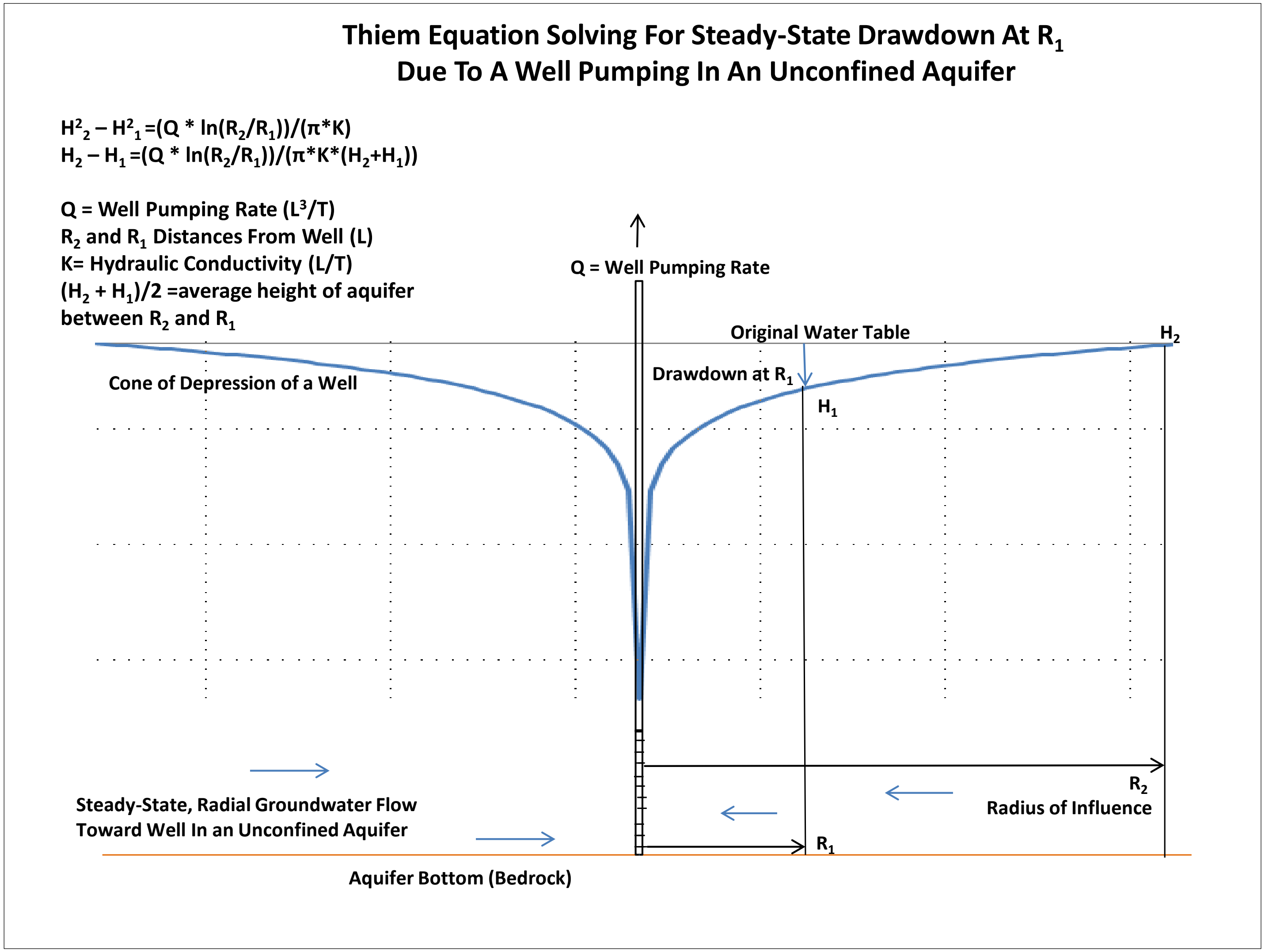

Figure 2 Thiem Equation For Steady-State Radial Flow In An Unconfined Aquifer

In order to apply the Thiem equation to the cone of depression test it will be necessary to reasonably estimate average aquifer transmissivity, well pumping rate and boundary conditions. Aquifer boundary conditions, as implemented in the Thiem equation, are characterized by the radius of influence of the well. Under pumping conditions a well's radius of influence expands outward from the well as pumping continues. The cone will continue to expand until it intercepts an amount of recharge that is equivalent to its pumping rate. If this condition occurs the well is interpreted to have achieved a steady-state between its discharge (pumping rate) and its recharge. If the recharge to the well is less than its pumping rate the cone of depression will continue to expand outward and transient conditions will persist.

For unconfined aquifers, where sufficient recharge may occur from direct precipitation on the land surface in the vicinity of the well, a simple relationship is available to estimate a well's radius of influence (De Smedt, 2009; Figure 3). In confined aquifers, with no vertical leakage near the well, a well's cone of depression will expand outward to a location where the aquifer is not confined and recharge occurs (De Smedt, 2009). In these situations the radius of influence of the well may be approximated by the distance between the well and the recharge area.

