AP - 75

AMENDED

STAGE 2 WORKPLANS

DATE: 2-26-10

Hansen, Edward J., EMNRD

From: Katie Jones [kjones@riceswd.com]
Sent: Friday, September 10, 2010 2:39 PM
To: Hansen, Edward J., EMNRD
Cc: Hack Conder; gil@trident-environmental.com
Subject: BD Jct. J-26 (AP-75) Amended Stage 2 Abatement Plan Addendum

Mr. Hansen,

ROC proposes the following Addendum to the BD Jct. J-26 (AP-75) Amended Stage 2 Abatement Plan submitted to the NMOCD February 26, 2010 and approved by the NMOCD on April 15, 2010.

Page 17, Section 7.2 Source Removal Testing and Proposed Abatement Options
Red, strikethrough font represents deleted items and blue font represents added items.

"A ~~three month~~four quarter source removal and test pumping program, utilizing monitoring well ~~MW-4~~MW-2, is proposed to determine if groundwater can be improved within a short period of time and assist in the evaluation of groundwater abatement options. Water from the recovery activities will be utilized for pipeline and well maintenance operations.

Upon completion of the ~~three month~~four quarter source removal and test pumping activities, ROC will submit the results to the NMOCD and propose a long-term groundwater remedy based on an evaluation of alternatives that provide the best abatement option."

If you have any questions or require any further information, please contact myself at (575)393-9174 or Hack Conder at (575)631-6432.

Thanks you.

Katie Jones
Environmental Project Coordinator
RICE *Operating Company*

Hansen, Edward J., EMNRD

From: Hack Conder [hconder@riceswd.com]
Sent: Thursday, April 15, 2010 11:20 AM
To: Hansen, Edward J., EMNRD; Katie Jones
Subject: Amended Stage 2 Abatement Plan for the BD Jct.J-26 Site (AP-75) addendum
Attachments: J-26 Proposed Well Schematic.pdf

Importance: Low

Edward Hansen,

I would like to submit a addendum to the Amended Stage 2 Abatement Plan for the BD Jct.J-26 Site (AP-75) dated February 26, 2010.Attached is a proposed well schematic for the Recovery well and this well will be sampled at separate intervals, deep sample at approximately 30' below GW level and shallow sample at approximately 10' below GW level per our discussion on April 14, 2010. If you have any questions or concerns please contact me.

Hack Conder
Environmental Manager
Rice Operating Company
575-393-9174
fax 575-397-1471

Logger:	Lara Weinheimer	**Proposed Well Schematic**	
Driller:	Harrison & Cooper, Inc. Drilling		
Consultant:	Trident		
Drilling Method:	Air rotary		
Start Date:	4/23/2009		
End Date:	4/23/2009		

RICE OPERATING COMPANY
ROC
SINCE 1955

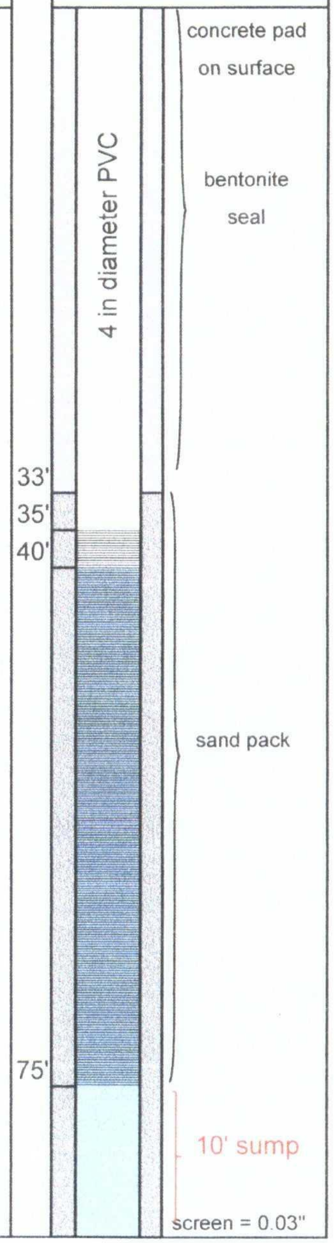
Project Name: BD jct. J-26	**Well ID:** RW-1
Location: UL/J sec. 26 T21S R37E	
Lat:	County: LEA
Long:	State: NM

Comments:

TD = 85 ft GW = 40 ft

Depth (feet)	chloride field tests (ppm)	LAB	PID	Description		Lithology
5						
10						
15						
20						
25						
30						
35						
40						
45						
50						
55						
60						
65						
70						
75						
80						
85						

Well Construction

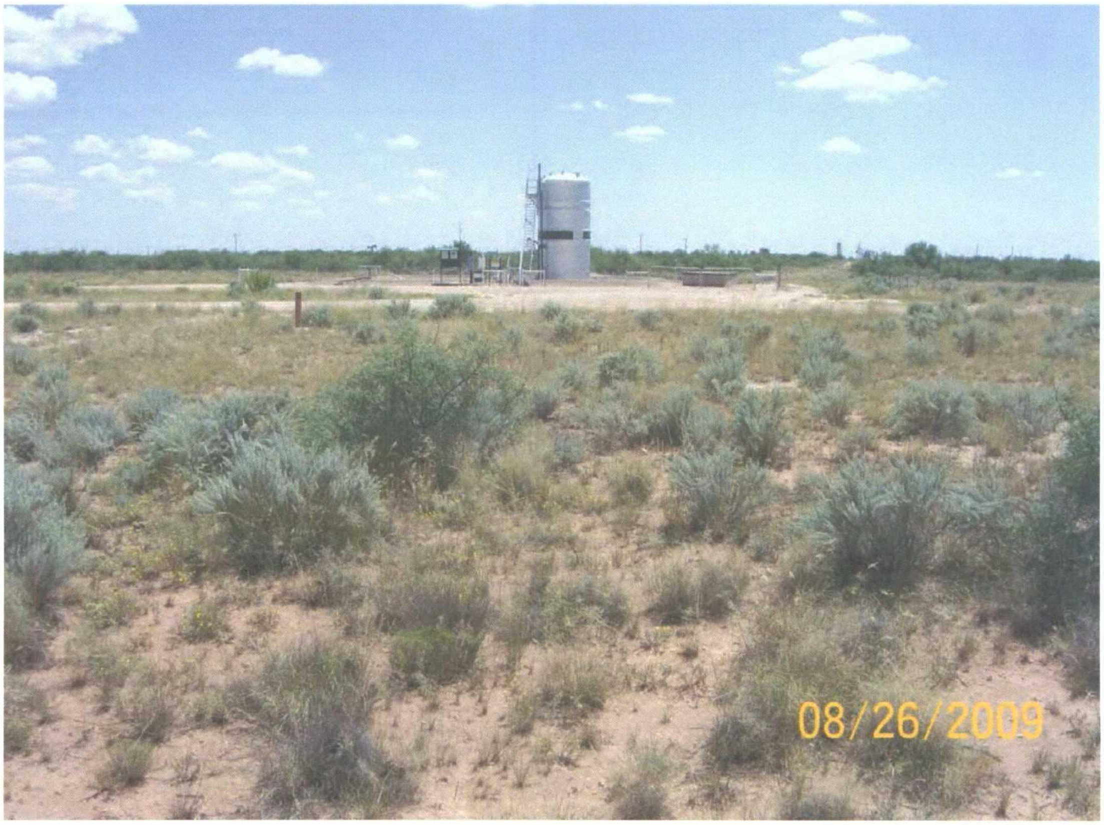


February 26, 2010

AMENDED STAGE 2 ABATEMENT PLAN

BD JCT. J-26 SITE (AP-75)

T21S, R37E, SECTION 26, UNIT LETTER J
LEA COUNTY, NEW MEXICO



Prepared by:

TRIDENT ENVIRONMENTAL

P. O. Box 7624
Midland, Texas 79708

Prepared for:

RICE OPERATING COMPANY
ROC
SINCE 1955

122 West Taylor
Hobbs, New Mexico 88240

TRIDENT
ENVIRONMENTAL

CERTIFIED MAIL
RETURN RECEIPT NO. 7099 3400 0017 1737 1803

February 26, 2010

RECEIVED
MAR - 1 2010
Environmental Bureau
Oil Conservation Division

Mr. Edward Hansen
New Mexico Energy, Minerals, & Natural Resources
Oil Conservation Division, Environmental Bureau
1220 S. St. Francis Drive
Santa Fe, New Mexico 87505

RE: Amended Stage Abatement Plan (AP-75)
BD Jct. J-26 Site
T21S-R37E-Section 26, Unit Letter J
Lea County, New Mexico

Mr. Hansen

On behalf of Rice Operating Company (ROC), enclosed is the *Amended Stage 2 Abatement Plan* for the above-referenced site in response to ROC's discussions with you in the December 16, 2009 quarterly meeting. This Stage 2 Abatement Plan replaces the amended plan submitted on May 28, 2008.

ROC is the service provider (agent) for the Blinebry Drinkard (BD) SWD System and has no ownership of any portion of pipeline, well, or facility. The BD SWD System is owned by a consortium of oil producers, System Parties, who provide all operating capital on a percentage ownership/usage basis.

If you have any questions please call Hack Conder at 575-393-9174.

Sincerely,

Gilbert Van Deventer, REM, PG
Trident Environmental

cc: Hack Conder (Rice Operating Co., Hobbs NM)
Larry Hill (NMOCD District 1, Hobbs, NM)

Gil Van Deventer

From: "Gil Van Deventer" <gilbertvandeventer@suddenlink.net>
To: "Hansen, Edward J., EMNRD" <edwardj.hansen@state.nm.us>
Cc: "Buddy Hill" <larry.hill@state.nm.us>; "Katie Jones" <kjones@riceswd.com>; "Haskell Conder" <hconder@riceswd.com>
Sent: Friday, February 26, 2010 11:23 AM
Attach: J-26_AS2AP.pdf; J-26_AS2AP_Xmit.pdf
Subject: Amended Stage 2 Abatement Plan for the BD Jct.J-26 Site (AP-75)

RECEIVED
MAR - 1 2010
Environmental Bureau
Oil Conservation Division

Subject: Amended Stage 2 Abatement Plan
Site Name: BD Jct.J-26 Site (AP-75)
Site Location: T21S-R37E-Section 26, Unit Letter J, Lea County, NM

Good Morning Edward:

As agent for Rice Operating Company (ROC), Trident Environmental submits the attached *Amended Stage 2 Abatement Plan* for the above-referenced site in response to ROC's discussions with you in the December 16, 2009 quarterly meeting. This Stage 2 Abatement Plan replaces the amended plan submitted on May 28, 2008. One complete hard copy and one copy on compact disk will be sent to you via USPS Certified Mail (# 7099 3400 0017 1737 1803) today. Upon receipt from Trident, ROC will also deliver a copy to the NMOCD District 1 office in Hobbs. If you have any questions please contact Hack Conder at 575-393-9174.

Thank you,
Gil

Gilbert J. Van Deventer, PG, REM
Trident Environmental
P. O. Box 7624, Midland TX 79708
Work/Mobile: 432-638-8740
Fax: 413-403-9968

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TABLES

FIGURES

APPENDICES

1.0 EXECUTIVE SUMMARY

This Amended Stage 2 Abatement Plan presents the results of the characterization activities performed by Trident Environmental and the characterization and site closure activities performed by ROC at the Jct. J-26 site. This report fulfills the obligations of ROC presented in the Stage 1 and 2 Abatement Plan of December 5, 2005, which was approved by NMOCD on June 26, 2006.

The following corrective actions were performed in accordance with the Stage 1 and 2 Abatement Plan:

- Quarterly groundwater monitoring activities of the three on site monitoring wells were continued to document the return of chloride and total dissolved solids (TDS) concentrations to background levels. The 2009 Annual Groundwater Monitoring Report will be submitted to the NMOCD by April 1, 2010.
- Regional groundwater sampling was conducted to confirm that remediation of the constituents of concern is taking place, changes in the local and regional groundwater flow directions were noted, and ambient groundwater chemistry was confirmed.
- Data was input into a fate and transport model (WinTran - Version 1.3) to forecast the movement and attenuation of the chloride/TDS plume by dispersion and abatement by the water supply wells.

Since July 2004, chloride and TDS concentrations at the Jct. J-26 site have generally remained at or near background levels in each of the three on site monitoring wells. Background concentrations of chlorides and TDS at the site have been confirmed through recent laboratory analysis of several surrounding wells and research of local groundwater data. There is strong evidence that the continual withdrawal of groundwater by several supply wells for the operation of the Eunice Gas Plant has assisted in the redirection and recovery of residual chloride and TDS constituents from the Jct. J-26 site. In addition, WinTran fate and transport simulations show the effects of the water supply wells and natural dispersion in attenuating chloride and TDS constituents.

On February 13, 2008 (Appendix E) the NMOCD requested via email communication for ROC to install additional monitoring wells and a groundwater recovery system downgradient of the BD Jct. J-26 Site. ROC proposes a phased approach for abatement by installing one downgradient monitoring well (MW-4) about 75 feet south of the bermed SWD collection facility. Based on historical groundwater flow directions, this proposed location is directly downgradient from the former junction box and pump station. The proposed well will be constructed of 4-in diameter well casing and screen for potential use as a groundwater recovery well. The well will be installed and sampled after appropriate development using methods consistent with industry standards (ASTM, EPA, and OCD). A more detailed scope of additional characterization and abatement options is included in section 7.0.

2.0 CHRONOLOGY OF EVENTS

April 23, 2002	Initial soil sampling activities were conducted to delineate the extent of chloride and hydrocarbon-impacted soils near the Jct. J-26.
September 2002	Excavation of chloride and TPH-impacted soil was completed to a depth of 42 feet bgs. 480 yd^3 of the impacted soils were removed and disposed. Imported backfill was placed in the deep excavation from 42 feet to 27 feet bgs. A 12-inch compacted clay layer was then installed prior to backfilling with the remediated soil in 3-foot lifts. A second 12-inch compacted clay layer was installed at 5 feet bgs. The remaining remediated soil was placed above the clay layer and contoured to drain rainwater away from the area. A new replacement junction box was installed about 60 feet north of the former location. The surface was then reseeded and monitored for growth which resulted in re-establishing the native vegetation.
October 10, 2002	One monitoring well (MW-1) was installed immediately adjacent to the southeast corner of the excavated area to further assess if groundwater was impacted with chlorides. Subsequent sampling of MW-1 confirmed that groundwater was impacted with chloride and TDS levels above WQCC standards; however, there was no hydrocarbon impact based on BTEX concentrations below laboratory detection limit of 0.001 mg/L.
October 29, 2002	The disclosure report detailing all of the above-referenced work was completed and forwarded to the NMOCD in early 2003 along with the disclosure reports for other sites.
December 13, 2002	ROC notified the NMOCD Environmental Bureau Chief of groundwater impact in accordance with NM Rule 116.
June 20, 2003	A work plan addressing further actions was submitted by Trident Environmental to Wayne Price at the NMOCD office in Santa Fe.
June 27, 2003	The work plan was approved by Wayne Price of the NMOCD office in Santa Fe.
August 19, 2003	Monitoring wells MW-2 and MW-3 were installed approximately 220 feet down gradient (south-southeast) and approximately 150 feet upgradient (northwest) of MW-1, respectively. Subsequent sampling results indicated MW-2 and MW-3 delineated the downgradient and upgradient extent of chloride and TDS impact to groundwater.

December 16, 2004	Trident Environmental submitted a request to Wayne Price of the NMOCD office in Santa Fe for further actions regarding the chloride and TDS-impacted groundwater at the BD Jct. J-26 site.
January 28, 2005	Trident Environmental submitted an Update to the Site Plan which described the findings of assessment activities and proposed corrective actions for the Jct. J-26 site.
May 5, 2005	Mr. Daniel Sanchez of the NMOCD requested that ROC submit an abatement plan to the NMOCD pursuant to Rule 19.
December 5, 2005	A Stage 1 and 2 Abatement Plan was prepared by R. T. Hicks Consultants Ltd. and submitted to the NMOCD
April 17, 2006	ROC submitted proof of public notifications to the NMOCD
June 26, 2006	NMOCD approved the Stage 1 & 2 Abatement Plan
August 1, 2006	Depth to water measurements and samples for chloride and TDS analysis were obtained from several off site wells in the surrounding area.
October 4, 2006	Trident Environmental initiated fate and transport simulations for the site.
November 22, 2006	Trident Environmental performed an aquifer test at two nearby water supply wells to determine site-specific hydrological parameters.
February 5, 2007	Trident Environmental submitted the 2006 Annual Groundwater Monitoring Report to the NMOCD.
February 19, 2007	Trident completed fate and transport simulations for the site.
November 20, 2007	Trident Environmental submitted a Stage 2 Final Investigation and Abatement Completion Report to the NMOCD.
February 13, 2008	NMOCD requested ROC to submit an Amended Stage 2 Abatement Plan that included additional downgradient monitoring wells and a groundwater recovery system.
March 18, 2008	Trident Environmental submitted the 2007 Annual Groundwater Monitoring Report to the NMOCD.
May 27, 2008	Trident Environmental submitted an Amended Stage 2 Abatement Plan to the NMOCD.
February 18, 2009	Trident Environmental submitted the 2008 Annual Groundwater Monitoring Report to the NMOCD.
December 16, 2009	During the 4th quarterly meeting between ROC and NMOCD, NMOCD recommended that ROC update the monitoring well data, edit steps under the work plan, and then re-submit the Amended Stage 2 Abatement Plan.

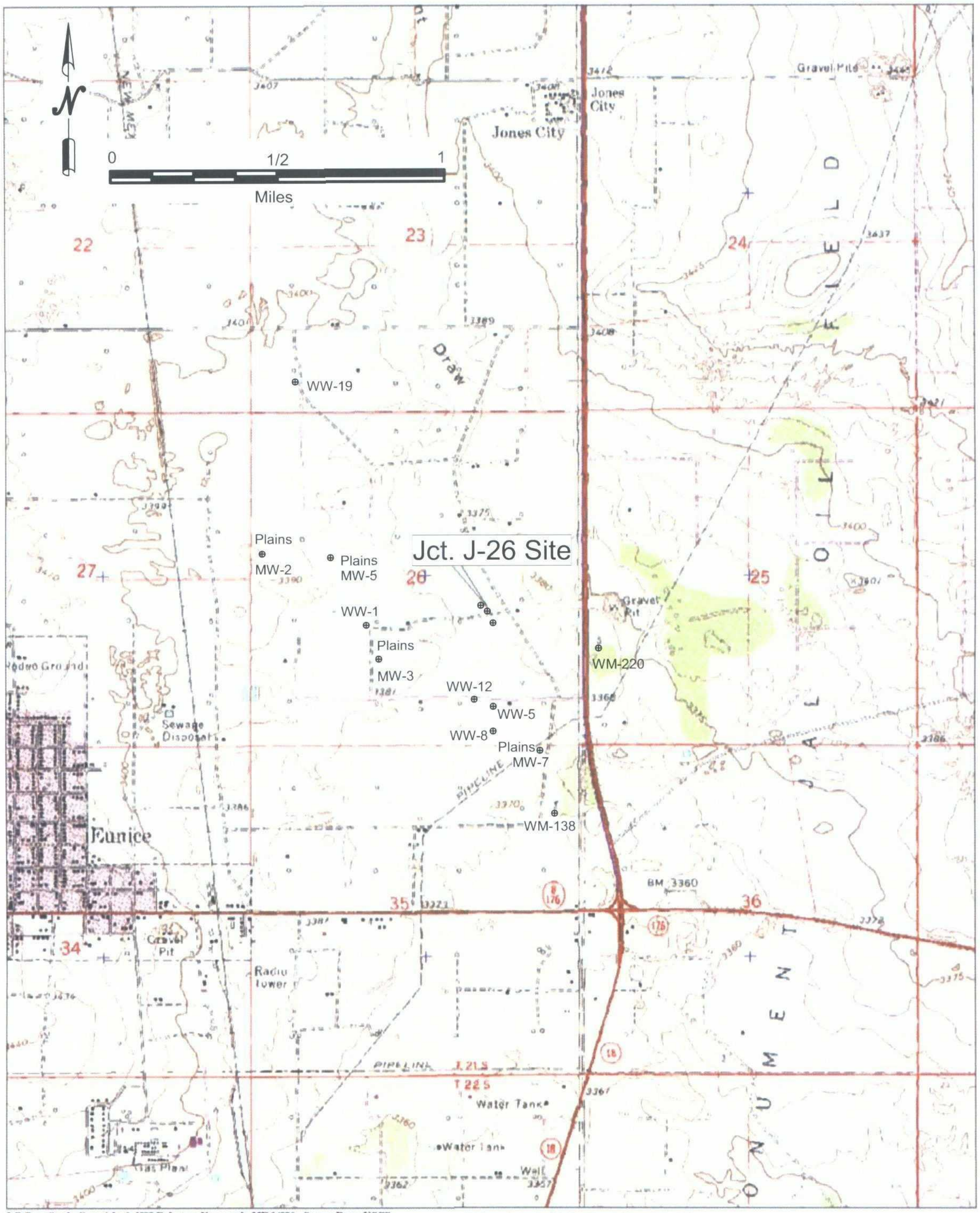
3.0 BACKGROUND

3.1 SITE LOCATION AND LAND USE

The Jct. J-26 site is located in township 21 south, range 37 east, section 26, unit letter J approximately 1 mile north-northwest of the intersection of NM State Highway 18 and County Highway 176 near Eunice, NM as shown on the attached topographic map (Figure 1) and aerial photographic map (Figure 2). Land in the site area is primarily utilized for oil and gas production and cattle ranching.