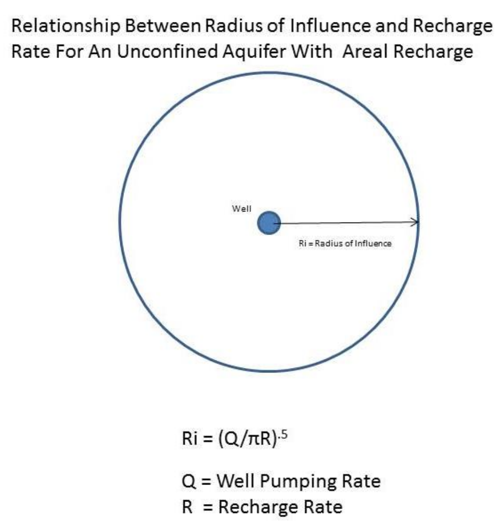

Figure 3 Relationship Between the Radius of Influence and the Recharge Rate in an Unconfined Aquifer

In situations where a well is located in an aquifer near a stream that can supply sufficient water (induced recharge), without running dry, the Principle of Superposition (superposition) can be applied to analyze the well's drawdown. Superposition, as applied to steady-state groundwater flow systems, assumes that the effects of multiple sinks (pumped wells, gaining stream, evapotranspiration) and sources (natural or artificial recharge, losing streams) are additive (Bouwer, 1978). Applying superposition to calculate the drawdown from a well near a stream requires the use of a "positive image well" that simulates the impact of recharge from the stream (Figure 4). In this situation the radius of influence is equal to twice the distance from the well to the edge of the stream (De Smedt, 2009).

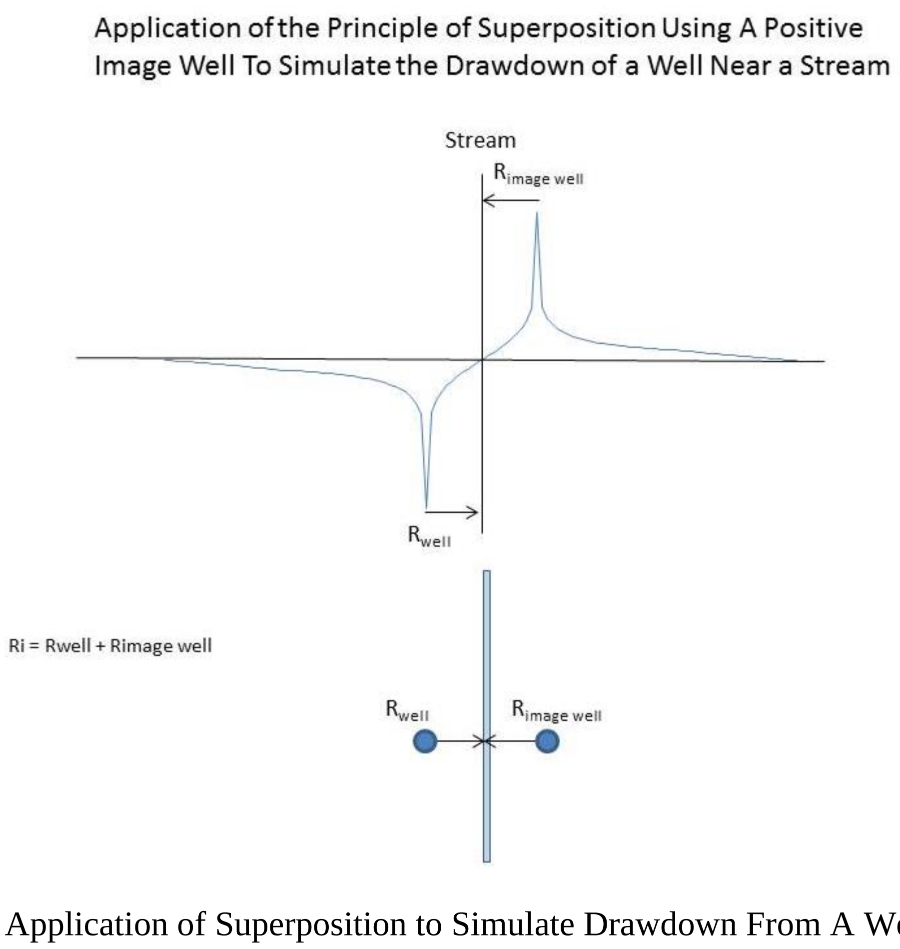

Figure 4 Application of Superposition to Simulate Drawdown From A Well Near A Stream

Application of the Thiem equation for a cone of depression test to determine the drawdown from a well at the edge of a subflow zone requires different assumptions concerning the impact of the well's pumping on stream flow and the well's radius of influence. For example, it is theoretically possible to apply the Thiem equation to calculate the steady-state drawdown at any distance between a well and a stream, including the drawdown at a subflow zone boundary, if it is assumed that the distance between the well and the stream is equal to the well's radius of influence. Using this assumption, the well could never pump any streamflow, but the drawdown caused by the well at a subflow zone boundary could be calculated. In other words, the Thiem equation does not model or account for any hydrologic interaction between the stream and aquifer, beyond the assumption of zero drawdown, unless an image well is used in the analysis. Figure 5 shows the calculated cone of depression for a well using the confined version of the Thiem equation for an assumed well pumping rate and aquifer transmissivity. In this example it was assumed that R_2 was the distance between the well and the stream (the assumed radius of influence) and R_1 was the distance between the well and the subflow zone boundary. The results indicate that 0.178 foot of drawdown would theoretically occur at the subflow boundary located on the shortest line between the well and the stream. This level of theoretical drawdown exceeds the 0.1 foot allowable drawdown limit that is currently associated with the well's cone of depression test at a sub-flow boundary.

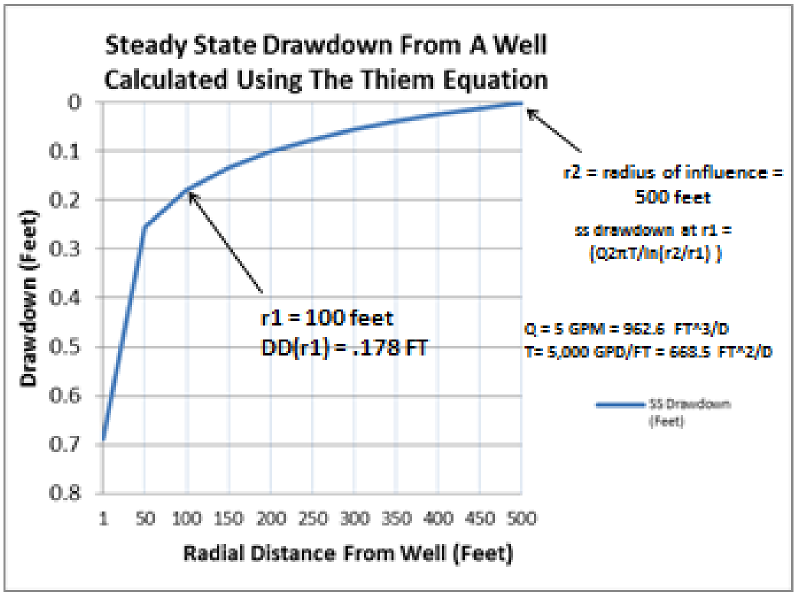

Figure 5 Theoretical Steady-State Drawdown of a Well Calculated Using the Thiem Equation

As a practical matter it may be necessary to conduct preliminary evaluations to determine whether a given well's pumping would meet the allowable standards of the cone of depression test. Based on the large number of wells that may potentially require review, a simplified method of evaluation of a well's theoretical steady-state drawdown at a subflow zone boundary has been prepared (Figure 6).

Review of Figure 6 shows that five allowable drawdown limit curves have been calculated, each with a different ratio of R_2/R_1. Assuming a constant ratio of R_2/R_1 for a given set of calculations, it was possible to determine combinations of maximum well pumping rate and minimum aquifer transmissivity that did not exceed 0.1 foot of drawdown at R_1 (which was assumed to be a subflow zone boundary). Any combination of well pumping rate and aquifer transmissivity that falls below a given curve would theoretically cause a drawdown at the boundary of a sub-flow zone that is less than 0.1 foot.

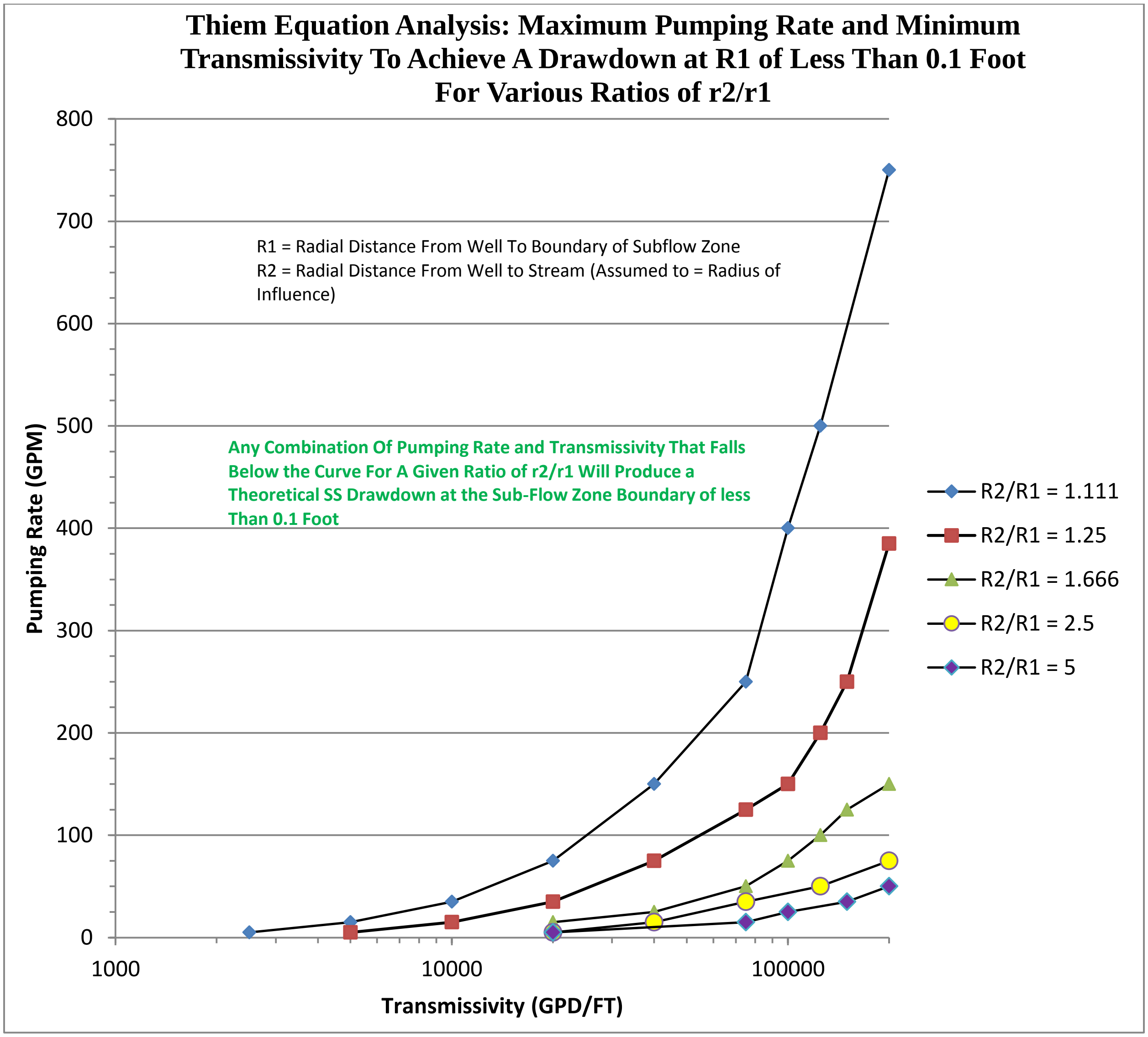

Figure 6 Maximum Pumping Rate and Minimum Transmissivity to Achieve a Maximum Drawdown of 0.01 feet at R_1 (Sub-flow Boundary) For Various Ratios of R_2/R_1