3.2 SUMMARY OF PREVIOUS WORK AND INVESTIGATIONS

Brief descriptions of previous work and investigations are summarized in chronological order in section 2.0.



3-D TopoQuads Copyright © 1999 DeLorme Yarmouth, ME 04096 Source Data: USGS | 700 ft Scale: 1 : 24,000 Detail: 13-0 Datum: NAD27

Rice Operating Company ROC Since 1955	BD Jct. J-26 Site (AP-75) T21S - R37E - Section 26 - Unit J Lea County, New Mexico	Figure 1 Topographic Map

RICE OPERATING COMPANY ROC SINCE 1955

BD Jct. J-26 Site (AP-75)

T21S - R37E - Section 26 - Unit J

Lea County, New Mexico

Figure 2

Aerial Photo (2005)

GEOLOGY AND HYDROGEOLOGY

4.1 REGIONAL AND LOCAL GEOLOGY

The Jct. J-26 site is situated within the center of Monument Draw. According to published information (Nicholson and Clebsch, 1961, Barnes, 1976, and Anderson, Jones, and Green, 1997) the site is underlain by Quaternary Colluvial Deposits composed of sand, silt, and gravel deposited by slopewash, and talus from the Tertiary Ogallala Formation. These colluvial deposits are often calichified (indurated with cemented calcium carbonate) with caliche layers from 1 to 20 feet thick. The thickness of the colluvial deposits and Ogallala Formation is approximately 45 feet; however, it varies locally as a result of significant paleo-topography at the top of the underlying Triassic Dockum Group. Since Cretaceous Age rocks in the region have been removed by pre-Tertiary erosion, the alluvium and Ogallala Formation rest unconformably on the Triassic Dockum Group. The uppermost unit of the Dockum Group is the Chinle Formation, which primarily consists of micaceous red clay and shale but also contains thin interbeds of fine-grained sandstone and siltstone. The red clays and shale of the Chinle Formation act as an aquitard beneath the water bearing colluvial deposits/Ogallala Formation and therefore limit the amount of recharge to the underlying Dockum Group.

Based on the lithologic log descriptions provided by Trident Environmental the subsurface soils are composed of caliche with varying amounts of very fine to fine-grained sand in matrix (0-40 ft), calcareous fine to medium-grained sand (40-50 ft), and fine to medium-grained sand (50-60 ft). More detailed descriptions of the subsurface lithology are provided on the lithologic logs in Appendix A of the Stage 1 and 2 Abatement Plan.

4.2 REGIONAL AND LOCAL HYDROGEOLOGY

Potable groundwater used in southern Lea County is derived primarily from the Ogallala Formation and the Quaternary alluvium. Water from the Ogallala and alluvium aquifers in southern Lea County is used for irrigation, stock, domestic, industrial, and public supply purposes.

Based on the total depths of water wells in the area (85 feet) and the depth to groundwater (average of 40 feet bgs), the saturated thickness of the Ogallala Formation in the site area is estimated at approximately 45 feet.

Nicholsen and Clebsch (1961) found that the regional gradient of the Ogallala and interconnected colluvial aquifer in the site area generally flows toward the southeast and the hydraulic gradient varies from approximately 0.001 to 0.01 feet/feet.

Based on the recent depth to groundwater data from accessible wells located within a mile of the Jct. J-26 site the magnitude of the regional groundwater gradient is 0.003 feet/foot and the direction of flow is to the southeast (Figure 3). However, the local groundwater gradient in the more immediate area of the site has indicated magnitudes of 0.005 feet/foot or greater with direction of flow towards the south (Figure 4). The difference between the localized and regional gradient is attributed to the effect of the continual groundwater withdrawal from several nearby water supply wells that provide water for the Eunice Gas Plant. Based on records from the New Mexico Office of the State Engineer (NMSEO) these wells have been pumping at a combined rate of approximately 82 gallons per minute between July 6, 2005 and January 8, 2007. The groundwater withdrawal induces groundwater to flow from the site towards the water supply wells, which are located south (WW-5, WW-8, and WW12) and west (WW-1) of the site, as evidenced by a local groundwater gradient trending to the south (Figure 4) which differs from the regional gradient to the southeast (Figure 3).

No water wells are located within 1,000 feet of the site. A summary of active water wells located in the vicinity of the Jct. J-26 site are listed in Table 1 below. These wells are also depicted in Figure 3.

Table 1
Summary of Water Well Data

Well ID	Well Type/Use	T21S-R37E		Distance from Jct. J-26 Site
		Sec	UL	
WM-220	Windmill/Livestock	25	I	1,610 ft East
WW-1	Industrial Supply	26	K	2,100 ft West
WW-5	Industrial Supply	26	P	1,450 ft South
WW-8	Industrial Supply	26	P	1,960 ft South
WW-12	Industrial Supply	26	O	1,410 ft SSW

There are no surface water bodies located within a mile of the site.

5.0 GROUNDWATER QUALITY

5.1 REGIONAL GROUNDWATER CONDITIONS

Background concentrations of chlorides and TDS at the site have been confirmed through recent laboratory analysis of several surrounding wells and research of regional groundwater data. During the third quarter (August 1, 2006) access was granted for a one-time monitoring event (depth to water measurements and chloride and TDS analysis) for the following wells:

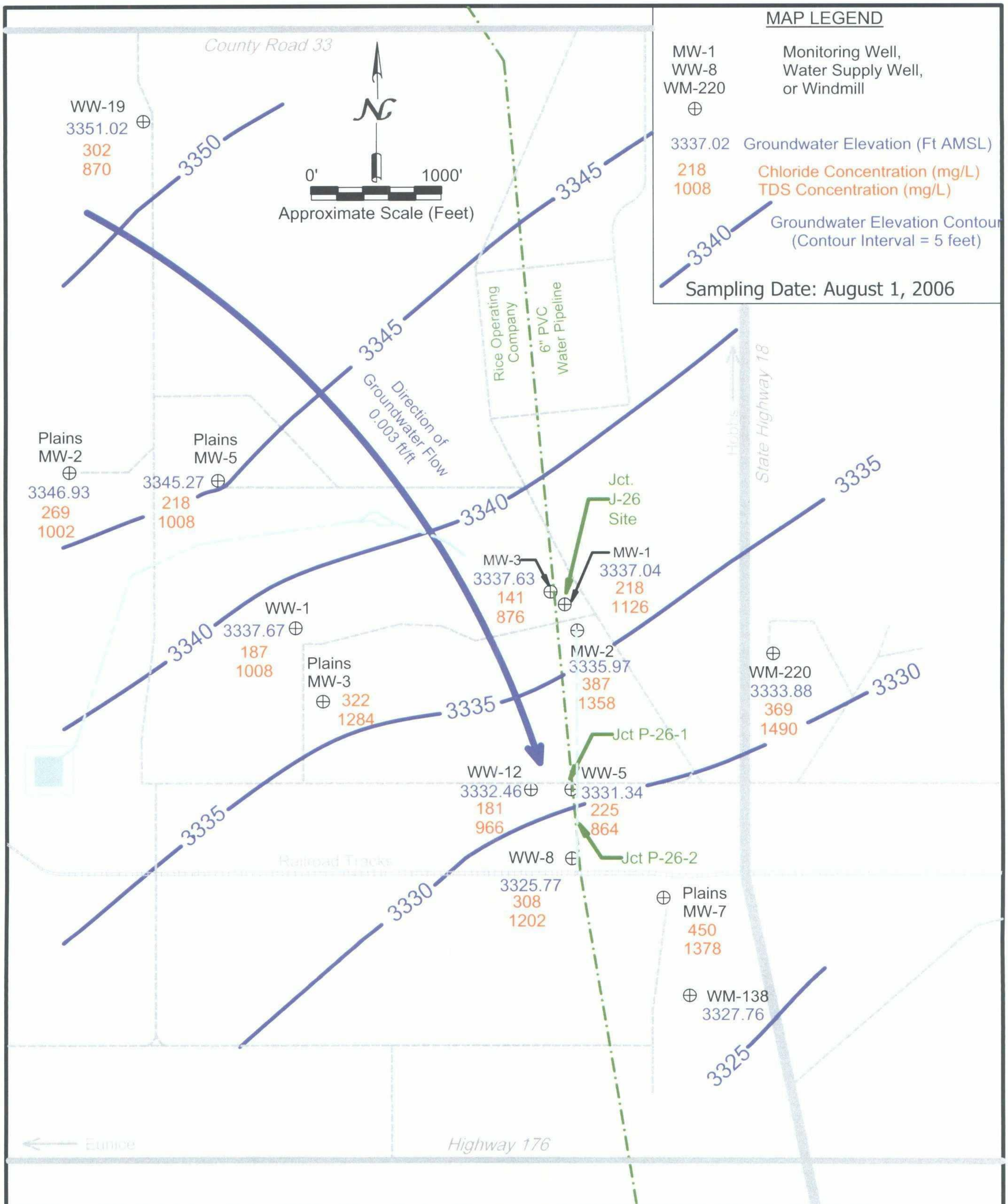
- Eunice Gas Plant water supply wells (WW-1, WW-5, WW-8, WW-12, WW-19).
- One monitoring well at each of four nearby Plains Petroleum monitoring sites.
- One windmill (L-0220)

Results of this one time sampling event are summarized in Table 2 below and depicted in Figure 3. A copy of the laboratory analytical reports and chains of custody form are included in Appendix D.

Table 2
Regional Groundwater Sampling Results (August 1, 2006)

Well ID	Well Type/Use	Site Name	Depth to Groundwater (feet BTOC)	Chloride (mg/L)	TDS (mg/L)
MW-1	Monitoring	Jct. J-26	38.80	218	1126
MW-2	Monitoring	Jct. J-26	39.35	387	1358
MW-3	Monitoring	Jct. J-26	38.22	141	876
WM-220	Windmill	L-0220	37.49	369	1490
MW-3	Monitoring	DH Gathering	45.52	322	1284
MW-7	Monitoring	Vacuum to Jal 14" Mainline#3	49.04	450	1378
MW-2	Monitoring	TNM 98-5B	47.82	269	1002
MW-5	Monitoring	TNM 98-5A	46.26	218	1008
WW-1	Industrial	Eunice Gas Plant	49.32	187	1008
WW-5	Industrial	Eunice Gas Plant	48.11	225	864
WW-8	Industrial	Eunice Gas Plant	51.00	308	1202
WW-12	Industrial	Eunice Gas Plant	49.28	181	966
WW-19	Abandoned	Eunice Gas Plant	47.28	302	870
Average (Background) Chloride and TDS Concentrations				275	1110

Based on the sampling results listed in the table above average (background) chloride and TDS concentrations in section 26 have ranged from 141 mg/L to 450 mg/L and 870 mg/L to 1,490 mg/L, respectively.



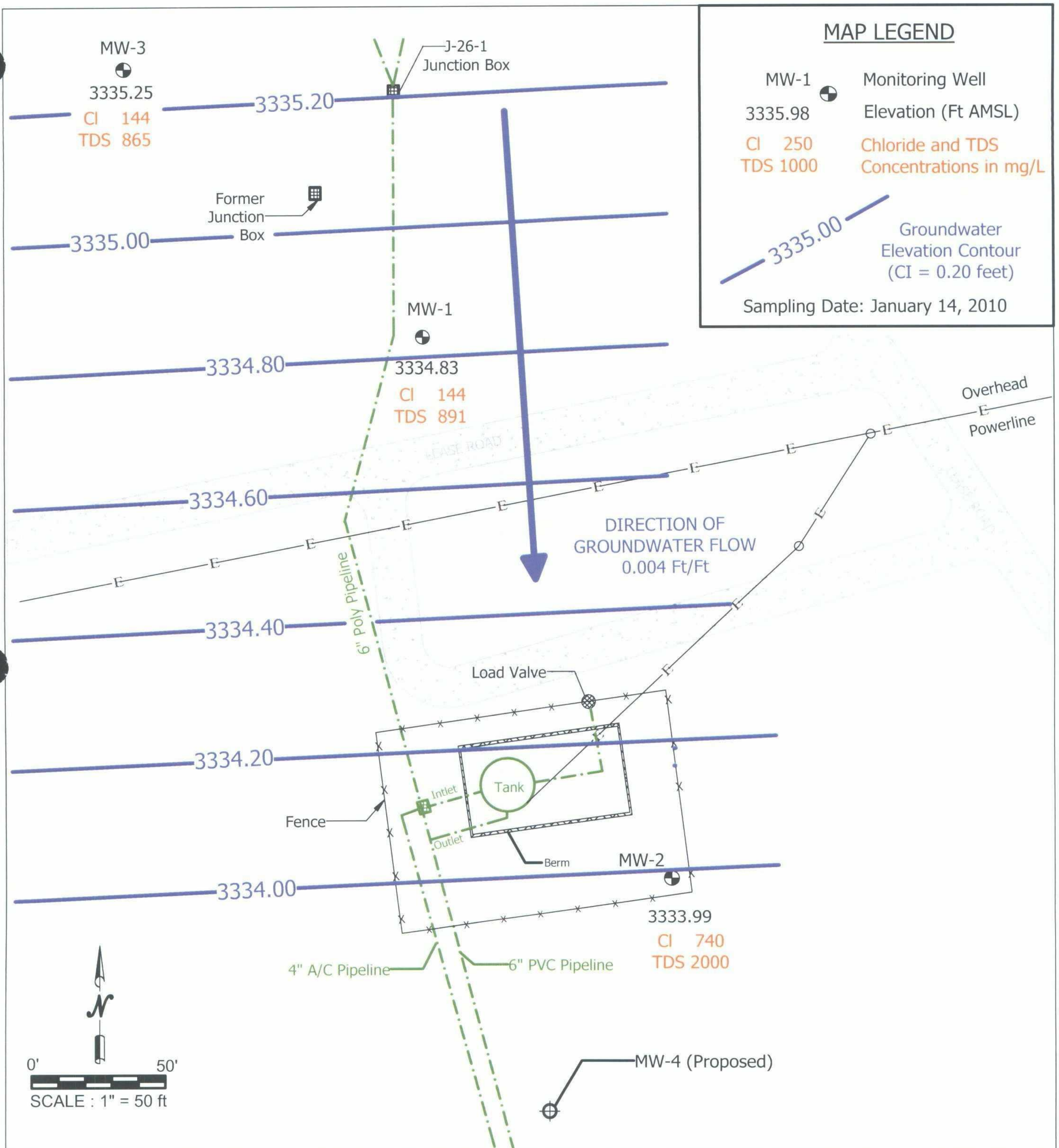
RICE OPERATING COMPANY ROC SINCE 1955	BD Jct. J-26 Site (AP-75) T21S - R37E - Section 26 - Unit J Lea County, New Mexico	Figure 3 Regional Groundwater Gradient & Chloride/TDS Concentration Map

5.2 Site Groundwater Conditions

The on site monitoring wells at the Jct. J-26 site have been sampled on a quarterly basis for major ions, TDS, and benzene, toluene, ethylbenzene, and xylenes (BTEX). A complete summary of historical analytical results and groundwater elevations are listed in Tables 3, 4, and 5. Each constituent of BTEX has been below the New Mexico Water Quality Control Commission (WQCC) standards at this site since the installation of monitoring well MW-1 in October 2002 (18 consecutive quarters).

The highest chloride (4,520 mg/L) and TDS (9,020 mg/L) concentrations in MW-1 were observed during the first sampling event on October 29, 2002. The decreased chloride and TDS concentrations observed in MW-1, as shown in the graph below, can be attributed to the excavation activities (source removal) and the effect of groundwater withdrawal from the industrial water wells that supply process water for the Eunice Gas Plant. The groundwater withdrawal induces groundwater to flow from the site towards the water supply wells, which are located south (WW-5, WW-8, and WW-12) and west (WW-1) of the site and thus has assisted in the removal of any remnant chloride/TDS mass from the area of the Jct. J-26 site. Further evidence for this conclusion is supported by the fate and transport modeling simulations as explained in the following section.

There is no longer a threat of impact from the vadose zone at this site because of the excavation, source removal, and backfilling with an infiltration barrier over the former source area near MW-1 that was completed in 2002. The surrounding area was re-seeded with a mixture of native grasses and plants which has resulted in the re-establishment of native vegetation as depicted on the cover page photo of this report. ROC has been monitoring the site for continued healthy growth of native vegetation.