The relationships shown in Figure 6 suggest that it might be a simple matter to apply the Thiem equation to develop a cone of depression test, if the distances between a well and the subflow boundary, and a stream are known. However, practical examples indicate such a method may be problematic to implement and provide improbable results. For example, Figure 7 shows a plot of two different hypothetical well locations that have the same ratio of R_2/R_1 (the ratio of the distance between the well and the stream and the distance between the well and the nearest subflow zone boundary). The calculated drawdown at the boundary of the subflow zone for each well is directly proportional to both the logarithm of R_2/R_1, and the pumping rate (Q); and inversely proportional to the transmissivity (T). Assuming equal transmissivity at both well locations, it follows that a well located at B could pump at the same rate as a well at A and have equal drawdown at the nearest subflow boundary, in spite of the fact that the distance between well B and its nearest subflow boundary is about one third the distance from well A and its nearest subflow boundary. This example shows the strong influence that assumed radius of influence has on calculated results (Figure 8). The results suggest that the assumption that a well's radius of influence under steady state conditions never extends past the nearest stream reach is unlikely in many situations.

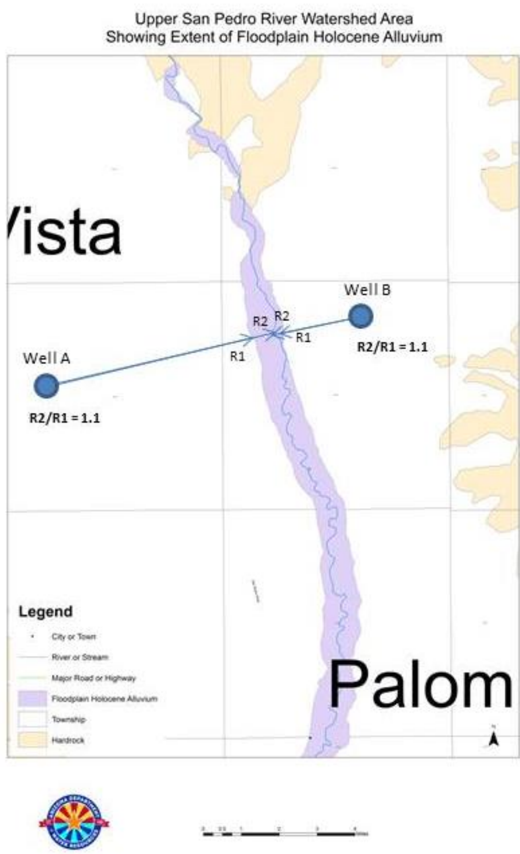

Figure 7 Map Showing R_2/R_1 Distances Vary Due to Subflow Zone and Stream Geometry

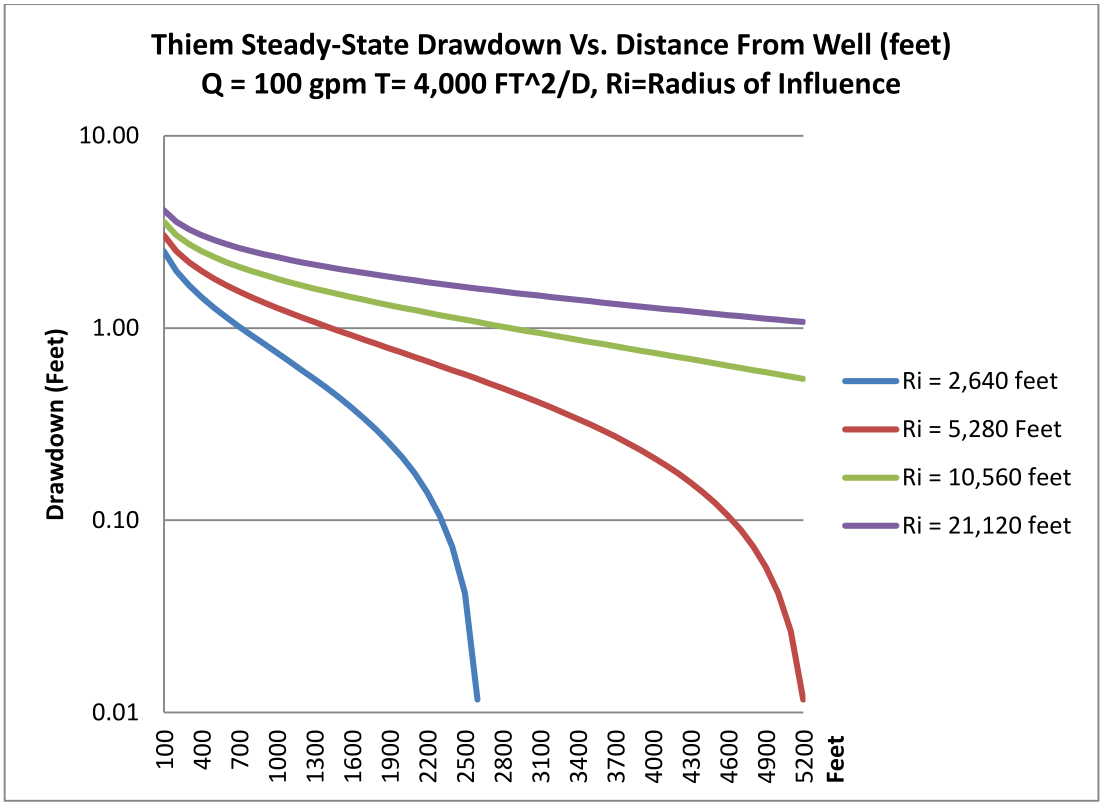

Figure 8 Sensitivity of Model Drawdown to Variation in Radius of Influence

The use of the Thiem equation to conduct cone of depression tests has potential advantages and significant limitations. Advantages include that the method is comparatively simple to implement with just a spreadsheet. The method also assumes homogenous aquifer conditions and therefore requires a single estimate of aquifer transmissivity. Additionally, implementation of complex boundary conditions using image wells is another potential limitation of the model. The Thiem model's reliance on an assumed or estimated radius of influence is a major limitation on its potential use. It will be necessary to further evaluate the relative impacts (sensitivity) of all model inputs to the Thiem equation (T, Q, radius of influence). Further analysis may reveal situations where it is appropriate to apply the equation for cone of depression tests.

WinFlow©

WinFlow© is a computer groundwater flow model tool that simulates two-dimensional flow for steady-state and transient conditions. WinFlow© is available in the commercial software package AquiferWin32© (ESI, 2011). The steady-state module in Winflow© uses the "analytical element method" (AEM) developed by Strack (1988). The AEM produces composite analytical solutions across a user-defined modeling domain by superimposing the cumulative effects of multiple "analytical elements" and boundary conditions defined by the user. Analytical elements represent hydrological features such as pumping wells, gaining or losing river reaches, areas of recharge, etc.

Traditional analytical solutions for idealized hydrologic features are limited in their usefulness due to their simplified assumed hydrologic settings. For example, consider application of the Thiem equation for a pumping well with a nearby stream:

1. Requires a priori assumption of the location of the radius of influence,
2. Cannot readily account for the effect(s) of other pumping well(s);
3. Approximates the stream as an infinitely long equipotential line; and
4. Cannot account for the effects of interaction between the stream and aquifer unless an image well is used.

In contrast, for the same analysis the AEM method:

1. Requires no a priori assumption of the radial extent of the cone of depression;
2. Allows effects of multiple pumping wells to be analyzed;
3. Models the stream as a "line sink" following the actual stream course; and
4. Includes effects of the stream's presence on the calculated drawdown results.

Analogous to the specification of the radius of influence when using the Thiem equation, an AEM model requires user specification of a problem-specific boundary condition. In WinFlow© this is done by introducing of a reference point somewhere in the model at which a reference head is specified. Since this point is introduced for mathematical purposes, and not for hydrological reasons, its location should be selected in such a manner that it as far as possible away from analytical elements such as pumping wells so that it does not influence the modeling results (Haitjema, 1995).

Unlike numerical-based computer groundwater flow models, such as MODFLOW discussed below, AEM computer models cannot readily account for heterogeneities in aquifer parameters. AEM models, like WinFlow©, therefore require more simplifications of the flow system than do numerical solutions, but they also require correspondingly fewer input data. The latter feature is attractive because field data acquisition is time-consuming and expensive, while some parameters remain uncertain or do not significantly affect the modeling results (Haitjema, 1995). In many cases, AEM models can produce similar results as more data-intensive numerical models.

Figure 9 compares WinFlow© output for a steady-state cone of depression to results obtained using the Thiem equation for the identical problem. For this comparison, the AEM reference head was placed at the same distance from the pumping well as the distance specified for the radius of influence for the Thiem equation, and equivalent well and aquifer properties were used in both methods. (ESI, 2011). This figure demonstrates that the calculated distribution of drawdown is consistent for both methods. It should be noted that the results obtained using the Thiem equation critically depend upon the user's assumption of the radius of influence for the well and neglects effects of hydrologic features other than the pumping well. Therefore, results produced independently by WinFlow© and by use of the Thiem equation will only coincide if the radius of influence is correctly assumed a priori and effects of other hydrologic features either do not exist or are not significant.