RICE OPERATING COMPANY ROC SINCE 1955	BD Jct. J-26 Site (AP-75) T21S - R37E - Section 26 - Unit J Lea County, New Mexico	Figure 4 Current Groundwater Conditions and Proposed Well Location

Table 3

Historical Groundwater Sampling Results

Monitoring Well	Sample Date	Depth to Groundwater (feet BTOC)	Groundwater Elevation (feet AMSL)	Chloride (mg/L)	TDS (mg/L)	Benzene (mg/L)	Toluene (mg/L)	Ethylbenzene (mg/L)	Xylene (mg/L)
MW-1	10/29/02	43.02	3332.82	**4520**	**9020**	< 0.001	< 0.001	< 0.001	< 0.001
	02/28/03	42.33	3333.51	**3470**	**6870**	< 0.001	< 0.001	< 0.001	< 0.001
	06/05/03	42.52	3333.32	**1460**	**3280**	< 0.001	< 0.001	< 0.001	< 0.001
	08/22/03	43.72	3332.12	**957**	**2620**	< 0.001	< 0.001	< 0.001	< 0.001
	10/30/03	43.91	3331.93	**620**	**2040**	< 0.001	< 0.001	< 0.001	< 0.001
	02/18/04	43.70	3332.14	**478**	**1630**	< 0.001	< 0.001	< 0.001	< 0.001
	05/05/04	40.80	3335.04	**390**	**1440**	< 0.001	< 0.001	< 0.001	< 0.001
	08/10/04	37.02	3338.82	195	**1080**	< 0.001	< 0.001	< 0.001	< 0.001
	11/09/04	36.61	3339.23	177	**1100**	< 0.001	< 0.001	< 0.001	< 0.001
	02/09/05	36.62	3339.22	179	**1090**	< 0.001	< 0.001	< 0.001	< 0.001
	05/05/05	37.00	3338.84	179	**1060**	< 0.001	< 0.001	< 0.001	< 0.001
	08/13/05	37.56	3338.28	193	**1000**	< 0.001	< 0.001	< 0.001	< 0.001
	11/07/05	37.98	3337.86	233	**1020**	< 0.001	< 0.001	< 0.001	< 0.001
	02/06/06	38.39	3337.45	**262**	**1080**	< 0.001	< 0.001	< 0.001	< 0.001
	05/08/06	38.55	3337.29	**282**	**1140**	< 0.001	< 0.001	< 0.001	< 0.001
	08/01/06	38.80	3337.04	218	**1126**	< 0.001	< 0.001	< 0.001	< 0.001
	10/23/06	39.21	3336.63	193	**1010**	---	---	---	---
	02/08/07	39.52	3336.32	182	912	---	---	---	---
	04/18/07	39.66	3336.18	161	898	---	---	---	---
	07/18/07	39.86	3335.98	149	900	---	---	---	---
	10/10/07	40.07	3335.77	160	915	---	---	---	---
	01/14/08	40.35	3335.49	152	904	---	---	---	---
	04/04/08	40.41	3335.43	140	890	---	---	---	---
	07/15/08	40.44	3335.40	132	907	---	---	---	---
	10/08/08	40.76	3335.08	128	952	---	---	---	---
	01/16/09	41.01	3334.83	136	890	---	---	---	---
	04/13/09	40.94	3334.90	140	899	---	---	---	---
	07/14/09	41.07	3334.77	144	893	---	---	---	---
	10/13/09	41.02	3334.82	148	911	---	---	---	---
	01/14/10	41.01	3334.83	144	891	---	---	---	---
			WQCC Standards:	250	1000	0.01	0.75	0.75	0.62

Chloride, TDS, and Groundwater Elevation Values Versus Time (MW-1)

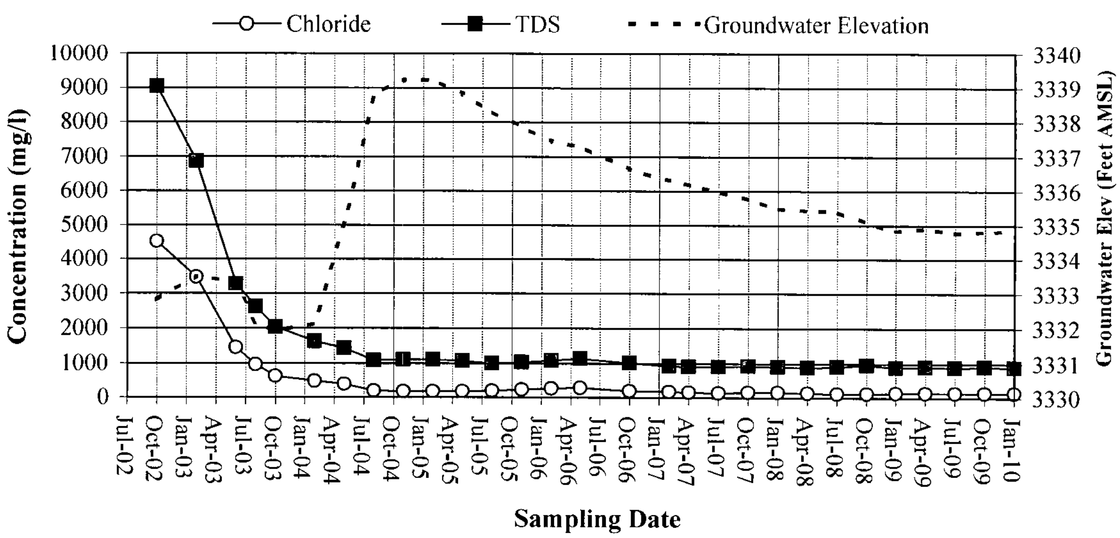


Table 4

Historical Groundwater Sampling Results

Monitoring Well	Sample Date	Depth to Groundwater (feet BTOC)	Groundwater Elevation (feet AMSL)	Chloride (mg/L)	TDS (mg/L)	Benzene (mg/L)	Toluene (mg/L)	Ethylbenzene (mg/L)	Xylene (mg/L)
MW-2	08/22/03	43.99	3331.33	239	**1180**	< 0.001	< 0.001	< 0.001	< 0.001
	10/30/03	44.17	3331.15	239	**1240**	< 0.001	< 0.001	< 0.001	< 0.001
	02/18/04	43.91	3331.41	221	**1150**	< 0.001	0.001	< 0.001	< 0.001
	05/05/04	40.98	3334.34	204	**1060**	< 0.001	0.001	< 0.001	< 0.001
	08/10/04	37.14	3338.18	230	**1120**	< 0.001	< 0.001	< 0.001	< 0.001
	11/09/04	36.99	3338.33	230	**1120**	< 0.001	< 0.001	< 0.001	< 0.001
	02/09/05	37.03	3338.29	**294**	**1220**	< 0.001	< 0.001	< 0.001	< 0.001
	05/06/05	37.46	3337.86	**257**	**1210**	< 0.001	< 0.001	< 0.001	< 0.001
	08/13/05	38.02	3337.30	237	**1180**	< 0.001	< 0.001	< 0.001	< 0.001
	11/07/05	38.44	3336.88	206	**1130**	< 0.001	< 0.001	< 0.001	< 0.001
	02/06/06	38.83	3336.49	**250**	**1090**	< 0.001	< 0.001	< 0.001	< 0.001
	05/08/06	39.02	3336.30	**332**	**1500**	< 0.001	< 0.001	< 0.001	< 0.001
	08/01/06	39.35	3335.97	**387**	**1358**	< 0.001	< 0.001	< 0.001	< 0.001
	10/23/06	39.71	3335.61	**395**	**1370**	---	---	---	---
	02/08/07	40.03	3335.29	**378**	**1220**	---	---	---	---
	04/18/07	40.09	3335.23	**446**	**1380**	---	---	---	---
	07/18/07	40.30	3335.02	**679**	**1720**	---	---	---	---
	10/10/07	40.52	3334.80	**730**	**1838**	---	---	---	---
	01/14/08	40.74	3334.58	**810**	**2061**	---	---	---	---
	04/04/08	40.80	3334.52	**860**	**2470**	---	---	---	---
	07/15/08	40.84	3334.48	**600**	**2270**	---	---	---	---
	10/08/08	41.20	3334.12	**730**	**2470**	---	---	---	---
	01/16/09	41.39	3333.93	**710**	**1960**	---	---	---	---
	04/13/09	41.30	3334.02	**670**	**1890**	---	---	---	---
	07/14/09	41.42	3333.90	**690**	**2030**	---	---	---	---
	10/13/09	41.31	3334.01	**720**	**2010**	---	---	---	---
	01/14/10	41.33	3333.99	**740**	**2000**	---	---	---	---
			WQCC Standards:	250	1000	0.01	0.75	0.75	0.62

Chloride, TDS, and Groundwater Elevation Values Versus Time (MW-2)

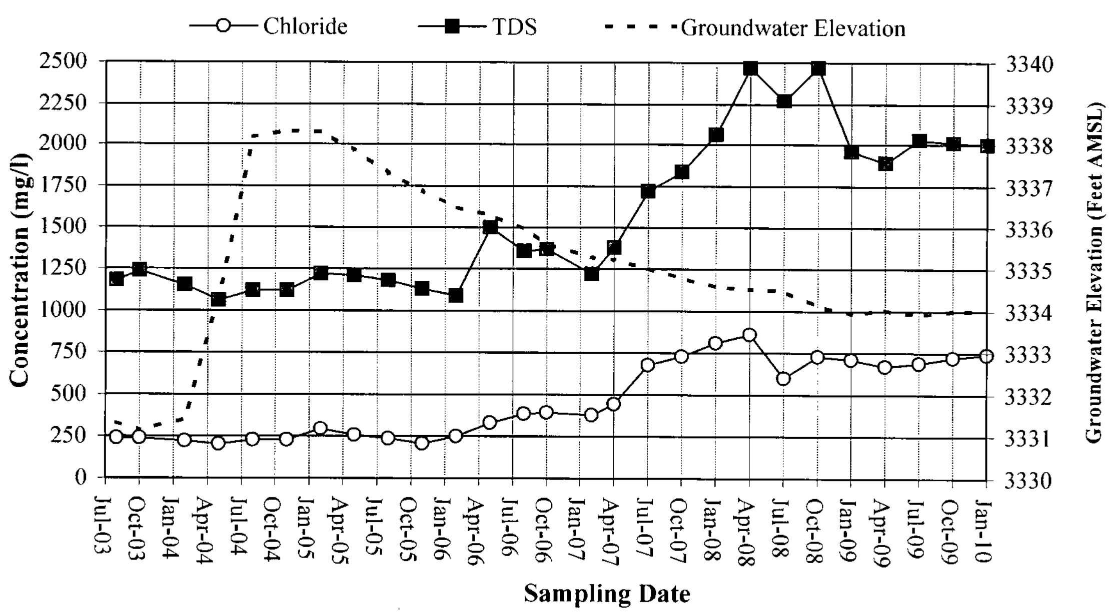
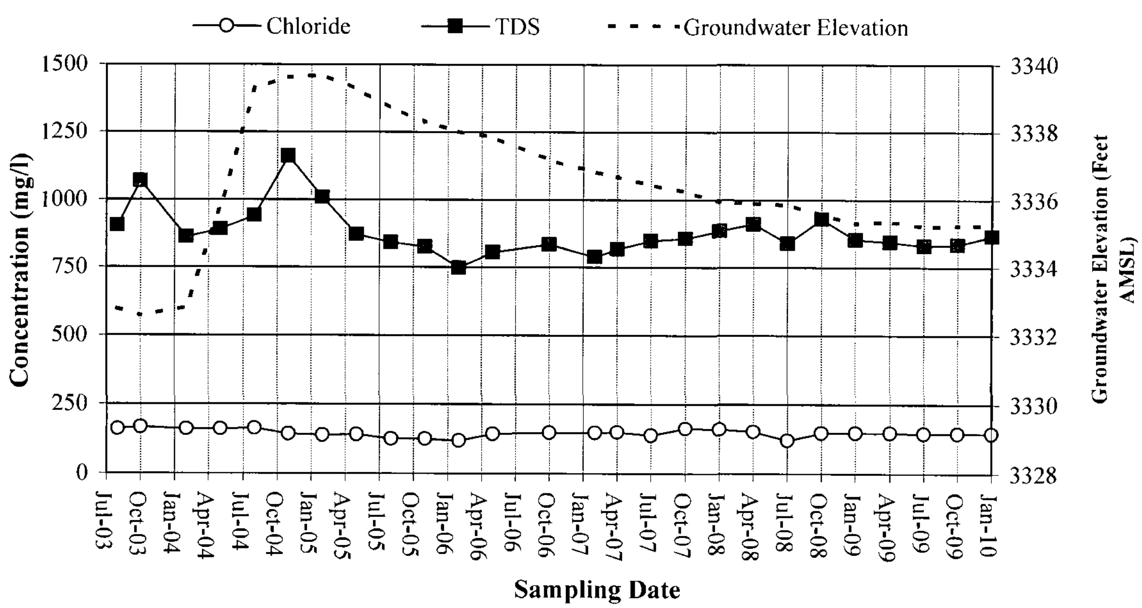


Table 5

Historical Groundwater Sampling Results

Monitoring Well	Sample Date	Depth to Groundwater (feet BTOC)	Groundwater Elevation (feet AMSL)	Chloride (mg/L)	TDS (mg/L)	Benzene (mg/L)	Toluene (mg/L)	Ethylbenzene (mg/L)	Xylene (mg/L)
MW-3	08/22/03	43.06	3332.79	160	904	< 0.001	< 0.001	< 0.001	< 0.001
	10/30/03	43.28	3332.57	168	**1070**	< 0.001	< 0.001	< 0.001	< 0.001
	02/18/04	43.03	3332.82	160	862	< 0.001	< 0.001	< 0.001	< 0.001
	05/05/04	40.04	3335.81	160	891	< 0.001	< 0.001	< 0.001	< 0.001
	08/10/04	36.55	3339.30	164	941	< 0.001	< 0.001	< 0.001	< 0.001
	11/09/04	36.22	3339.63	142	**1160**	< 0.001	< 0.001	< 0.001	< 0.001
	02/09/05	36.17	3339.68	138	**1010**	< 0.001	< 0.001	< 0.001	< 0.001
	05/06/05	36.56	3339.29	141	870	< 0.001	< 0.001	< 0.001	< 0.001
	08/13/05	37.12	3338.73	125	842	< 0.001	< 0.001	< 0.001	< 0.001
	11/07/05	37.55	3338.30	125	826	< 0.001	< 0.001	< 0.001	< 0.001
	02/06/06	37.84	3338.01	119	748	< 0.001	< 0.001	< 0.001	< 0.001
	05/08/06	38.00	3337.85	142	806	< 0.001	< 0.001	< 0.001	< 0.001
	08/01/06	38.22	3337.63	141	876	< 0.001	< 0.001	< 0.001	< 0.001
	10/23/06	38.68	3337.17	147	834	---	---	---	---
	02/08/07	39.01	3336.84	147	788	---	---	---	---
	04/18/07	39.16	3336.69	150	818	---	---	---	---
	07/18/07	39.40	3336.45	139	848	---	---	---	---
	10/10/07	39.60	3336.25	164	857	---	---	---	---
	01/14/08	39.90	3335.95	160	886	---	---	---	---
	04/04/08	39.95	3335.90	152	911	---	---	---	---
	07/15/08	39.99	3335.86	120	840	---	---	---	---
	10/08/08	40.27	3335.58	148	929	---	---	---	---
	01/16/09	40.54	3335.31	148	853	---	---	---	---
	04/13/09	40.50	3335.35	148	844	---	---	---	---
	07/14/09	40.63	3335.22	144	831	---	---	---	---
	10/13/09	40.61	3335.24	144	835	---	---	---	---
	01/14/10	40.60	3335.25	144	865	---	---	---	---
			WQCC Standards:	250	1000	0.01	0.75	0.75	0.62

Chloride, TDS, and Groundwater Elevation Values Versus Time (MW-3)



6.0 FATE AND TRANSPORT MODELING RESULTS

6.1 FATE AND TRANSPORT MODELING

As proposed in the NMOCD-approved Stage 1 and 2 Abatement Plan, fate and transport model simulations were performed to forecast the movement and attenuation of the chloride plume by dispersion and abatement by the water supply wells. Simulations were conducted with the two-dimensional groundwater flow and contaminant transport model WinTran, version 1.03 (1995) designed and distributed by Environmental Simulations, Inc. WinTran is built around a steady-state analytical element flow model, which is uniquely linked to a finite element contaminant transport model. A detailed description of the modeling procedure, parameter inputs, and the simulated results are provided in Appendix A. The features, equations, and benchmarking documentation are included in Appendix B.

The fate and transport model simulations demonstrate how chloride concentrations in the center of the plume will decrease to background levels by the year 2047 as the mass of the plume is captured by the water supply wells and does not migrate beyond them. The results of the fate and transport modeling simulations support the conclusion that the chloride plume is not likely to impact any drinking water, livestock, municipal, or irrigation water supplies, the closest of which is a windmill (NM File No. CP-220) located approximately 1,610 feet east of the Jct. J-26 site. This windmill, which is used for livestock watering, is cross-gradient from the junction box and, therefore not in the direct path of the simulated plume.

7.0 AMENDED STAGE 2 ABATEMENT PLAN

Since July 2004, chloride and TDS concentrations at the Jct. J-26 site have generally remained at or near background levels in each of the three on site monitoring wells. Chloride and TDS concentrations in downgradient monitoring well MW-2 have exhibited a slight increase over background levels in the most recent quarter; however, that is consistent with the modeling simulations as described in Appendix A. The fate and transport modeling simulates chloride concentrations in MW-2 peaking at 737 mg/L in year 2009 and then resume a decreasing trend.

On February 13, 2008 (Appendix E) the NMOCD requested via email communication for ROC to install additional monitoring wells and a groundwater recovery system downgradient of the BD Jct. J-26 Site. ROC proposes to utilize the additional downgradient monitoring well (MW-4) for groundwater recovery after first confirming that the groundwater resource in the area will achieve the highest environmental benefit via a groundwater extraction system.

7.1 PROPOSED MONITORING/RECOVERY WELL INSTALLATIONS

ROC will install one downgradient monitoring well (MW-4) about 75 feet south of the bermed SWD collection facility as shown in Figure 4. Based on historical groundwater flow directions, this proposed location is directly downgradient from the former junction box and pump station. The proposed well will be constructed of 4-in diameter well casing and screen for potential use as a groundwater recovery well. The well will be installed and sampled after appropriate development using methods consistent with industry standards (ASTM, EPA).

7.2 SOURCE REMOVAL TESTING AND PROPOSED ABATEMENT OPTIONS

A three month source removal and test pumping program, utilizing monitoring well MW-4, is proposed to determine if groundwater can be improved within a short period of time and assist in the evaluation of groundwater abatement options. Water from the recovery activities will be utilized for pipeline and well maintenance operations.

Upon completion of the three month source removal and test pumping activities, ROC will submit the results to the NMOCD and propose a long-term groundwater remedy based on an evaluation of alternatives that provide the best abatement option.

7.3 SCHEDULE OF ACTIVITIES

1. Install downgradient monitoring well as proposed in section 7.1 after OCD approval.
2. Commence groundwater testing program as proposed in section 7.2.
3. Submit notices of activities to NMOCD.
4. Implement a NMOCD-approved groundwater remedy if warranted.
5. At the completion of corrective actions, a final report will be submitted to the NMOCD with a request for termination of the Part 30 regulatory file associated with this site.

APPENDIX A

Description of Fate and Transport Modeling Procedures and Parameter Inputs

Conceptual Model

Produced water containing high concentrations of chloride, and resultant high levels of total dissolved solids (TDS), reportedly leaked from the J-26 junction box. Extrapolating from current conditions for decades into the future, taking account of both advective flow and attenuation by hydrodynamic dispersion, enables prediction of the probable distance that the residual plume will travel as well as the gradually declining concentrations in the plume.

Basic Site Data

Information about site conditions was obtained from data collected by Rice Operating Company and Trident Environmental. This included lithologic records from well installations, water level data, and water quality analytical results.

Simulation Model

Simulations were conducted with the two-dimensional groundwater flow and contaminant transport model WinTran, version 1.03 (1995) designed and distributed by Environmental Simulations, Inc. (ESI) of Herndon, Virginia. WinTran is built around a steady-state analytical element flow model, linked to a finite element contaminant transport model. The Windows interface allows for rapid data input, processing, parameter manipulation and optimization, and output in multiple formats. The fundamental mathematics of the model solutions, model verification (benchmarked against MODFLOW), and use of WinTran is documented in the "Guide to Using WinTran" published by ESI.

Base Map

A simplified site base map, edited with TurboCAD (Version 12), was exported to a universal drawing exchange file (DXF) file format. The DXF base map was imported into WinTran, which preserves the original units of measurement.

Model Input Parameters

The following table lists the various parameters input into the fate and transport model simulations.