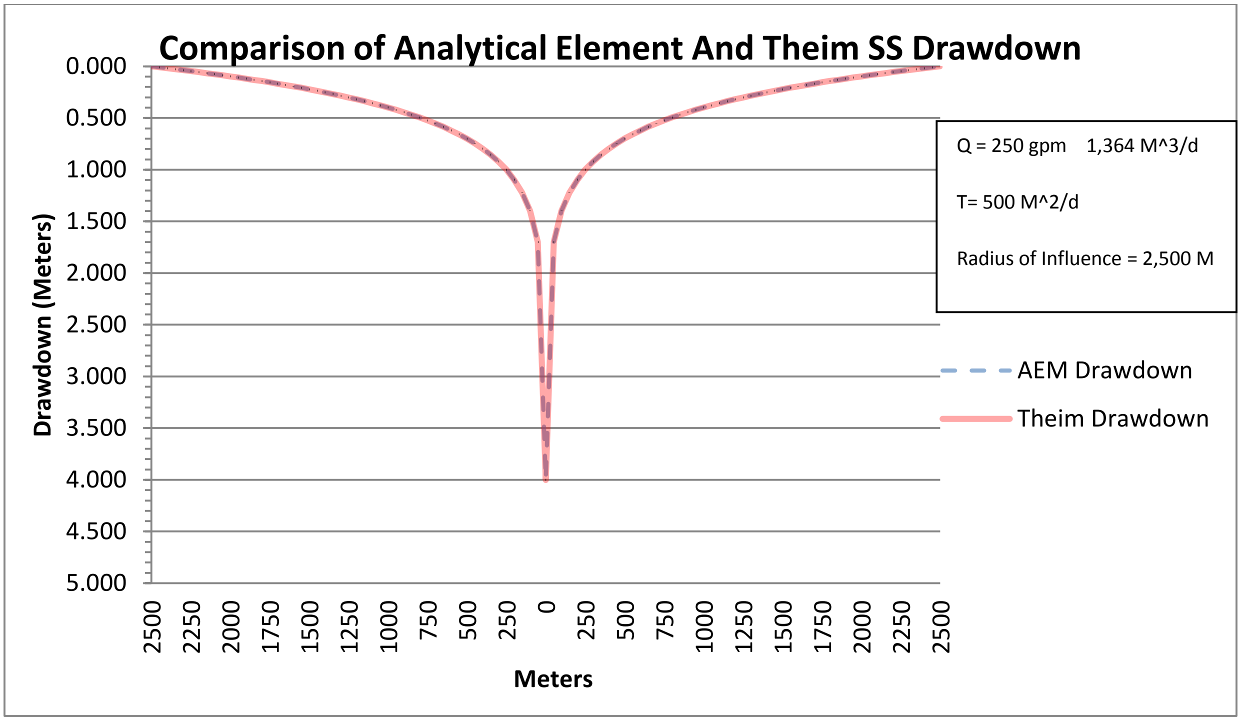

Figure 9 Comparison of Analytical Element and Thiem Drawdown

The use of the AEM method has many of the same fundamental advantages and limitations as the Thiem equation. However, some types of boundary conditions should be easier to simulate using the AEM method compared to the Thiem method by using specified head and flux line sinks that are available in the AquiferWin32 software package. Model development, execution and output data processing would likely be more efficient using the AquiferWin32 graphical user interface (GUI). It is important to note that the AEM requirement of a specified reference head is an important assumption that can significantly impact model results. For the most part, the sensitivity analysis that will be conducted for the Thiem model inputs will be applicable to the AEM model as well.

MODFLOW

Numerical groundwater flow models such as the USGS – MODFLOW model (USGS, 2000) simulate groundwater flow using a finite-difference approximation for the fundamental groundwater flow equations. Finite-difference models, such as MODFLOW, normally overlay a rectilinear model grid over an aquifer system and represent different aquifer units with one or more model layers (Figure 10). Once a model grid and layering structure has been established, representative hydraulic properties (hydraulic conductivity, storage coefficient, etc.) and boundary conditions (active, inactive, specified head or flux, etc.) are assigned to each model cell. If applicable, various stresses (pumping, recharge, evapotranspiration, etc.) are assigned to the model cells where the stresses occurred. After the model framework is developed and stress assignments are complete, models are typically calibrated to simulate historic steady-state and transient conditions. During the calibration process various model inputs are iteratively adjusted to improve the match between model simulated water levels and fluxes and observational data (Figure 11). Once a suitable match is achieved between simulated and observed data, the model is described as being “calibrated”.

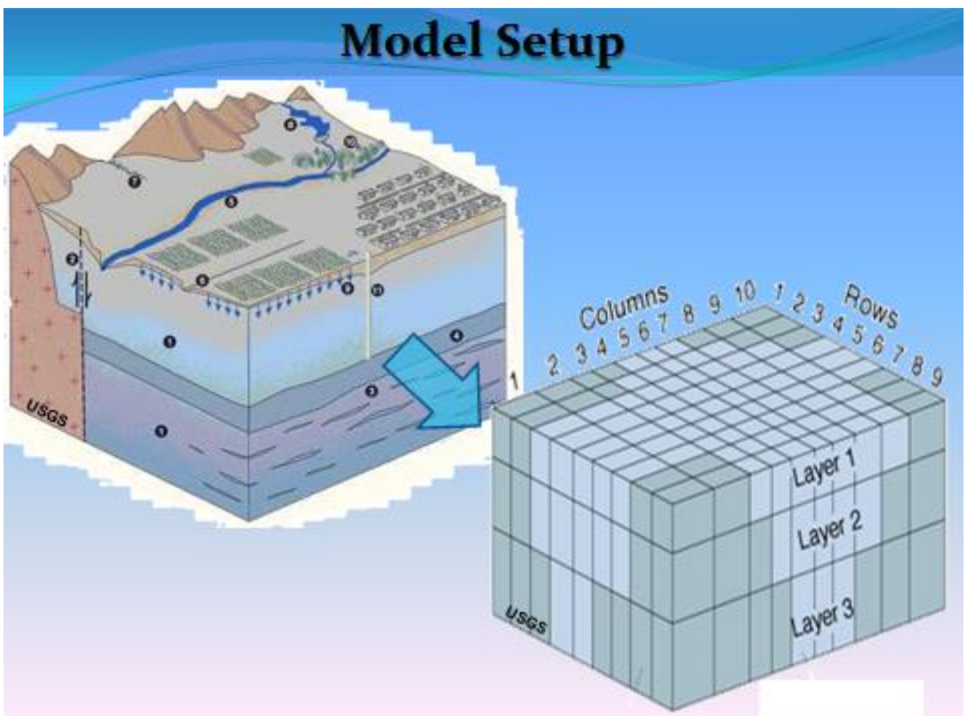

Figure 10 Numerical Model Setup

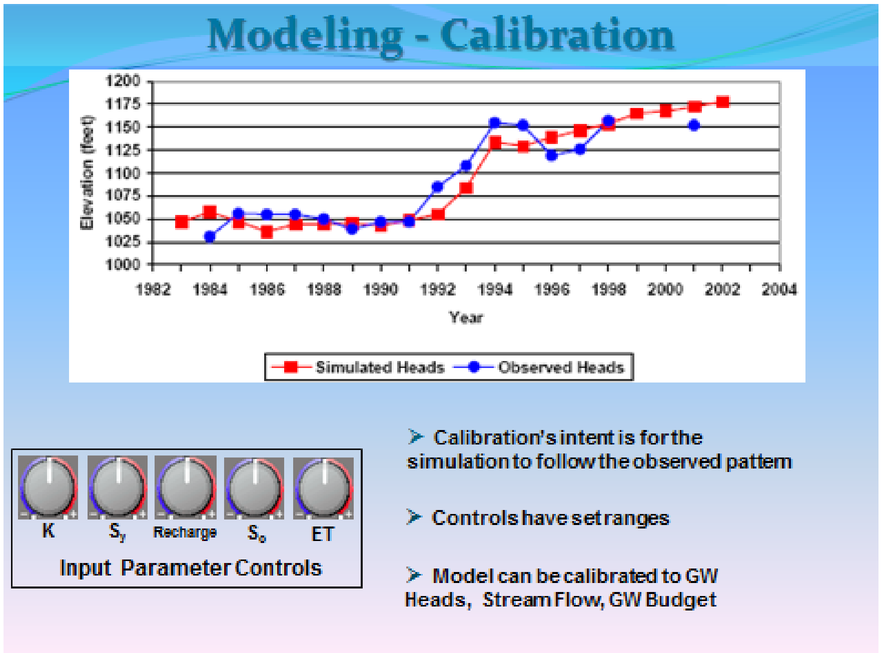

Figure 11 Model Calibration

Properly calibrated numerical groundwater flow models are generally considered to be effective and reliable tools for analyzing groundwater flow systems. Advantages that properly constructed and calibrated numerical groundwater flow models have over analytical models include the ability to simulate aquifer heterogeneity, complex boundary conditions, multiple stresses, etc.

Although versatile and generally reliable, numerical groundwater flow models have certain limitations related to model cell size that potentially affect their accuracy for cone of depression testing. Normally, the grid spacing of a numerical groundwater flow model is established to provide a network of cells that can sufficiently represent aquifer heterogeneities and boundary conditions. Model cell sizes often vary from tens to hundreds of meters. The USGS Upper San Pedro groundwater flow model has a uniform horizontal grid spacing of 250 meters (Pool and Dickinson, 2007). The potential issue with model cell size is related to the averaging of simulated model heads over the area of the model cell (Figure 12). As that diagram shows, the differences between analytical and numerical model solutions are greater near a well where the cone of depression is steeper and more non-linear. While a grid spacing of 250 meters may be sufficient for most regional groundwater modeling purposes, it is uncertain whether a 250 meter model cell dimension is sufficient to accurately determine a steady-state drawdown to 0.1 foot at the subflow boundary.

Model grid spacing issues can be addressed by decreasing the grid size in an area of interest, such as in the area of the stream and subflow zone. Various MODFLOW packages have been developed to provide this type of feature. The newest version of MODFLOW that offers this feature is the Unstructured Grid Package (MODFLOW – USG, USGS, 2013). Using this package it would potentially be possible to modify existing model grid networks to sufficiently address accuracy issues associated with grid size (Figure 13).

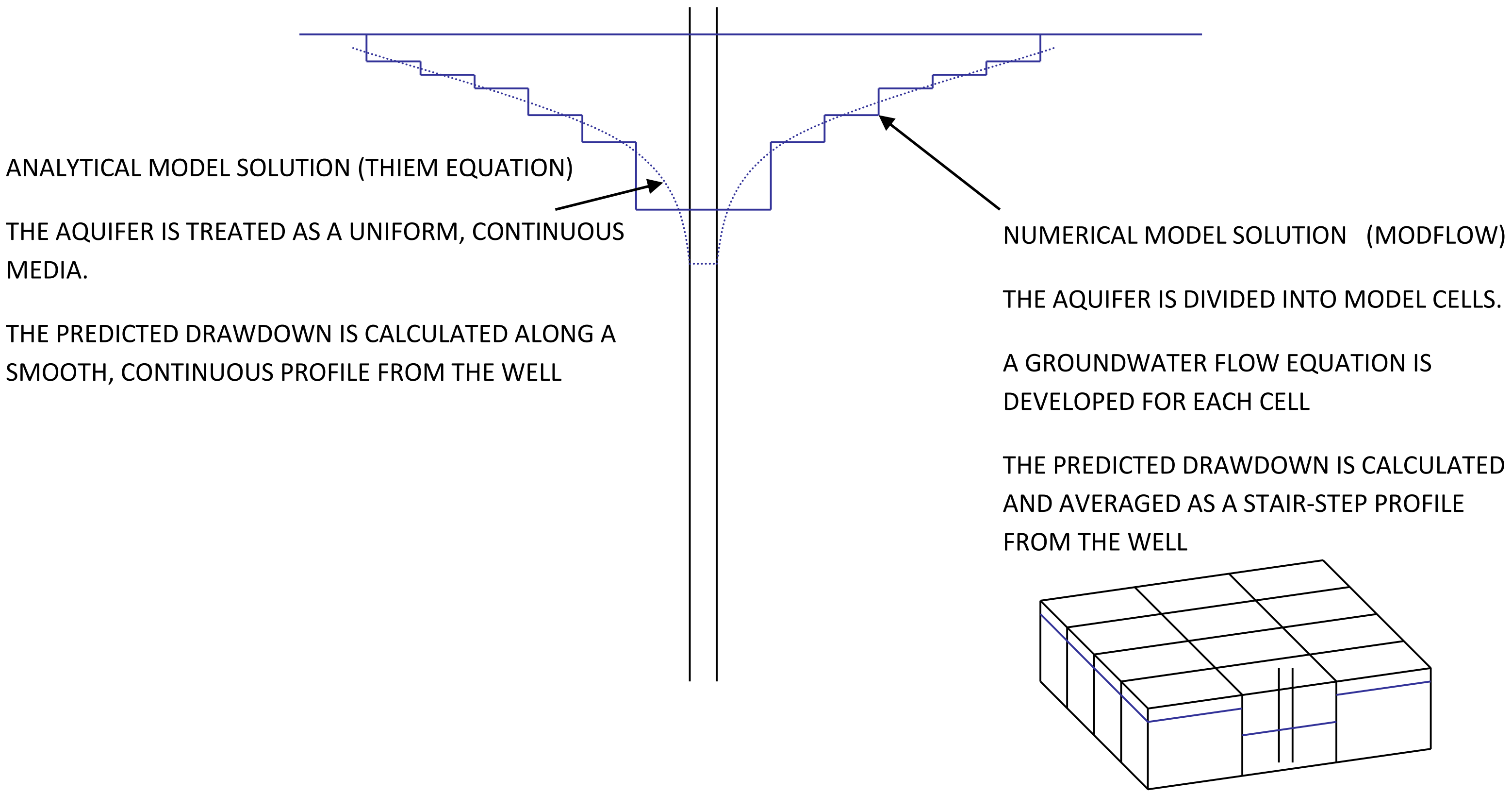

Figure 12 Comparison of drawdown simulated with analytical and numerical groundwater models