Parameter	Value	Source of Data
Hydraulic Conductivity (K_x, K_y, K_z)	4.4 ft/day (1.2E-03 cm/sec)	Aquifer test (Appendix C)
Hydraulic Gradient	0.003 ft/ft	Observed and measured
Gradient Direction	56° south of due east (SE)	Observed and measured
Longitudinal Dispersivity	328 ft	Estimated plume length (2002)
Transverse Dispersivity	32.8 ft	One-tenth of longitudinal
Porosity	0.25	Professional judgement
Base elevation of aquifer	3250 ft AMSL	Observed and measured
Depth to groundwater	40 ft	Observed and measured
Saturated thickness	45 ft	Observed and measured
Model X Extent (100 nodes)	2.5 miles	Professional judgement
Model Y Extent (100 nodes)	2.5 miles	Professional judgement
Coefficient of molecular diffusion	0.34 ft^2/yr (1.0E-07 cm^2/sec)	Bear and Verruijt (1987)

Flow Parameters

Input requirements for the steady-state groundwater flow simulation include: hydraulic gradient and direction of flow, hydraulic conductivity, aquifer top and bottom elevations, and reference head. The values used were based on the following sources:

- Hydraulic gradient – measured gradient of 0.003 feet/foot based on historical site measurements.
- Direction of flow – measured direction of approximately 56° south of due east (SE) based on past local and current regional measurements.
- Hydraulic conductivity – This is one of the most critical parameters used for any fate and transport modeling effort, and the various published values researched range widely from less than 2 ft/day to 200 ft/day. Therefore an aquifer test was performed at two nearby industrial water supply wells (WW-1 and WW-5) to determine the most accurate site-specific value. A hydraulic conductivity of 4.4 ft/day was determined by performing a Cooper-Jacob analysis of the recovery data, and a program from USGS Open-File 02-197 (Keith Halford, 2002). Documentation of the aquifer test procedures, results, and USGS program is included in Appendix C).
- Aquifer top and bottom elevations – bottom elevation of Ogallala Formation at 3250 feet based on published information (Nicholson & Clebsch, 1961). The top elevation for an unconfined aquifer must be greater than the reference head. An elevation of 3400 feet was assumed.
- Reference head – measured unconfined head of 3345 feet located upgradient of the site so as not to be influenced by pumping wells during modeling simulations.

Transport Parameters

Input requirements for the contaminant transport numerical simulation include: longitudinal and transverse dispersivity, porosity, diffusion coefficient, contaminant half-life, and retardation coefficient. The values used were based on the following sources:

- Longitudinal and transverse dispersivity – Longitudinal dispersivity represents the spreading of the contaminant plume in the direction of groundwater flow. The transverse component represents spreading perpendicular to the flow direction. Dispersivity is a scale-dependent parameter which is generally larger as the scale of the contaminant plume increases. Fetter (1993, Section 2.11, pp. 71-77) notes the apparent scale-dependency of longitudinal dispersivity, which typically may be about 0.1 times the flow length. However, values of dispersivity reported in the literature generally range from 1 to 100 percent of the problem scale (Gelhar, 1986). For the current site scale, a conservative value of 328 feet (100 meters) was selected for longitudinal dispersivity. A value of 32.8 feet (i.e., 10 meters, or one-tenth of the longitudinal value) was selected for transverse dispersivity. These conservative values also minimized modeling transport errors.

- Porosity – no site measurements were available; therefore a literature value based on saturated zone lithology was selected. Typical lithology is described as silty sand and very fine sand. A range of 0.25 to 0.50 is typically given for unconsolidated "sand" (e.g., Freeze & Cherry, 1979, Table 2.4, p. 37); however, the Ogallala Formation is predominantly very fine grained, compacted and partly cemented, and may also fit within the range of 0.05 to 0.30 for sandstone. Fetter (1988, Table 4.3 and Figure 4.10, pp. 74-75) cites an average value of 0.20 for the specific yield of very fine sands. Specific retention of silty fine sand is approximately 0.05, for a total porosity of 0.25, which is the value selected for the transport modeling. WinTran uses the porosity term to estimate groundwater velocity, and actually requires an effective porosity value. Fetter (1988, Section 4.4, pp. 84-85) notes that pores of most sediments down to clay size are interconnected and that the effective porosity is virtually equal to the total porosity.

- Diffusion coefficient – occurs when a contaminant spreads in water due to concentration gradients. That is, dissolved contaminants will spread in water from areas of high concentration to areas of lower concentration. This process is caused by random movement of molecules in a fluid. The coefficient of molecular diffusion (or simply the diffusion coefficient) is expressed in units of L^2/T (e.g., cm^2/s) and is often assumed to equal zero in advective-dominated transport. Only in very slow-moving groundwater is diffusion important. Bear and Verruijt (1987) estimate the diffusion coefficient to be approximately 1 x 10-5 cm^2/s (0.34 ft^2/yr) in dilute systems.

- Contaminant half-life – this parameter accounts for chemical decay (e.g., radioisotopes, biological transformation of organic molecules); however, the species of interest in the present case are inorganic ions (chloride) and are not expected to decay to any appreciable extent. A conservative value of 1000 years was used, which produces a negligible decay coefficient of less than 0.001 yr^{-1}.

- Retardation coefficient – this parameter accounts for sorption processes that slow the movement of contaminants relative to the groundwater velocity. Inorganic ions such as chloride are commonly taken as conservative tracers in groundwater and are not considered to be retarded; therefore, a value of 1.0 was selected for the retardation coefficient.

Flow Model Calibration

The vicinity of the site where water level measurements were recorded between October 2002 and August 2006 is simulated closely by the flow model.

Transport Model Calibration

The objective of the transport modeling was to first obtain a plume configuration with concentration values that closely match current observed values. This was done by importing a grid file created from an isopleth map using Surfer (version 6.04) contouring program, producing the configuration and constituent concentration distribution observed in October 2002 at the completion of the upgrade of the junction box. The model again ran for 4 years (2002 to 2006) after entering in the known concentrations at each of the three monitoring wells and other area wells (gas plant water recovery wells and two monitoring wells from nearby Plains Petroleum sites, and a windmill east-southeast of the site).

Simulation of Fate and Transport

After model calibration, estimation of the fate and transport of chlorides was then achieved by restarting the transport model from the end of 2006 by retaining the distribution of contaminant mass and projecting into the future. Hydrodynamic dispersion serves to broaden the dimensions of the plume while reducing the concentrations in the middle of the plume. Advective flow moves the center of plume mass downgradient (southeast) while the groundwater withdrawal from the industrial supply wells directs the plume in a more southerly direction. Water supply wells WW-1 and WW-12 cause further dilution of the plume by directing the chloride mass transverse to the natural gradient direction. Similarly water supply wells WW-5 and WW-8 direct the chloride mass in a southerly direction. Various time increments were input to show the fate and transport of the chloride mass over a 41 year period (Years 2006 through 2047) after which the chloride plume center attenuated to a concentration of 276 mg/L (background conditions). Results of the fate and transport modeling output (Years 2010, 2015, 2020, 2025, 2030, 2035, 2040 and 2047) are depicted on site maps in the pages that follow.

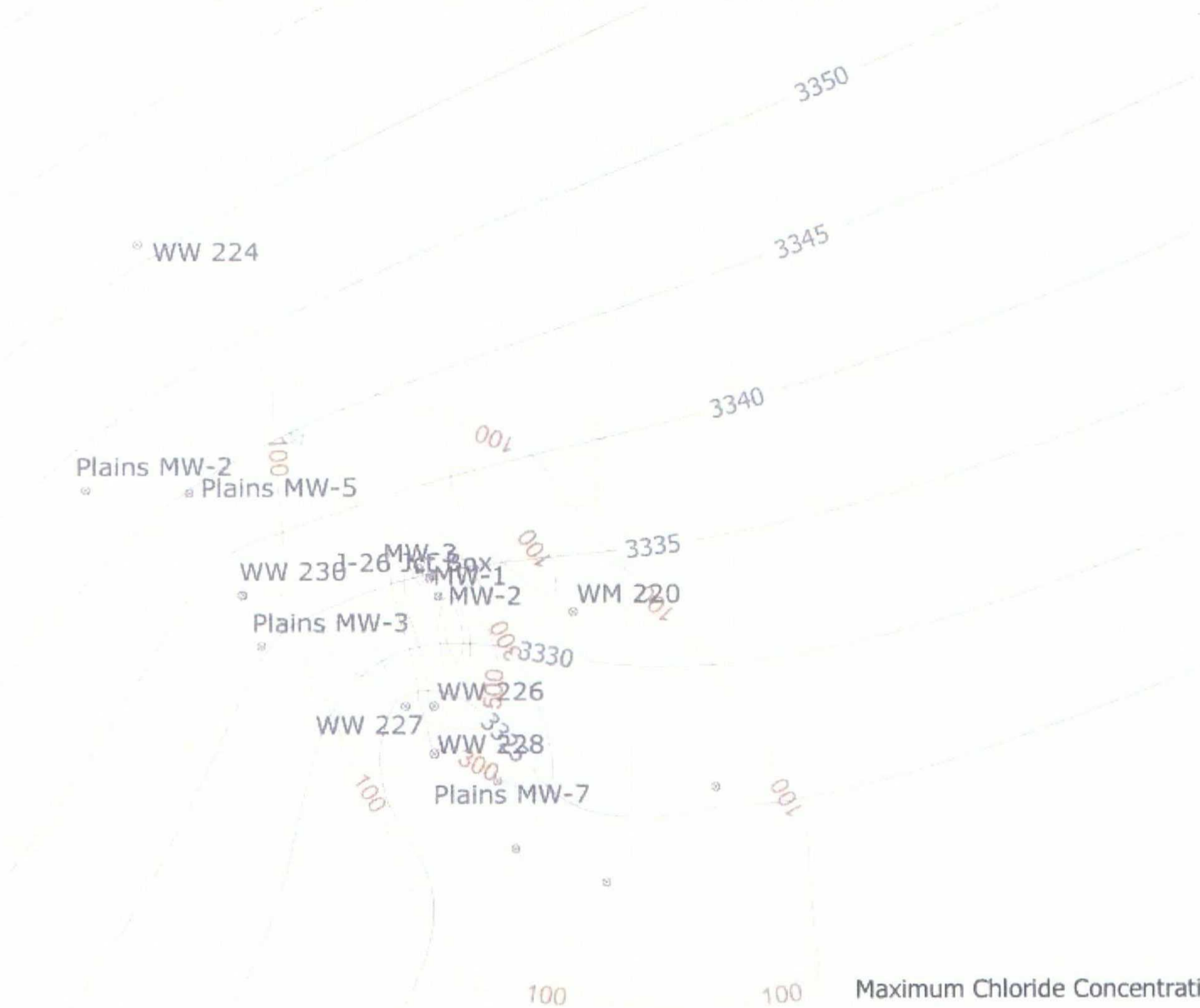
For a hydraulic conductivity value of 4.4 ft/day the resultant average velocity is 14.9 ft/yr based on the darcy expression: $v = (k \cdot i) / n$, where k is the hydraulic conductivity (ft/yr), i is the hydraulic gradient (ft/ft), and n is the effective porosity (unitless). The center of the modeled plume moves at a greater rate (22.8 ft/yr) over successive time intervals than the average groundwater velocity based on Darcy's law, due to the added effect of dispersion and the capture effect from the water supply wells.

The fate and transport model simulations demonstrate how chloride concentrations in the center of the plume will decrease to background levels by the year 2047 as the mass of the plume is captured by the water supply wells. These results strongly support the evidence that the chloride plume is not likely to impact any existing sources of water supply, the closest of which is a windmill (NM File No. CP-220) located approximately 1,610 feet east of the Jct. J-26 site. This windmill, which is used for livestock watering, is cross-gradient from the junction box and, therefore not in the direct path of the simulated plume.

Continued operation of the water supply wells is essential in maintaining the operation of the Eunice Gas Plant. The withdrawal of groundwater by several of these wells has resulted in redirecting and recovery of residual chloride and TDS constituents from the Jct. J-26 site. In addition, the fate and transport modeling simulations show the capture effects of the water supply wells and natural dispersion in attenuating chloride and TDS constituents.

It is not necessary to simulate the fate and transport of TDS because those concentrations are closer to meeting background concentrations in comparison with chloride values. In other words, the standard for TDS concentrations will be met before those for chloride concentrations.

BD J-26 Junction Box Site
WinTran Fate & Transport Modeling Results

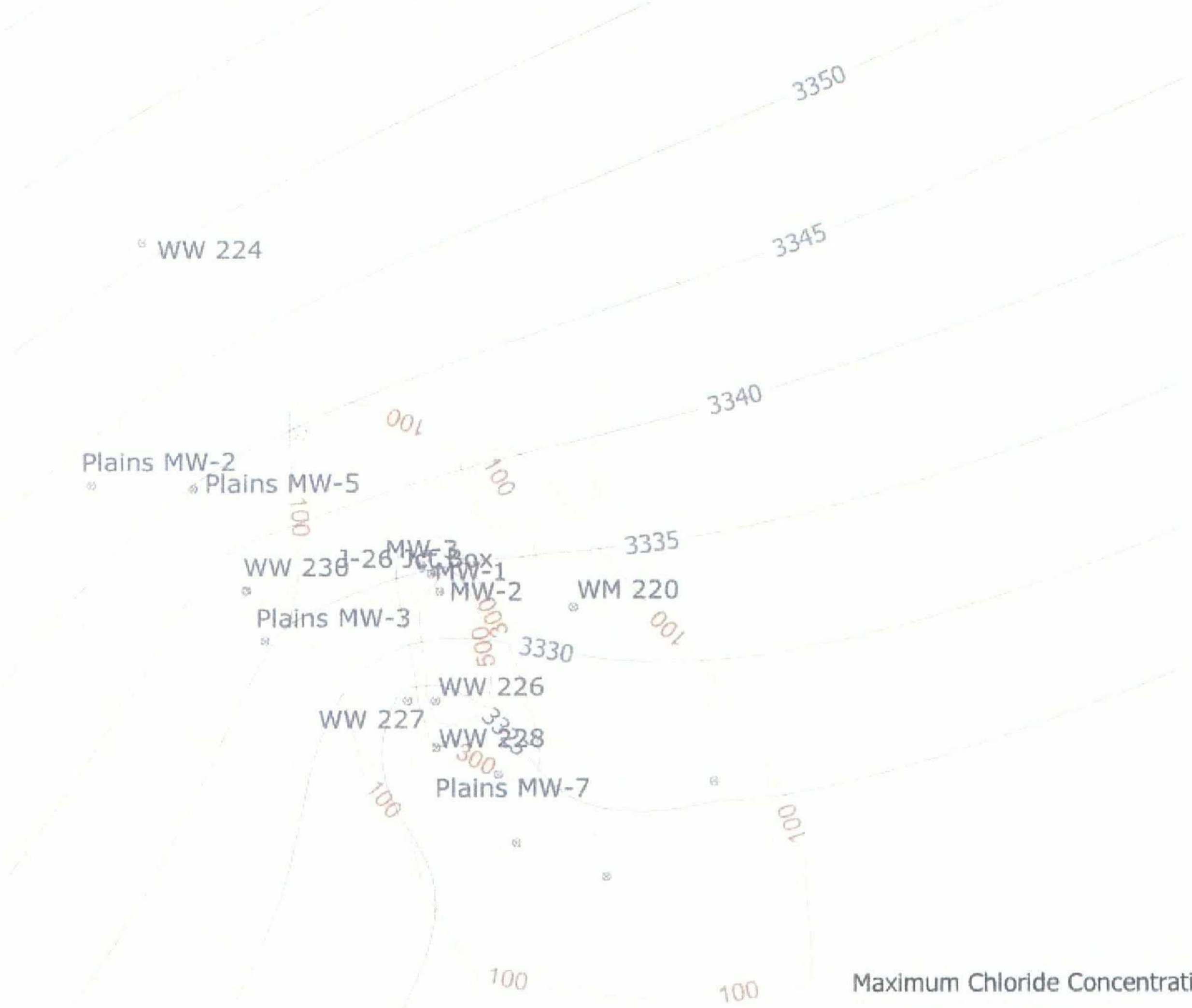


Maximum Chloride Concentration
(Center of Plume)
1089 mg/L

Estimated Conditions for Year 2010

Modeling Assumptions
Hydraulic Conductivity = 1600 ft/yr (4.4 ft/day)
Hydraulic Gradient = 0.003 ft/ft (SE)
Longitudinal Dispersivity = 328 ft
Transverse Dispersivity = 32.8 ft
Diffusion Coeficient = 0.3349 ft2/day
Porosity = 0.25 percent
Aquifer Bottom at 3250 ft AMSL
Imported Surfer Initial WinTran 2002.grd

BD J-26 Junction Box Site
WinTran Fate & Transport Modeling Results



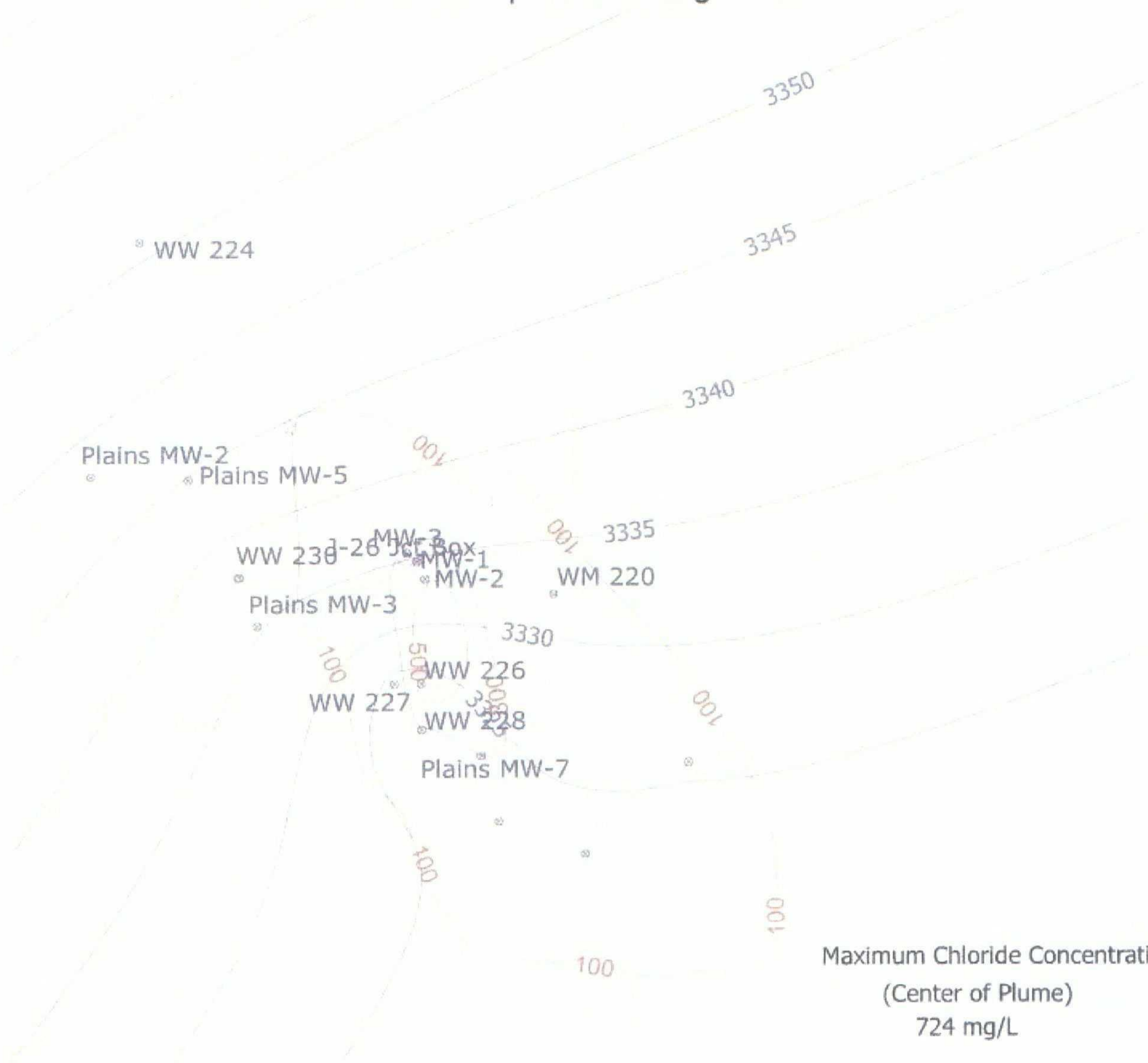
Maximum Chloride Concentration
(Center of Plume)
878 mg/L

5280 feet

Estimated Conditions for Year 2015

Modeling Assumptions
Hydraulic Conductivity = 1600 ft/yr (4.4 ft/day)
Hydraulic Gradient = 0.003 ft/ft (SE)
Longitudinal Dispersivity = 328 ft
Transverse Dispersivity = 32.8 ft
Diffusion Coeficient = 0.3349 ft2/day
Porosity = 0.25 percent
Aquifer Bottom at 3250 ft AMSL
Imported Surfer Initial WinTran 2002.grd

BD J-26 Junction Box Site
WinTran Fate & Transport Modeling Results



5280 feet

Estimated Conditions for Year 2020

Modeling Assumptions
Hydraulic Conductivity = 1600 ft/yr (4.4 ft/day)
Hydraulic Gradient = 0.003 ft/ft (SE)
Longitudinal Dispersivity = 328 ft
Transverse Dispersivity = 32.8 ft
Diffusion Coeficient = 0.3349 ft2/day
Porosity = 0.25 percent
Aquifer Bottom at 3250 ft AMSL
Imported Surfer Initial WinTran 2002.grd

BD J-26 Junction Box Site
WinTran Fate & Transport Modeling Results

Maximum Chloride Concentration
(Center of Plume)
598 mg/L

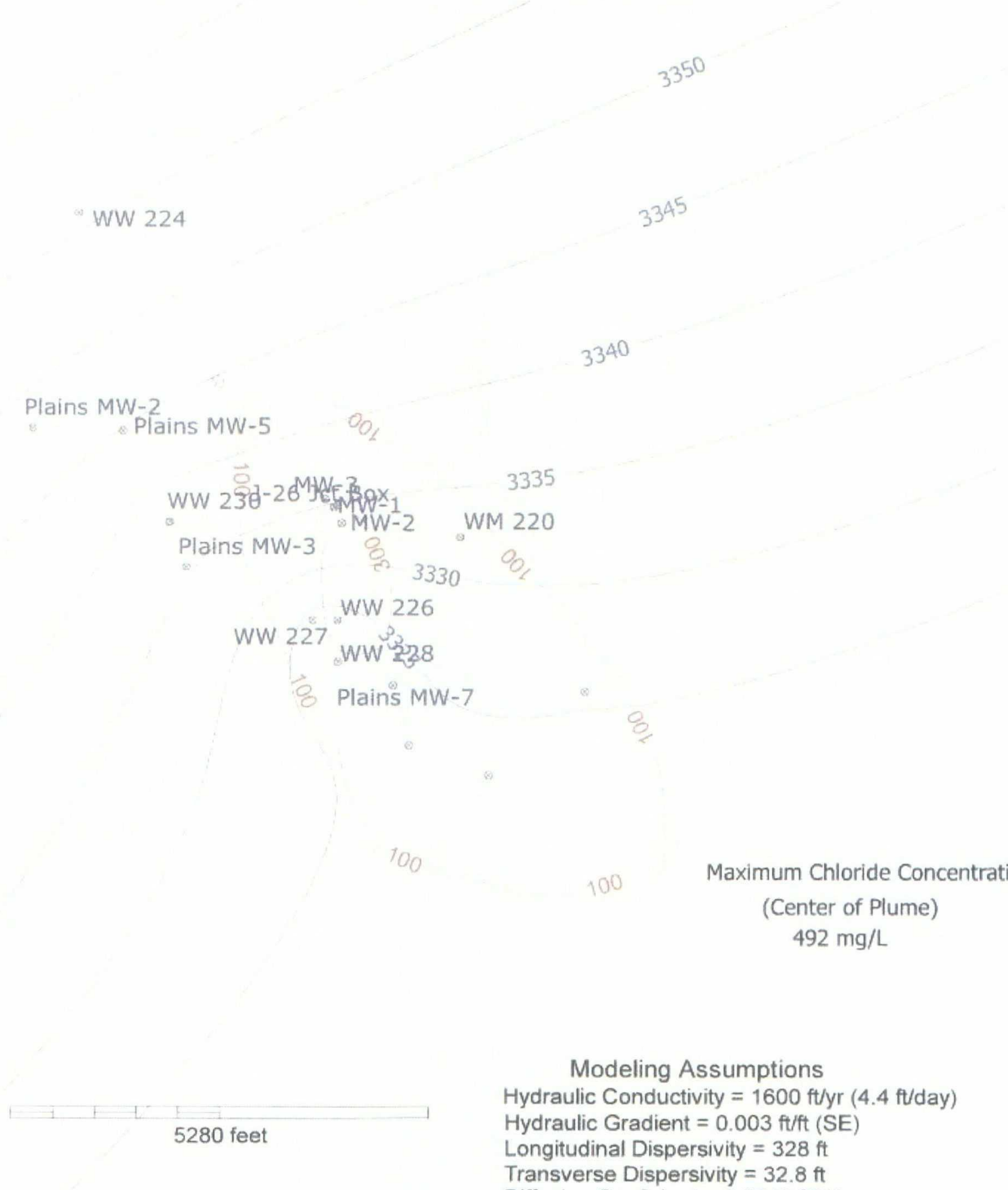
5280 feet

Estimated Conditions for Year 2025

Modeling Assumptions

Hydraulic Conductivity = 1600 ft/yr (4.4 ft/day)
Hydraulic Gradient = 0.003 ft/ft (SE)
Longitudinal Dispersivity = 328 ft
Transverse Dispersivity = 32.8 ft
Diffusion Coeficient = 0.3349 ft2/day
Porosity = 0.25 percent
Aquifer Bottom at 3250 ft AMSL
Imported Surfer Initial WinTran 2002.grd

BD J-26 Junction Box Site
WinTran Fate & Transport Modeling Results

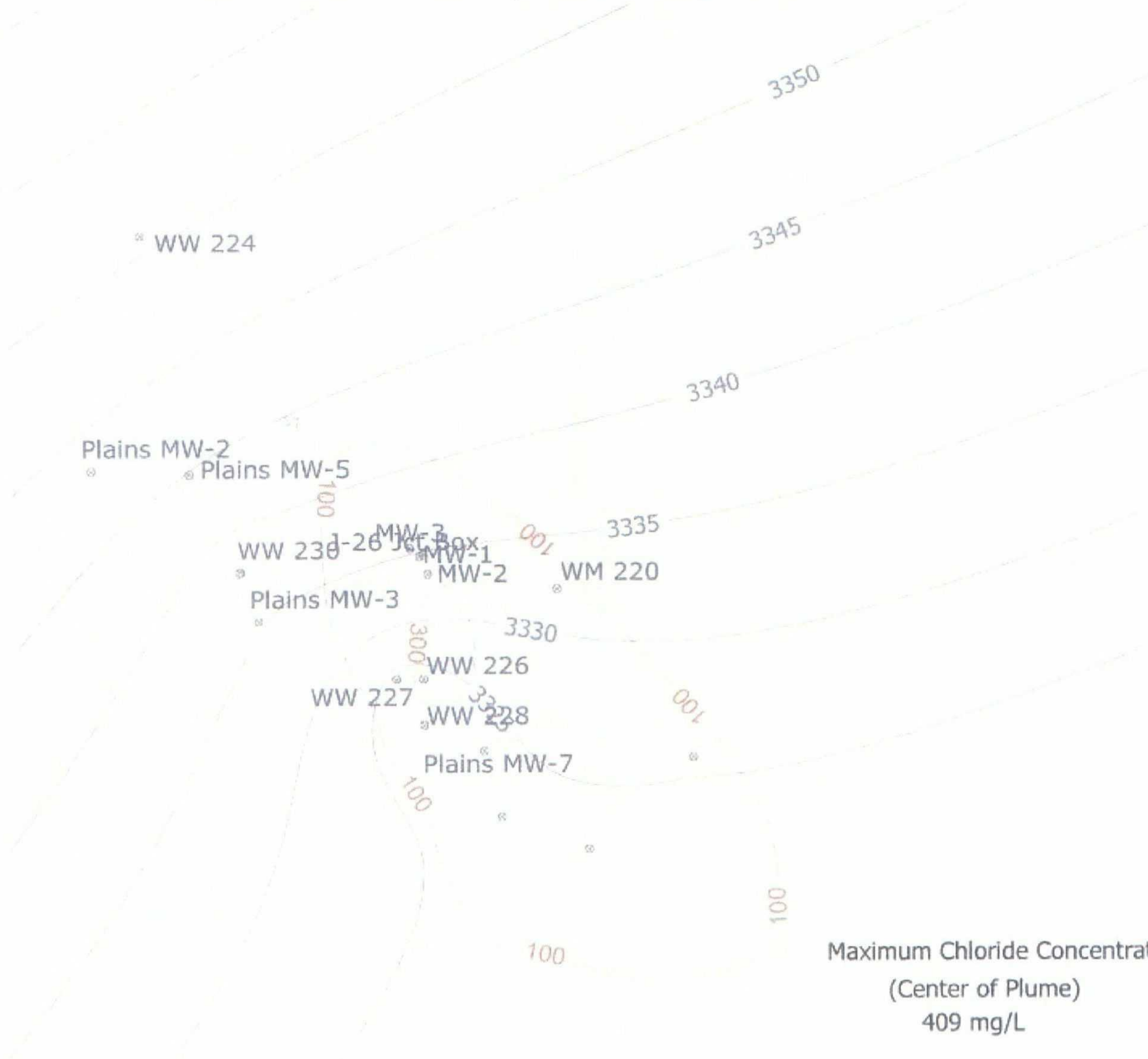


Maximum Chloride Concentration
(Center of Plume)
492 mg/L

Estimated Conditions for Year 2030

Modeling Assumptions
Hydraulic Conductivity = 1600 ft/yr (4.4 ft/day)
Hydraulic Gradient = 0.003 ft/ft (SE)
Longitudinal Dispersivity = 328 ft
Transverse Dispersivity = 32.8 ft
Diffusion Coeficient = 0.3349 ft2/day
Porosity = 0.25 percent
Aquifer Bottom at 3250 ft AMSL
Imported Surfer Initial WinTran 2002.grd

BD J-26 Junction Box Site
WinTran Fate & Transport Modeling Results



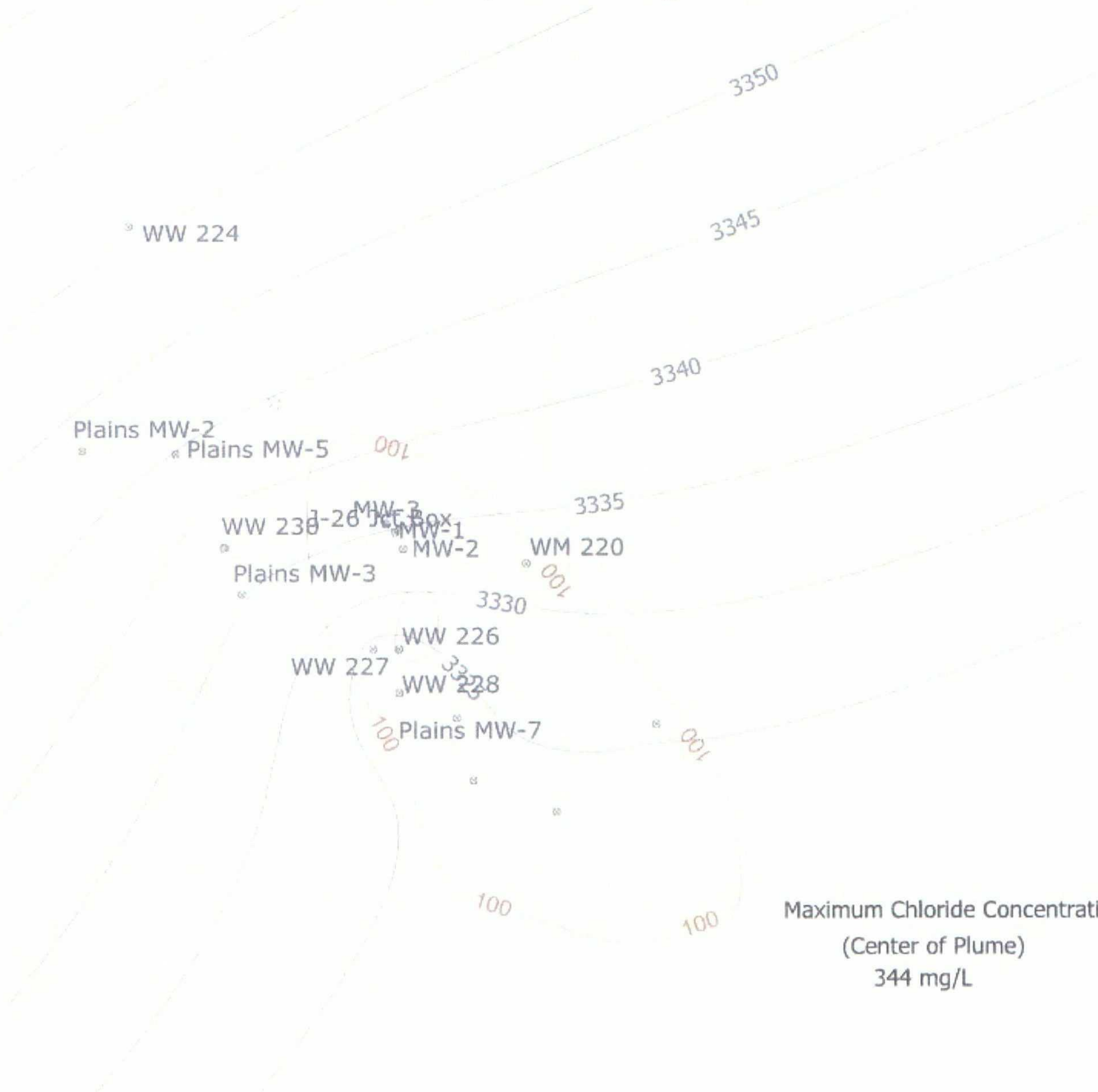
Maximum Chloride Concentration
(Center of Plume)
409 mg/L

5280 feet

Estimated Conditions for Year 2035

Modeling Assumptions
Hydraulic Conductivity = 1600 ft/yr (4.4 ft/day)
Hydraulic Gradient = 0.003 ft/ft (SE)
Longitudinal Dispersivity = 328 ft
Transverse Dispersivity = 32.8 ft
Diffusion Coeficient = 0.3349 ft2/day
Porosity = 0.25 percent
Aquifer Bottom at 3250 ft AMSL
Imported Surfer Initial WinTran 2002.grd

BD J-26 Junction Box Site
WinTran Fate & Transport Modeling Results

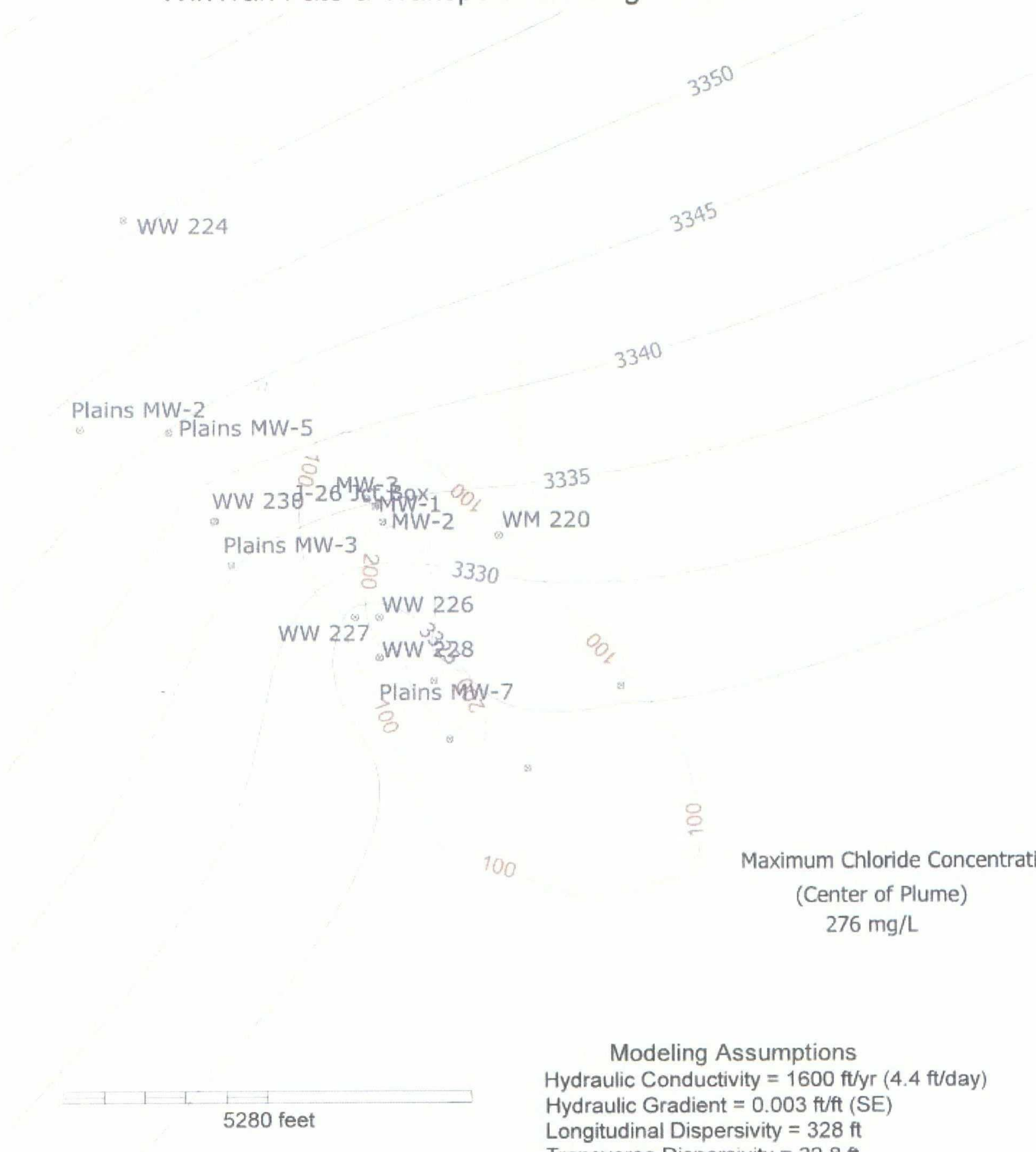


5280 feet

Estimated Conditions for Year 2040

Modeling Assumptions
Hydraulic Conductivity = 1600 ft/yr (4.4 ft/day)
Hydraulic Gradient = 0.003 ft/ft (SE)
Longitudinal Dispersivity = 328 ft
Transverse Dispersivity = 32.8 ft
Diffusion Coeficient = 0.3349 ft2/day
Porosity = 0.25 percent
Aquifer Bottom at 3250 ft AMSL
Imported Surfer Initial WinTran 2002.grd