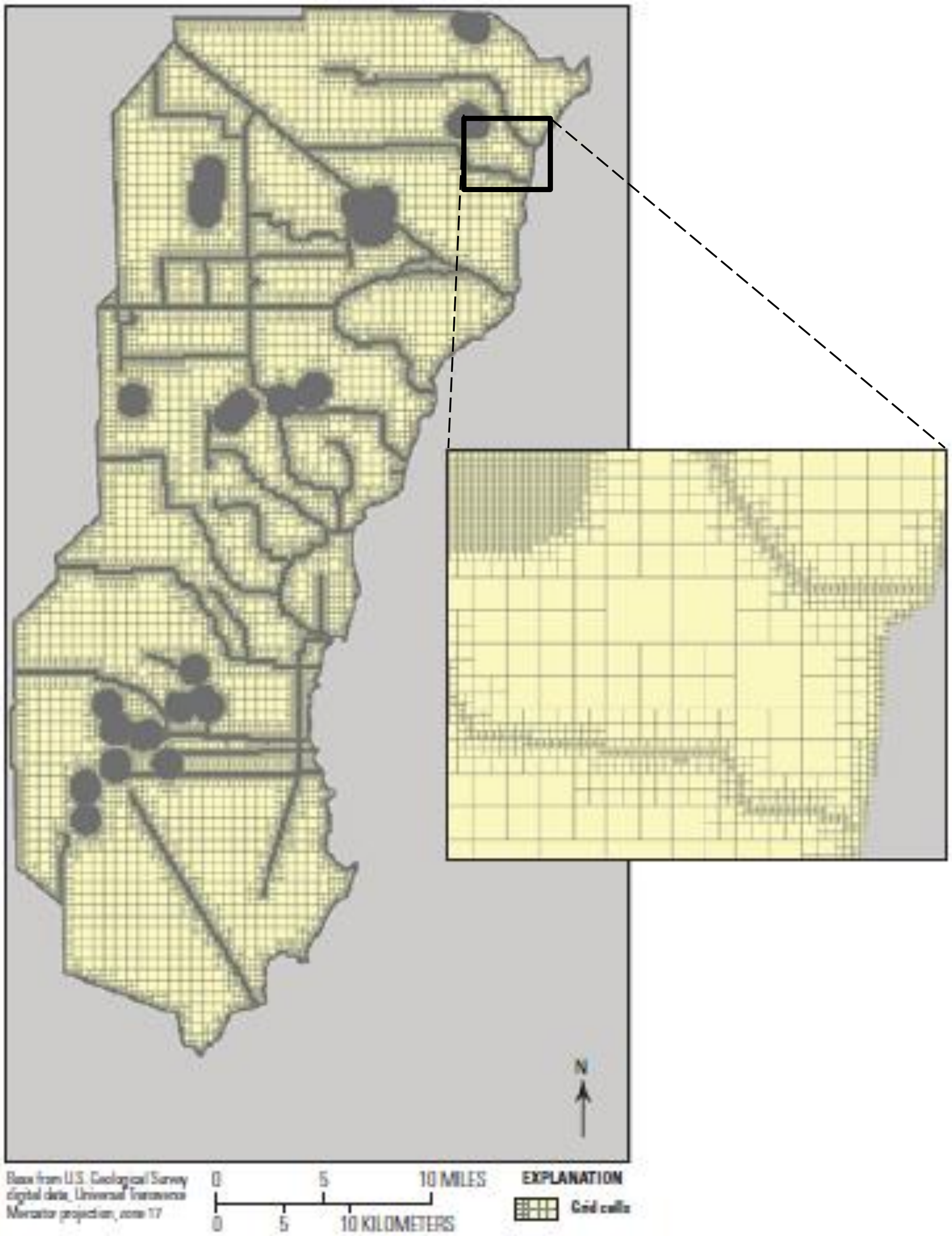

Figure 13 Example of grid cell variability provided using MODFLOW-USG in a groundwater model of Biscayne Bay (USGS Techniques and Methods 6-A45)

One issue of potential concern is the fact that numerical models have not been developed for all areas of the San Pedro River. The USGS model of the Upper San Pedro area only covers the Sierra Vista sub-watershed. No other numerical groundwater flow models of other areas of the San Pedro River watershed have been developed by public agencies at this time. Models of similar complexity and detail would be costly and take years to develop for other areas of the San Pedro River watershed.

Aside from concerns related to model cell-size, the adaption of an existing groundwater flow model requires an assessment of whether its conceptual model and numerical implementation are applicable to calculating drawdown with requisite accuracy and precision. The USGS model of the Sierra Vista Subwatershed has acknowledged certain limitations regarding the simulation of stream flow (USGS, 2007, pg. 43-44). Additionally, the assumption that a true "steady-state" existed for pre-development conditions is in question (USGS, 2007, pg.45). The distinctly seasonal nature of the hydrologic system in the Sierra Vista Subwatershed made it necessary to simulate both "true" and "cyclic" steady-state conditions to provide initial conditions for transient modeling. Assumptions made regarding the extent and nature of riparian vegetation in the "steady-state" era also require consideration. How these features and assumptions have been implemented in existing models and what potential impacts they may have on the results of cone of depression tests requires future evaluation.

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