BD J-26 Junction Box Site
WinTran Fate & Transport Modeling Results



Maximum Chloride Concentration
(Center of Plume)
276 mg/L

Estimated Conditions for Year 2047

Modeling Assumptions

Hydraulic Conductivity = 1600 ft/yr (4.4 ft/day)
Hydraulic Gradient = 0.003 ft/ft (SE)
Longitudinal Dispersivity = 328 ft
Transverse Dispersivity = 32.8 ft
Diffusion Coeficient = 0.3349 ft2/day
Porosity = 0.25 percent
Aquifer Bottom at 3250 ft AMSL
Imported Surfer Initial WinTran 2002.grd

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WinTran
Analytical Model of 2D Ground-Water Flow and
Finite-Element Contaminant Transport Model

Developed by

James O. Rumbaugh, III

Douglas B. Rumbaugh

==

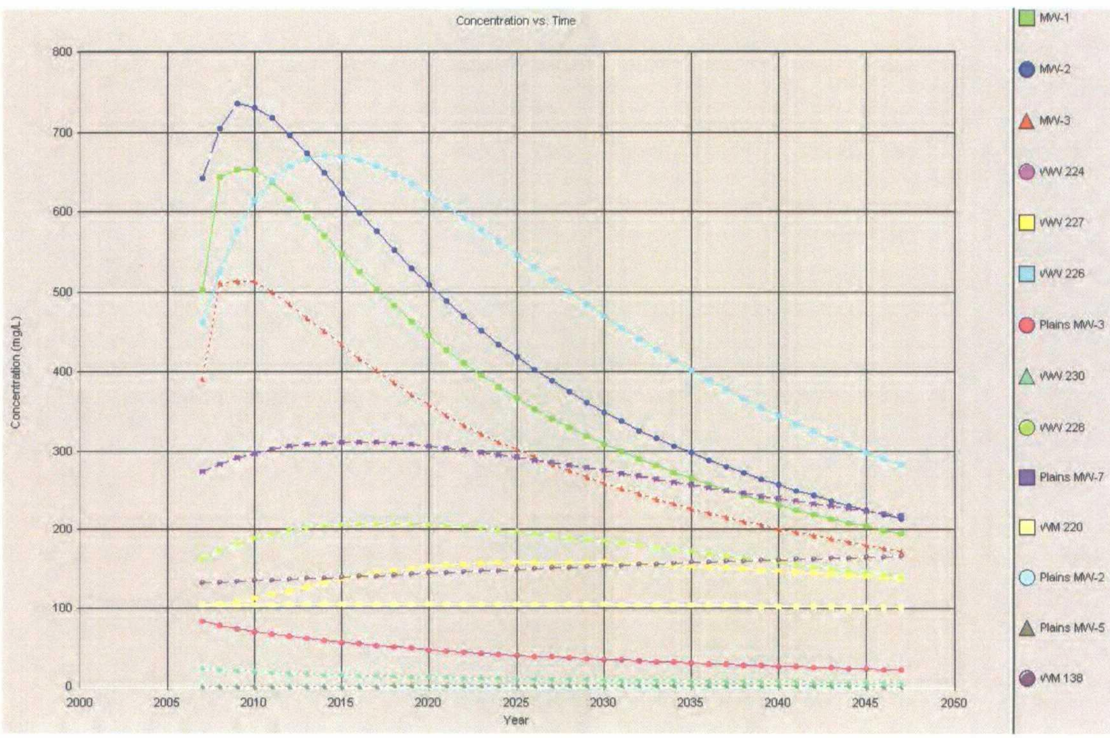
Model performed by: Trident Environmental (Gilbert Van Deventer)

Date: 03/02/07

Time: 13:19:54.00

Input File: 2006 CHLORIDE J26

Map File : D:\PROJECTS\RICE\BD\J-26\WINTRAN RESULTS\WINTRAN2002BASE.MAP



```
================================================================================
                                 Model Entities

Number of Wells = 17

     Well #1
        Center of Well --  x: 3873.000000   y: 5443.000000
        Radius = 0.083330
        Pumping Rate = 0.000000
        Concentration of Injected Water = 218.000000
        Head at Well Radius            = 3334.738437
     Well #2
        Center of Well --  x: 3969.000000   y: 5243.000000
        Radius = 0.083330
        Pumping Rate = 0.000000
        Concentration of Injected Water = 387.000000
        Head at Well Radius            = 3333.495421
     Well #3
        Center of Well --  x: 3764.000000   y: 5540.000000
        Radius = 0.083330
        Pumping Rate = 0.000000
        Concentration of Injected Water = 141.000000
        Head at Well Radius            = 3335.402430
     Well #4
        Center of Well --  x: 631.000000   y: 9185.000000
        Radius = 0.083330
        Pumping Rate = 0.000000
        Concentration of Injected Water = 302.000000
        Head at Well Radius            = 3355.727045
     Well #5
        Center of Well --  x: 3611.000000   y: 4012.000000
        Radius = 0.375000
        Pumping Rate = 721412.000000
        Concentration of Injected Water = 181.000000
        Head at Well Radius            = 3318.357873
     Well #6
        Center of Well --  x: 3921.000000   y: 4012.000000
        Radius = 0.375000
        Pumping Rate = 543819.000000
        Concentration of Injected Water = 225.000000
        Head at Well Radius            = 3318.856940
     Well #7
        Center of Well --  x: 2012.000000   y: 4694.000000
        Radius = 0.083330
        Pumping Rate = 0.000000
        Concentration of Injected Water = 322.000000
        Head at Well Radius            = 3335.282440
     Well #8
        Center of Well --  x: 1802.000000   y: 5262.000000
        Radius = 0.375000
        Pumping Rate = 1202639.000000
        Concentration of Injected Water = 187.000000
        Head at Well Radius            = 3328.076355
     Well #9
        Center of Well --  x: 3927.000000   y: 3481.000000
        Radius = 0.375000
        Pumping Rate = 2748248.000000
        Concentration of Injected Water = 308.000000
        Head at Well Radius            = 3289.944035
     Well #10
        Center of Well --  x: 4628.000000   y: 3178.000000
        Radius = 0.083330
```

```
      Pumping Rate = 0.000000
      Concentration of Injected Water = 450.000000
      Head at Well Radius           = 3323.670009
   Well #11
      Center of Well --  x: 5472.000000   y: 5065.000000
      Radius = 0.250000
      Pumping Rate = 1000.000000
      Concentration of Injected Water = 620.000000
      Head at Well Radius           = 3332.262314
   Well #12
      Center of Well --  x: 60.000000   y: 6446.000000
      Radius = 0.083330
      Pumping Rate = 0.000000
      Concentration of Injected Water = 269.000000
      Head at Well Radius           = 3348.295561
   Well #13
      Center of Well --  x: 1205.000000   y: 6403.000000
      Radius = 0.083330
      Pumping Rate = 0.000000
      Concentration of Injected Water = 225.000000
      Head at Well Radius           = 3344.810629
   Well #14
      Center of Well --  x: 4829.000000   y: 2410.000000
      Radius = 0.250000
      Pumping Rate = 0.000000
      Concentration of Injected Water = 341.000000
      Head at Well Radius           = 3324.074809
   Well #15
      Center of Well --  x: 5838.000000   y: 2032.000000
      Radius = 0.250000
      Pumping Rate = 0.000000
      Concentration of Injected Water = 971.000000
      Head at Well Radius           = 3323.649345
   Well #16
      Center of Well --  x: 7050.000000   y: 3103.000000
      Radius = 0.375000
      Pumping Rate = 100000.000000
      Concentration of Injected Water = 405.000000
      Head at Well Radius           = 3324.822825
   Well #17
      Center of Well --  x: 3914.520000   y: 5464.310000
      Radius = 4.000000
      Pumping Rate = 0.000000
      Concentration of Injected Water = 60000.000000
      Head at Well Radius           = 3334.824298

Reference Head = 3345.000000    Defined at -- x: 2360.290000   y: 7094.260000
```

```
================================================================================
                              Aquifer Properties

   .... Steady-State Flow Model ....

   Permeability...............= 1606.000000 [L/T]
   Porosity...................= 0.250000
   Elevation of Aquifer Top....= 3400.000000
   Elevation of Aquifer Bottom.= 3250.000000
   Uniform Regional Gradient...= 0.003000
   Angle of Uniform Gradient...= 304.000000
   Recharge...................= 0.000000


   .... Transient Transport Model ....

   Longitudinal Dispersivity...= 328.000000 [L]
   Transverse Dispersivity.....= 32.800000 [L]
   Diffusion Coefficient.......= 0.000000 [L2/T]
   Contaminant half-life...... = 0.000000 [T]
   Retardation Coefficient.....= 1.000000
   Upstream Weighting in X.....= 0.000000
   Upstream Weighting in Y.....= 0.000000

   .... Time Stepping Information ....

   Number of time steps........= 41
   Starting time value.........= 2006.000000
   Initial time step size......= 1.000000
   Time step multiplier....... = 1.000000
   Maximum time step size......= 1.000000
   Time stepping scheme........= Central Differencing

   .... Simulation Summary ....

   Starting time..............= 2006.000000
   Ending time................= 2047.000000
   Number of time steps........= 41

   (NOTE: following mass balance errors expressed as percent)
   Transport Mass Balance Error= 7.032368

   Peclet Criterion...........= 0.516657
   Courant Number.............= 0.867743
   Flow Model Type............= Analytic Element
```

APPENDIX B

Documentation of WinTran (Version 1.03)
Fate and Transport Model
Capabilities and Benchmarking

Introduction

Combined Manual

Aquifer^{Win32}, WinFlow and WinTran are now basically the same product so we have merged the manual into one. With the exception of the program name, the default icon, and the types of document files you can create everything is the same.

An Aquifer^{Win32} Flow Model document file is identical to a WinFlow document file and the user-interfaces are identical as well. The only reason we sell two products is for those who want the modeling capabilities but not the pumping test analysis capabilities. In that case, WinFlow is the solution. For everyone else, one of the levels of Aquifer^{Win32} is the solution.

We have eliminated WinTran as a separate product and included it in both WinFlow and the Modeling Version of Aquifer^{Win32}.

The Modeling version of Aquifer^{Win32} contains the capabilities of all three products!

What is Aquifer^{Win32}?

Aquifer^{Win32} is the most sophisticated and most Windows™ compliant application for the analysis and presentation of aquifer tests including pump tests, slug tests, step tests and analytic element flow and contaminant transport models. The analysis of these data incorporates a wide variety of solution types with comprehensive plotting features.

Aquifer^{Win32} comes in four different versions, *Modeling*, *Professional*, *Standard*, and *Slug Test*. Aquifer^{Win32} is an OLE Full Server allowing the results to be linked to or embedded in OLE client applications. The *Slug Test* version is limited to the analysis of slug test data using any one of the 6 slug test solutions; these solutions range from the simple Hvorslev to the complex Kansas Geological Survey (KGS) Model supporting confined or unconfined conditions, partial penetration, well skin effects and the response of a monitoring well. The *Standard* version adds over a dozen pump test analyses including solutions for confined, leaky confined, unconfined and fracture rock aquifers with support for variable pumping rates, partial penetration, delayed yield and well bore storage. The *Professional* version adds derivative analysis, Step tests and a Pump Test Simulator. The *Modeling* version extends many of the pump test solutions into a modeling environment supporting any number of pumping wells with variable pumping rates. Output includes contour maps of hydraulic head or drawdown, color floods, particle traces and graphs of drawdown versus time at any number of monitoring wells. Auto-calibration to any number of transient targets is also supported.

The following are some of the most important features of Aquifer^{Win32}:

About data entry…

- As simple as entering or importing data into a spreadsheet, characterize pumping and monitoring well, select solution type and match data
- Alternatively, designed as a repository for raw aquifer test data with programmatic data conversions
  - Define a site plan including a site map, well locations and well construction information
  - Define an aquifer test including pumping schedule, wells monitored and raw drawdown versus time data
  - Define an analysis by grouping wells, transforming and clipping well response data, optionally adjust for radial distance on a well by well basis

About data analysis…

- Primary support for traditional manual curve matching techniques
- User selectable and unlimited type curves on curve match graph
- Multiple parameters available as type curves for many analyses
- Graphically visualize the impact of specific parameters with custom type curve suites
- Extensive curve match optimization capability
  - Control which parameters are optimized
  - Set minimum and maximum bounds on parameters
  - Optimize any parameters across multiple data sets
- Manual and optimized curve match of the first-order derivative of the data to first-order derivative type curves
- Support for variable pumping rates
- Pump test simulations with contour maps and time/drawdown graphs
- Steamline and particle trace analysis
- Analytic element modeling with recharge, ponds, linesinks etc.
- Auto-calibration of flow modeling parameters

About units…

- Full control of parameter and data units on a parameter by parameter and well by well basis
- On-the-fly unit conversions
- Peer review process assisted by instantaneous global unit conversions without affecting match results
- Parameter-based unit conversion calculator

About graphics...

- Full control of graphs including size, titles, axes, colors, fonts, dash patterns and line thickness
- Type curve graph, predicted drawdown curve through data points, observed drawdown data
- Contours of predicted drawdown at a given time and predicted drawdown versus time data at any number of monitoring wells
- Annotate maps and graphs with text, parameters, symbols, lines, frames and legends
- Frames support display of bitmaps and metafiles
- Exports to DXF, Windows Metafile and ArcView™ Shapefile formats
- Site map and well location plan displayed in map view
- Color flood maps in addition to or as an alternative to contour maps
- Three dimensional perspective display using the Visualization Toolkit (vtk), written and copyrighted by Ken Martin, Will Schroeder and Bill Lorensen.

About printing...

- WYSIWYG printing with Print Preview of all views
- Customizable margins and scaling
- Customizable headers and/or footers supporting bitmaps and metafiles
- Supports any Windows™ printer driver

About Windows™ features...

- Multiple Document Interface
- OLE Full-server supporting linked and embedded items
- Copy views to clipboard as metafiles and OLE objects
- Tab views including spreadsheet, type curves, predicted curves, map and simulator
- Data spreadsheet in split window
- Context-sensitive help
- Context menus
- Property Sheets (Tab Dialogs) to maximize ease of use
- Tip of the Day
- Dockable toolbars with tool tips

Slug Test Analyses

Hvorslev, 1951	Time Lag and Soil Permeability in Ground-Water Observations

Bouwer & Rice, 1976	Slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells
Black, 1978	The use of the slug test in groundwater investigations (Modified Bouwer & Rice unconfined aquifer slug test analysis using an exponential type curve)
Cooper, Bredehoeft & Papadopulos, 1967	Response of a Finite-Diameter Well to an Instantaneous Charge of Water
Hyder, Butler, McElwee & Liu, 1994	Slug tests in partially penetrating wells (KGS Model including well skin and monitoring well response)
Kipp, 1985	Type Curve Analysis of Inertial Effects in the Response of a Well to a Slug Test

Pumping Test Analyses

Cooper and Jacob, 1946	A generalized graphical method for evaluating formation constants and summarizing well field history. (Cooper Jacob Straight Line Method)
Theis, 1935	Constant discharge from a fully penetrating well in a nonleaky aquifer*
Theis, 1935 (Unconfined)	Constant discharge from a fully penetrating well in a nonleaky aquifer*
Theis, 1946 (Recovery)	Recovery test after constant discharge from a fully penetrating well in a nonleaky aquifer
Hantush, 1961	Constant discharge from a partially penetrating well in a nonleaky aquifer*
Papadopulos and Cooper, 1967	Constant discharge from a fully penetrating well of finite diameter in a nonleaky aquifer*
Hantush, 1960	Constant discharge from a well in a leaky aquifer with storage of water in the confining beds*
Hantush and Jacob, 1955	Constant discharge from a fully penetrating well in a leaky aquifer*
Hantush, 1964	Constant discharge from a partially penetrating well in a leaky aquifer*
Neuman, 1972	Theory of flow in unconfined aquifers considering delayed response of the water table*
Neuman, 1974	Effects of partial penetration on flow in unconfined aquifers considering delayed aquifer response*
Moench, 1984	Double-Porosity Models for a Fissured Groundwater Reservoir with Fracture Skin*
Moench, 1985	Transient Flow to a Large-Diameter Well in an Aquifer With Storative Semiconfining Layers*
Moench, 1997	Flow to a well of finite diameter in a homogeneous, anisotropic water table aquifer

*** Analysis available for use in pump test simulator**

Step/Variable Rate Test Analyses

Eden and Hazel, 1973	Step-drawdown test analysis for fully penetrating well in a confined aquifer. Determines well losses and aquifer transmissivity.
Birsoy and Summers, 1980	Variable or intermittent discharge rate analysis for well in a confined aquifer. Determination of aquifer transmissivity and storage.

Model Solutions

Theis, 1935	Constant discharge from a fully penetrating well in a nonleaky aquifer
Hantush, 1960	Constant discharge from a well in a leaky aquifer with storage of water in the confining beds
Hantush and Jacob, 1955	Constant discharge from a fully penetrating well in a leaky aquifer
Neuman, 1972	Theory of flow in unconfined aquifers considering delayed response of the water table
WinFlow	Analytic element flow model developed by ESI
WinTran	Analytic element flow and Finite element contaminant transport model developed by ESI

What is WinFlow?

WinFlow is a powerful yet easy-to-use groundwater flow model. The user-interface represents the most sophisticated and Windows™ compliant available today. WinFlow provides an extensible common user-interface for analytical analyses and models capable of hosting other calculation engines in the future.

WinFlow is an interactive, analytical modeling tool that simulates two-dimensional steady-state and transient ground-water flow. The steady-state module simulates ground-water flow in a horizontal plane using analytical functions developed by Strack (1989). The transient module uses equations developed by Theis (1935) for confined aquifers, Hantush and Jacob (1955) and Hantush (1960) for leaky aquifers, and Neuman (1972) for unconfined aquifers. Each module uses the principle of superposition to evaluate the effects from multiple analytical functions (wells, etc.) in a uniform regional flow field.

The steady-state module simulates the effects of the following analytic elements in two-dimensional flow: wells, uniform recharge, circular recharge/discharge areas, and line sources or sinks. Any number of these elements may be added to the model, including a uniform regional hydraulic gradient. The model depicts the flow field using streamlines, particle traces, and contours of hydraulic head. The streamlines are computed semi-analytically to illustrate ground-water flow directions. Particle-tracking techniques are implemented numerically to compute travel times and flow directions. Both confined and unconfined aquifers are simulated with the steady-state module.

The transient module simulates the effects of wells, circular ponds, linear sources/sinks, and a uniform regional gradient for confined and leaky aquifers. Numerical particle-tracking is also available in the transient module. The transient module computes hydraulic heads using the Theis (1935) equation for confined aquifers and the Hantush and Jacob (1955) or Hantush (1960) equation for leaky aquifers. Neuman's method (1972) can also be used for unconfined aquifers with delayed yield from storage.

In addition to the WinFlow calculation engine described above, WinFlow extends other analytical solutions from the popular Aquifer^{Win32} pumping test analysis application into its modeling environment. These additional solutions support any number of pumping wells with variable pumping rates. Auto-calibration to any number of transient targets is also supported for these additional solutions.

WinFlow is simple to use and highly interactive, allowing you to create an analytical model in minutes. The software features standard Windows pulldown menus and tab dialogs to facilitate the model design. The model is recomputed and recontoured either by selecting a menu item or by pressing a toolbar button. Streamlines and particle-traces are added interactively and recomputed each time new wells or other elements are added.

WinFlow can import a Drawing Interchange Format (DXF) file (from AutoCAD for example) to use as a digitized base map. QuickFlow and ModelCad-format map files may also be imported into WinFlow. The digitized map gives the modeler a frame of reference for designing the analytical model.

WinFlow produces report-quality graphics using any Windows device driver. Output may also be exported to a wide variety of file types, including SURFER, Geosoft, Spyglass, Windows Metafiles, and AutoCAD-compatible DXF files.

What is WinTran?

WinTran is designed to be an easy-to-use model for simulating the fate and transport of dissolved contaminants in fully saturated groundwater systems. The WinTran model couples the steady-state groundwater flow model from WinFlow, with a contaminant transport model. The transport model feels like an analytic model but is actually an embedded finite-element simulator. The software automatically constructs the finite-element transport model so that you may quickly get answers to your groundwater problems.

The steady-state flow model in WinTran uses analytic functions developed by Strack (1989) to simulate the effects of wells, uniform recharge, circular recharge/discharge areas (called ponds), and line sources or sinks. Any number of these elements may be added to the model. The model depicts the flow field using streamlines, particle-traces, contours of hydraulic head (water levels) and color floods of hydraulic heads. Both confined and unconfined aquifers may be simulated with the WinTran flow model.

The contaminant transport model uses a finite-element formulation whereby the finite-element mesh is identical to the head contour matrix. The contour matrix is a rectangular array of points where head is computed by the flow model. WinTran computes groundwater velocity at each "node" in the contour matrix for use in the finite-element transport model. Diagnostic information is displayed on the status bar at the bottom of the window as the transport model runs. These data alert you to potential problems in the numerical transport model. These diagnostic data include the mass balance error, Peclet number, and Courant number. If these error criteria indicate problems, you may stop the simulation, choose new simulation options, and start the simulation again.

Contaminant mass may be injected or extracted using any of the analytic elements from the groundwater flow model, including wells, ponds, and linesinks. In addition, constant concentration elements may be placed in the model to keep the source contaminant concentration at a specified value. WinTran displays both head and concentration contours. Concentration versus time data may be calculated and graphically displayed for selected monitoring locations. The transport model includes the effects of dispersion, linear sorption (retardation), and first-order decay. The latter may be used to simulate the biologic decay of organic compounds, such as benzene or the radioactive decay of elements such as uranium.

WinTran can import a Drawing Interchange Format (DXF) file (from AutoCAD, for example) to use as a digitized base map. The digitized map gives you a frame of reference for designing the flow and transport models.

WinTran produces report-quality graphics using any Windows device driver. Output may also be exported to a wide variety of file types, including SURFER, Geosoft, Spyglass, Windows Metafiles, and AutoCAD-compatible DXF files.

Installation

Aquifer^{Win32} and WinFlow are distributed on CD-ROM and use a sophisticated installation wizard that is similar to other Windows™ products. You simply run "Setup" from the CD-ROM and follow the directions as the installation proceeds. Start by placing the CD-ROM in the drive. Now, select **Run** from the **Start** menu and enter the following:

d:\setup.exe

You must first agree to the "ENVIRONMENTAL SIMULATIONS SOFTWARE LICENSE AGREEMENT" in order to continue installing the software. The next page prompts for the directory where the files will be stored. The default is "c:\aquifer3" or "c:\winflow3". If you would like to place the files in a different directory, click the **Browse** button and locate a new directory. Click the **Next** button when you are done. Select **Cancel** at any time to terminate the installation process. The next step is to decide which optional components to install. By default, example files are installed and documentation files, in .pdf format, are not. Click the **Next** button after checking the optional components you want to install.

The next page of the wizard allows you to specify the name of the submenu to add to the **Start->Programs** menu; the default name is AquiferWin32 Version 3 or WinFLow Version 3. To change this, you may select from an existing submenu listed or type a new name. Select **Next** to accept your choice. Finally, select the **Next** button again to begin the installation. After all the files have been installed, another wizard will be started to install the security block device driver; you must have administrator rights to install this driver. After the device driver installation is complete, click the **Finish** button on this wizard and on the main installation wizard.

Optionally Obtaining a Security Code

Aquifer^{Win32} and WinFlow are protected by a security block (dongle) or an optional security code that is tied to the computer you install it on. By default, Aquifer^{Win32} and WinFlow both ship with a security block. If you opt for a security code instead, you are licensed to run Aquifer^{Win32} or WinFlow on only one computer and you must obtain a security code in order to complete the installation. If you obtain a security block, you are licensed to install Aquifer^{Win32} or WinFlow on any number of computers; however, Aquifer^{Win32} and WinFlow will require the security block to be installed on a given computer before its full functionality is activated.

WinFlow/WinTran Mathematical Models

Steady-state Model

The equations used in the steady-state portion of WinFlow are derived by Otto D. L. Strack's Groundwater Mechanics (Strack, 1989). If you intend to use WinFlow routinely, you should get a copy of Groundwater Mechanics. It is well written and will give you valuable insight into the underlying assumptions of the analytical equations. You will also be introducted to more advanced techniques not included in WinFlow. The book contains sample FORTRAN source code for the analytical functions in WinFlow.

Dr. Strack is well known for his SLAEM software (Single Layer Analytic Element Model), which is much more advanced than WinFlow. He has also developed a three-dimensional version of SLAEM. If you like analytical modeling with WinFlow but need more power and flexibility, you may be interested in SLAEM. Dr. Strack can be reached in the Civil and Mineral Engineering Department of the University of Minnesota.

The analytic functions developed by Strack (1989) use the principle of superposition to compute the head at a point in the aquifer system. The total effect resulting from several analytic functions, such as a pumping wells, is equal to the sum of the individual effect caused by each analytic function acting separately. For example, if you wanted to compute the total drawdown at a point resulting from three pumping wells, you would compute the drawdown caused by each well at that point and then sum the drawdowns.

WinFlow allows you to select from a number of analytic functions to simulate two-dimensional horizontal ground-water flow, including

Uniform regional flow,

Wells,

Recharge (elliptical area),

Circular recharge areas (Ponds), and

Line sinks and sources.

The head at any point in the system may be computed by summing the effects of any number of the above functions. The equations used to compute the head are described below.

The analytic equations are expressed in terms of discharge potential to keep the equations linear for both confined and unconfined flow. The discharge vector points in the direction of ground-water flow and the magnitude of the discharge potential equals the volume of water flowing through a cross-section of unit width. In computing head at a point, the discharge potential is computed first and then converted to head using the following equations:

for confined flow:

$$\phi = \frac{\Phi + \frac{1}{2} K H^2}{KH}$$

and for unconfined flow:

$$\phi = \sqrt{\frac{2\Phi}{K}}$$

where:

Φ = discharge potential (L^3/T)

K = hydraulic conductivity (L/T)

H = aquifer thickness (L)

ϕ = head (L)

Using these formulae, WinFlow automatically accounts for the transition from confined to unconfined flow. The following equations are used to compute the discharge potential at any point (x,y) in the system. The equations above are then used to convert the discharge potential to head.

Uniform Flow

$$\Phi(x, y) = -Q_o(x \cos\alpha_u + y \sin\alpha_u) + C$$

Wells

$$\sum_{j=1}^{n} \frac{Q_j}{4\pi} \ln[r_j^2(x, y)] +$$

Recharge

$$-\tfrac{1}{2}\frac{N}{a^2+b^2}[(a^2\sin^2\alpha_r+b^2\cos^2\alpha_r)(x-x_r)^2-$$

$$2(a^2-b^2)(x-x_r)(y-y_r)\sin\alpha_r\cos\alpha_r$$
$$+(a^2\cos^2\alpha_r+b^2\sin^2\alpha_r)(y-y_r)^2-a^2b^2]$$

Ponds

Inside Pond:

$$-\sum_{j=1}^{n}\tfrac{1}{4}[(x-x_{p_j})^2+(y-y_{p_j})^2-R^2_{p_j}]N_{p_j}$$

Outside Pond:

$$-\sum_{j=1}^{n}\tfrac{1}{4}[R^2_{p_j}\ln[\frac{(x-x_{p_j})^2+(y-y_{p_j})^2}{R^2_{p_j}}]]N_{p_j}$$

Linesinks of Known Flux

$$+\sum_{j=1}^{n}\frac{\sigma_j L_j}{4\pi}\Re\{(Z_j+1)\ln(Z_j+1)-(Z_j-1)\ln(Z_j-1)+2\ln[\frac{1}{2}(\frac{2}{z_j}-\frac{1}{z_j}]-2\}$$

where:

x	= x coordinate of calculation point
y	= y coordinate of calculation point
Q_o	= uniform flow [L^2/T]
α_u	= angle between uniform flow and x-axis
Q_j	= discharge of well j [L^3/T]
r_j	= distance from well j to calculation point [L]
N	= recharge rate [L/T]
a	= length of a-axis of recharge ellipse [L]
b	= length of b-axis of recharge ellipse [L]
x_r	= x coordinate of center of recharge ellipse [L]
y_r	= y coordinate of center of recharge ellipse [L]
α_r	= angle between a-axis and x-axis

x_{pj}	= x coordinate of center of pond j [L]
y_{pj}	= y coordinate of center of pond j [L]
R_{pj}	= radius of pond j [L]
N_{pj}	= infiltration rate of pond j
σ_j	= flow per unit length for linesink j [L^2/T]
L_j	= length of linesink j [L]
z^1	= starting coordinates of linesink j
z^2	= ending coordinates of linesink j
C	= constant
z	= x + iy

$$Z_j = Z_j(z, \overset{1}{z_j}, \overset{2}{z_j}) = \frac{z - \frac{1}{2}(\overset{1}{z_j} + \overset{2}{z_j})}{\frac{1}{2}(\overset{2}{z_j} - \overset{1}{z_j})}$$

The uniform flow component above does not contain a gradient term explicitly, even though you enter the gradient in WinFlow to define uniform regional flow. The Q_o term represents the flow per unit width of aquifer and is computed as Q_o = KBi, where: i = the gradient, K = hydraulic conductivity, and B = saturated thickness. WinFlow computes the Q_o term at the reference point; therefore, you do not need to enter Q_o.

There are two equations for ponds depending upon whether the point (x,y) is located inside the pond or outside of the pond. Thus, either pond equation is used, but not both.

The term that computes the contribution to the discharge potential for line sinks is expressed in terms of complex numbers. The expression $\Re\{\}$ signifies that the real portion of the complex number computed by the complex expression { } is used in the equation.

The expression for the discharge potential contains one unknown constant C. The constant C is evaluated by requiring that the potential be known at some point (x_o,y_o) in the system. Once this potential is known, the equation is solved for the constant C. An important ramification of this approach is that the head always equals the reference head at the reference point. This approach is equivalent to setting a constant head cell in a numerical model. It is very important to keep this reference head as far as possible from the area of interest.

WinFlow allows you to specify linesinks of unknown flux by defining a head at the center of the linesink. For *n* linesinks of specified head, there are *n+1* unknowns (the flux for each linesink and the constant C). In this case, the equations are solved numerically to compute the constant C and the flux for each linesink of specified head.

Transient Model

Basic Models

The transient model in WinFlow uses the analytical solutions of Theis (1935) and Hantush and Jacob (1955) to compute drawdown from a pumping well. Drawdowns from multiple individual wells are then added using the principle of superposition (Reilly et al., 1987) to compute the effective drawdown at a point. Finally, the cumulative drawdown is subtracted from a planar potentiometric surface. The surface may be horizontal or inclined at some angle, given by the uniform gradient vector.

The procedure for calculating the head at any point and time (x,y,t) is given below:

$$\phi(x,y,t) = C - G(x\cos\alpha + y\sin\alpha) - \sum_{j=1}^{n} s_j$$

where:

ϕ	= head
G	= regional gradient [L/L]
α	= angle between regional gradient and x-axis
(x,y)	= coordinates of calculation point
t	= time to compute drawdown
s_j	= drawdown computed for well j
C	= constant

The constant C is computed using the reference head, as in the steady-state model. The main difference between the steady-state model and the transient model is that the reference head is maintained at a constant value in the steady-state model. However, the reference head is simply a starting point for calculations in the transient model. That is, drawdowns computed at the reference location are subtracted from the reference head. The constant C is evaluated as follows:

$$C = \phi_r + G(x_o\cos\alpha + y_o\sin\alpha)$$

where:

ϕ_r	= reference head
x_o	= x coordinate of reference head
y_o	= y coordinate of reference head

There is an option, however, to keep the reference head at a constant value. This option was added so that the results would be consistent with the steady-state model. If you elect to keep the reference head constant in the transient model, drawdown is computed at the reference head location and then added to all heads in the contour matrix. The result is that the potentiometric surface is raised by a constant value.

Although the absolute values of head will be different between the two approaches, the flow directions and travel times (using particle-tracking) will be identical. The reference head should not be held constant if a drawdown model is being calculated because there would be zero drawdown at the reference head location.

The drawdown (s_j) is computed from one of two equations. If the leakage factor (L) is zero, the Theis equation is used. If leakage is nonzero, the Hantush and Jacob leaky aquifer solution is computed.

The Theis (1935) equation for unsteady flow to a well in a confined aquifer makes the following simplifying assumptions:

aquifer has infinite areal extent;

aquifer is homogeneous, isotropic, and of uniform thickness;

aquifer potentiometric surface is initially horizontal;

pumping rate is constant;

well fully penetrates the aquifer;

horizontal ground-water flow;

aquifer is confined;

flow is unsteady;

water is released instantaneously from storage with decline of hydraulic head;

diameter of pumping well is very small so that storage in the well can be neglected;

Drawdown is calculated as described below.

$$s = \frac{Q}{4\pi T} w(u)$$

where:

w(u) = Theis well function = $\int_u^\infty \frac{e^{-y}}{y} dy$

$u = r^2 S / (4 T t)$

r = distance from well to point (x,y)

T = aquifer transmissivity [L^2/T]

S = storage coefficient [dimensionless]

t = time

Q = pumping rate [L^3/T]

The Theis well function, also known as the exponential integral, is computed in WinFlow using a numerical approximation given by Abramowitz and Stegun (1965). This approach is verified in the next chapter.

The Hantush and Jacob (1955) equation for unsteady flow to a well in a semi-confined aquifer with no storage in aquitards makes the following simplifying assumptions:

- aquifer has infinite areal extent;
- aquifer is homogeneous, isotropic, and of uniform thickness;
- aquifer potentiometric surface is initially horizontal;
- pumping rate is constant;
- well fully penetrates the aquifer;
- horizontal ground-water flow;
- aquifer is semi-confined;
- flow is unsteady;
- water is released instantaneously from storage with decline of hydraulic head;
- diameter of pumping well is very small so that storage in the well can be neglected;
- confining bed(s) has infinite areal extent, uniform vertical hydraulic conductivity, and uniform thickness;
- confining bed(s) is overlain or underlain by an infinite constant-head plane source; and
- flow in the aquitard is vertical.

Drawdown is calculated as described below.

$$s = \frac{Q}{4\pi T} w(u, \frac{r}{B})$$

where:

w(u,r/B) = Hantush well function =	$\int_u^\infty \frac{1}{y} e^{[-y - \frac{r^2}{4B^2 y}]} dy$
u	$= r^2 S / (4 T t)$
B	$= \sqrt{\frac{Tb'}{K'}}$
b'	= thickness of aquitard [L]
K'	= vertical hydraulic conductivity of aquitard [L/T]
T	= aquifer transmissivity [L^2/T]

The Hantush and Jacob well function is evaluated numerically using a method described by Case et al. (1979). The next chapter verifies that the Hantush and Jacob (1955) well function calculations are accurate.

Implementing Ponds and Linesinks

Ponds and linesinks are available for the transient model as well as the steady-state model. The pond element is implemented using the Hantush (1967) analytical solution for computing the water-table rise beneath a circular recharging area. Linesinks (flux only) are implemented approximately using a series of wells evenly spaced along the linesink. You may determine the number of wells used to approximate each linesink. It will be more accurate as the number of wells increases. Both pond and linesink transient elements are described below.

Ponds are computed in the transient model using the Hantush (1967) method for circular recharge areas. WinFlow uses the approximate version of the Hantush mound equation, given as follows:

for r < R:

$$h^2 - h_i^2 = \frac{V}{2\pi K}[W(u_0) - (\frac{r}{R})^2 e^{-u_0} + \frac{1}{u_0}(1 - e^{-u_0})]$$

and for r > R:

$$h^2 - h_i^2 = \frac{V}{2\pi K}[W(u) + 0.5\, u_0 e^{-u}]$$

where:

h	= the water-table elevation (above the datum plane)
h_i	= the initial water-table elevation without the pond
K	= hydraulic conductivity (L/T) of the aquifer
W(u)	= Theis well function
u_0	= $R^2/4vt$
u	= $r^2/4vt$
t	= time after start of infiltration
v	= Kb/S
V	= $w\pi R^2$
w	= constant percolation rate (L/T)
S	= storativity

b		$= 0.5[h_i + h]$
R		= radius of the pond (L)
r		= radius of calculation point from center of pond (L)

The Hantush (1967) mound solution was developed with the following simplifying assumptions:

the water-table rise is less than 2 percent of the saturated thickness

$t \geq 0.5\ r^2/v\ (u \leq 0.5)$ for $r < R$

$t \geq 0.5\ R^2/v$ for $r > R$

otherwise, it uses the same assumptions as the Theis solution.

Linesinks are simulated in the transient model using an approximate method. The linesink is discretized into *n* evenly spaced wells with one well located at either end of the linesink. Each well in the interior of the linesink pumps at a rate of Q/(n-1) and the wells at the endpoints of the linesink pump at a rate of 0.5 Q/(n-1). This approximation becomes more accurate as the number of wells increases. You control the number of wells used to approximate linesinks in WinFlow.

Solute Transport Model

Introduction

Closed form analytical solutions to the governing equations of ground- water flow have wide application in subsurface remediation projects. Complex flow problems can be solved using these analytical techniques. The analytic element method developed by Strack (1989), as discussed in the previous section, is especially useful in modeling complex two- dimensional ground- water flow systems. The analytic elements include wells, line- sinks, and recharge areas, among others, that can be used to simulate a variety of subsurface remedial alternatives. While these analytic techniques cannot treat the range of complexity provided by numerical techniques, the analytical models have advantages over numerical models in ease of use and speed of application.

Analytical solutions to the solute transport equations, on the other hand, are not as directly applicable to remediation projects. One of the primary problems with transport analytical solutions is the inability to treat changes in the flow field caused by wells, drains, and recharge. Transport solutions are normally limited to a uniform groundwater flow field. In order to obtain useful solutions to transport problems, therefore, the modeler must resort to more powerful numerical techniques, which require more time and effort to simulate.

A hybrid technique has been developed for use in WinTran that combines an analytical flow model with a numerical transport model. This technique combines the ease of use of an analytical model with the flexibility of a numerical model. The flow model utilizes the analytical element techniques of Strack (1989). The transport model is based upon the finite- element method using rectangular elements and linear basis functions. The two models are both contained within WinTran.

The hybrid model first solves for the flow field using the analytic element method. Boundary conditions for the finite- element model are then automatically taken from the analytical flow model. The finite- element mesh is coincident with the head matrix used to contour results obtained from the flow simulation. Thus, you do not need to explicitly design a numerical grid or mesh system of nodes. You simply specify the location of the mesh and the number of rows and columns in the mesh. Because you are somewhat insulated from the mesh design, significant error-checking facilities are provided to warn of large mass balance errors and other potential problems such as violating specified Peclet and Courant criteria.

The Hybrid Approach

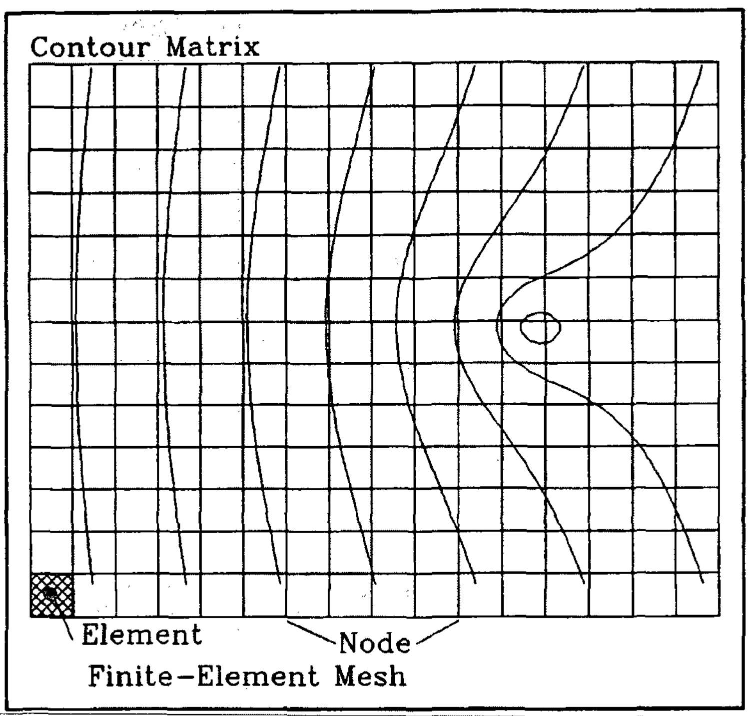
The hybrid analytical flow/numerical transport model combines the analytic element method developed by Strack (1989) with a finite- element transport technique developed by Huyakorn and others (1983). The model is constructed in six stages, most of which are transparent to the user. The six stages indude the following:

(1) The modeler designs the analytical flow model by specifying uniform aquifer properties, a regional hydraulic gradient, and analytic elements (e.g. wells, line sinks, circular recharge areas, and uniform recharge). The flow model was derived from the WinFlow model (ESI, 1995).

(2) The analytical flow model is infinite in extent; however, the user must specify a rectangular region of interest where head is computed and contoured.

(3) Head is computed at discrete points over the rectangular area of interest and a contour map is produced. These points are arranged in a regular mesh of n rows by m columns called the contour matrix. The spacings between rows and between columns are constant.

(4) Ground- water velocities are computed analytically at the centroid of each rectangular cell in the contour matrix (See the Figure below). These velocities are provided directly to the transport model and the contour matrix defines the finite-element mesh.



(5) Specify initial concentrations over the contour matrix and the nature and extent of contaminant sources.

(6) The finite- element transport model is solved for the specified simulation time(s) and results are contoured.

These six stages require relatively little user- intervention. For example, the finite- element mesh data are generated automatically. In addition, ground- water velocities are recomputed each time a change is made to the flow model. The element velocities are passed automatically to the transport model.

The Finite Element Transport Model

The solute transport model solves the partial differential equation describing the advection and dispersion of the dissolved species, as shown below:

$$\frac{\partial}{\partial x}(D_{xx}\frac{\partial c}{\partial x})+\frac{\partial}{\partial y}(D_{yy}\frac{\partial c}{\partial y})+\frac{\partial}{\partial x}(D_{xy}\frac{\partial c}{\partial y})+\frac{\partial}{\partial y}(D_{yx}\frac{\partial c}{\partial x})$$

$$-V_x\frac{\partial c}{\partial x}-V_y\frac{\partial c}{\partial y}=\phi R\frac{\partial c}{\partial t}+\lambda\phi Rc+q(c-c^*)$$

where c is the solute concentration (M/L^3); c' is the solute concentration in the injected water (M/L^3); D_{xx}, D_{yy}, D_{xy}, and D_{yx} are the components of the hydrodynamic dispersion tensor (L^2/T); ϕ is porosity (dimensionless); R is the retardation factor (dimensionless); q is the injection rate per volume of aquifer material ($L^3/T/L^3$); and λ is the first- order decay coefficient (T^{-1}). The Darcy velocity components are computed by the analytical flow model at the element centroids, as described above.

The dispersion coefficients are computed as described below:

$$D_{xx}=\frac{(\alpha_L-\alpha_T)V_x^2}{|V|}+\alpha_T|V|+D_{xx}^*$$

$$D_{yy}=\frac{(\alpha_L-\alpha_T)V_y^2}{|V|}+\alpha_T|V|+D_{yy}^*$$

$$D_{xy}=D_{yx}=\frac{(\alpha_L-\alpha_T)V_yV_x}{|V|}$$

where α_L is the longitudinal dispersivity, α_T is the transverse dispersivity, D* is the molecular diffusion coefficient (L^2/T), and |V| is the magnitude of the Darcy velocity (L/T).

The retardation factor is computed from the aquifer bulk density (ρ_s in M/L^3) and the distribution coefficient (k_d in L^3/M) as described below:

$$R=\frac{\rho_s k_d}{\phi}+1$$

Boundary conditions for the transport model include prescribed concentration and mixed- type boundaries. The latter are used around the edges of the finite- element mesh, where solute is removed if flow is exiting the model domain.

The solute transport equation is solved at each node in the finite element mesh using the Galerkin finite element method. A simplification has been adopted for rectangular elements with linear basis functions. The technique is called the influence coefficient method and is described by Huyakorn and others (1983). The finite element formulation results in a system of linear algebraic equations with an asymmetric banded coefficient matrix. The matrix is solved using a direct solver based on the LU decomposition of a banded matrix. The finite element equations are not presented but can be found in Huyakorn and others (1983) or in Huyakorn and Pinder (1983).

WinFlow/WinTran Verification

Introduction

Verification is the process of demonstrating that the computer program performs as documented. In the case of a model, such as WinFlow, verification tests for proper implementation of the applicable equations. These equations are documented in Chapter 5 and are tested in this chapter.

The steady-state and transient models are tested separately, as described below. In each case, the model is first tested using a simple example that can be solved with a calculator. Next, WinFlow computations are compared against either another code solving the same problem or against published answers. The steady-state model is further tested by comparing WinFlow results against those of a popular numerical model, MODFLOW (McDonald and Harbaugh, 1988).

Steady-state Model

Three sets of verification problems are presented for the steady-state analytical functions used in WinFlow. In the first problem, a simple uniform flow field with a single pumping well is solved using WinFlow and a calculator. This is one of the more common uses for WinFlow and illustrates that the basic code functions are programmed accurately. In the second case, a series of problems are benchmarked against the program SLWL (Strack, 1989). Finally, a simple test case of a single well in a uniform unconfined flow field is a benchmark against the numerical model, MODFLOW.

Case 1: Uniform Flow with a Single Well

The steady-state analytic function for a single well in a uniform flow field is given by Strack (1989) as follows:

$$\Phi = -Q_o(x\cos\alpha + y\sin\alpha) + \frac{Q}{4\pi}\ln[r^2(x, y)] + C$$

where

Φ	= discharge potential [L^3/T],
Q_o	= uniform ground-water flow [L^2/T],
x,y	= coordinates of the calculation point,
α	= angle between uniform flow and x-axis,
r(x,y)	= distance from the well to the calculation point (x,y),
Q	= well discharge [L^3/T],
C	= constant.

In a confined aquifer system, the discharge potential, Φ, is converted to head (ϕ) by the following equation.

$$\phi = \frac{\Phi + \frac{1}{2}KH^2}{KH}$$

where

ϕ	= head [L],
K	= hydraulic conductivity [L/T],
H	= aquifer thickness [L].

The constant, C, is evaluated by specifying a reference head at a certain location within the flow system. The reference head remains constant during all subsequent calculations. The constant, C, is computed as follows:

$$C = \Phi_o + Q_o(x_o \cos\alpha + y_o \sin\alpha) - \frac{Q}{4\pi}\ln[r^2(x_o, y_o)]$$

where

Φ_o	= reference discharge potential,
(x_o, y_o)	= coordinates of reference head.

In the first verification problem, the aquifer is confined with a uniform regional gradient parallel to the x-axis. The problem assumptions and parameters are listed below.

K = 100 ft/d

H = 100 ft

Gradient (i) = 0.01 ft/ft

$Q_o = KiH = 100\ ft^2/d$

reference head, $\phi_o = 200$ ft at (x_o=0,y_o=0)

$\Phi_o = KH\phi_o - ½KH^2 = 1500000\ ft^3/d$

Q = 100,000 ft^3/d at (x=1000,y=1000)

Using these parameters and equation (3), the constant C equals 1,384,541. Table 1 lists the results of hand calculations and WinFlow results (using the Point Calculation option) for a series of coordinates. The two results are identical to five significant figures; the calculator results were rounded to five figures. Thus, WinFlow computes the correct answer for this test case.

Table 1 Comparison between WinFlow and calculator results for test case 1.

X	Y	Φ	ϕ	ϕ (WinFlow)
0	1000	1,494,480	199.45	199.448
250	1000	1,464,902	196.49	196.491
500	1000	1,433,449	193.34	193.345
750	1000	1,397,417	189.74	189.742
1000	1000	1,284,441	178.44	178.444
1250	1000	1,347,417	184.74	184.742
1500	1000	1,333,449	183.34	183.345
1750	1000	1,314,902	181.49	181.491
2000	1000	1,294,481	179.45	179.448

Case 2: Benchmark with SLWL

The SLWL program is provided with the book, Groundwater Mechanics, (Strack, 1989). SLWL performs the same calculations as WinFlow. The primary difference between the two codes is that SLWL is written in FORTRAN, while WinFlow is written in the C programming language. SLWL has additional capabilities to those of WinFlow but is not as user-friendly nor does SLWL have good output capabilities.

A series of twelve test cases are developed to test each of the major components in WinFlow, including wells, ponds, linesinks, and recharge. Each feature added to the simulation is designed to produce a significant impact on the flow field, so that significant errors would be easily detected. Both confined and unconfined conditions are tested. These verification data sets are included on the WinFlow disk. The data file names are VER1.WFL, VER2.WFL, ..., and VER12.WFL.

SLWL was modified to export a SURFER contour matrix (grid file) in the same manner as WinFlow. The SURFER grid files were then subtracted from one another to create a matrix of differences. A simple program was created to compute the mean and maximum difference. The results are summarized in Table 2. The features tested in each simulation are summarized in Table 2, along with the mean and maximum differences between the two codes. The specific details of each test may be examined by retrieving the verification data files from within WinFlow.

The maximum difference for each simulation was a uniform value of 0.000198 feet. The maximum error was constant, probably due to a consistent difference in the computational algorithms used in the C and FORTRAN compilers used for the two codes (Microsoft FORTRAN and Microsoft Visual C++). The mean error for each run varied from a low of 0.00000186 (VER6.WFL) to a high of 0.0000139

(VER7.WFL). In all cases, the differences between the two codes are on the order of 1.0×10^{-6} percent.

Table 2 Mean and maximum differences between WinFlow and SLWL in 12 test cases.

Data File	Uniform	Wells	Ponds	Line-sinks (head)	Line-sinks (flux)	Recharge	Aquifer Type (C/U)	Max. Error	Mean Error
ver1.wfl	✓	✓					C	0.000198	0.0000037
ver2.wfl	✓	✓					U	0.000198	0.0000019
ver3.wfl	✓	✓	✓				C	0.000198	0.0000038
ver4.wfl	✓	✓	✓				U	0.000198	0.0000020
ver5.wfl	✓	✓		✓			C	0.000198	0.0000051
ver6.wfl	✓	✓		✓			U	0.000198	0.0000019
ver7.wfl	✓	✓			✓		C	0.000198	0.0000014
ver8.wfl	✓	✓			✓		U	0.000198	0.0000066
ver9.wfl	✓	✓	✓	✓	✓		C	0.000198	0.0000048
ver10.wfl	✓	✓	✓	✓	✓		U	0.000198	0.0000030
ver11.wfl	✓	✓	✓	✓	✓	✓	C	0.000198	0.0000048
ver12.wfl	✓	✓	✓	✓	✓	✓	U	0.000198	0.0000030

Case 3: Benchmark with Numerical Model

A final test of the steady-state analytic functions in WinFlow is a comparison with a numerical model. The model chosen for comparison is MODFLOW (McDonald and Harbaugh, 1988), which is a three-dimensional, finite-difference ground-water flow model developed by the United States Geological Survey. MODFLOW is one of the most widely used numerical ground-water flow models.

A simple problem involving a single pumping well in a uniform flow field is chosen as the test case. The aquifer is unconfined with homogeneous properties. The model parameters are summarized below for the WinFlow data set.

K = 100 ft/d;

Aquifer bottom elevation = 0.0 ft;

Gradient (i) = 0.001 ft/ft at an angle of 0° to the x-axis;

$Q_o = KiH = 10\ ft^2/d$;

$\phi_o = 100$ ft at ($x_o=0$, $y_o=0$).

A single well located at coordinates (x=5000, y=5000) pumps 100,000 ft^3/d. The WinFlow input data file for this problem is provided on the distribution disk. The file name is "modf1.wfl".

Additional information is required to simulate the same system with a numerical model, such as MODFLOW. A finite-difference grid was constructed measuring 10,000 feet in both the x- and y-directions. There are 125 rows and 125 columns in the grid, with a cell spacing of 80 ft. A constant head of 100 ft was placed along the first column and a constant head of 89.532 was placed along the last column. The odd number was used to maintain a constant regional flow of 10 $ft^3/d/ft$ across the finite-difference grid under nonpumping conditions. The MODFLOW data set for this problem are contained on the WinFlow disk. Several files are required for input to the MODFLOW code. The files have a common root file name of "wflow" and a three-letter extension designating the MODFLOW package name. The MODFLOW files for this problem are as follows:

WFLOW.BAS	Basic Package Input
WFLOW.BCF	Block-Centered-Flow Package Input
WFLOW.SIP	Strongly Implicit Package Input
WFLOW.WEL	Well Package Input
WFLOW.OC	Output Control Input

The WinFlow and MODFLOW calculations were compared by producing a SURFER grid file with 50 rows and 50 columns. The grid corners are located at (x=200, y=200) and (x=9800, y=9800). The two grid files were subtracted from each other to obtain a head difference file. A simple program was written to compute the maximum and mean differences. Contour maps produced for the WinFlow and MODFLOW results are also shown in Figure 1.

In the initial test case, MODFLOW and WinFlow compare favorably, with a maximum error of 0.84 feet and a mean error of 0.25 feet. The change in head across the model is 10.468 feet. Thus, there is a maximum difference of about 8 percent between the two codes. The contour maps shown in Figure 1 for the two codes are very similar. The primary difference is the behavior of the contours at the upper and lower (north and south) edge of the model. Contours from the MODFLOW run are perpendicular to the boundary, while WinFlow generated contours hit the boundary at an angle. This happens because MODFLOW treats the edge of the model as a no-flow or impermeable boundary forcing the contours to hit the boundary at right angles. WinFlow, on the other hand, assumes that the aquifer is infinite without any no-flow or impermeable boundaries.

A second test case was simulated by both WinFlow and MODFLOW in which no-flow boundaries were simulated with WinFlow. The northern and southern no-flow boundaries were reproduced in WinFlow using image wells. Two image wells were placed at coordinates (x=5000, y=15000) and (x=5000, y=-5000). Each image well pumped 100,000 ft^3/d. Contour maps for the second test case are shown in Figure 2. Now the WinFlow contours also strike the boundary at close to right angles. The maximum difference between WinFlow and MODFLOW for the second case is 0.39 feet, with a mean difference of 0.11 feet. This represents a significant improvement over the first test case. The maximum difference is 3.7 percent in this case.

The two test cases presented for the benchmark between WinFlow and MODFLOW show that both codes calculate similar head fields for the same problem. Even though the method of solution is different (analytical vs. numerical), each software package gives similar results. These comparisons provide the user with confidence that WinFlow is solving the ground-water flow equations properly.

MODFLOW

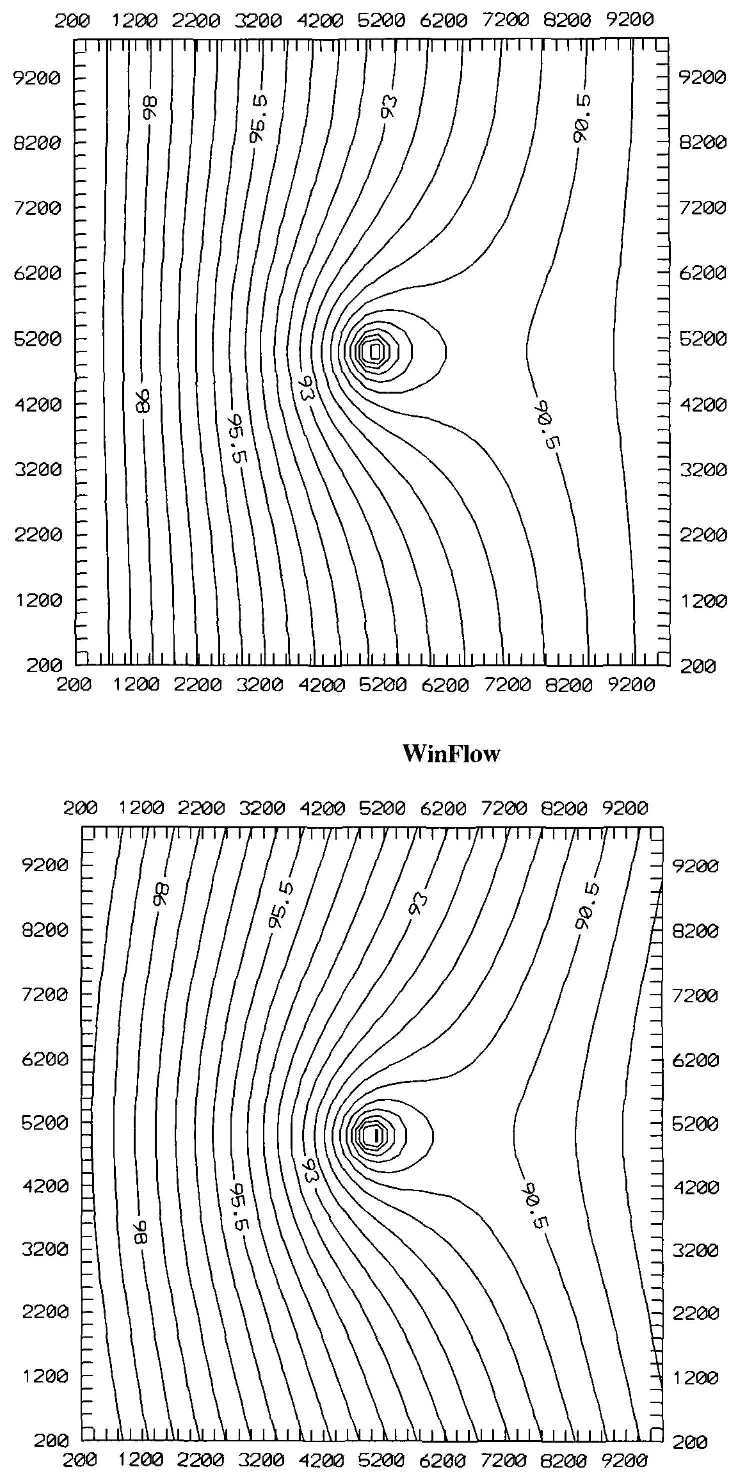
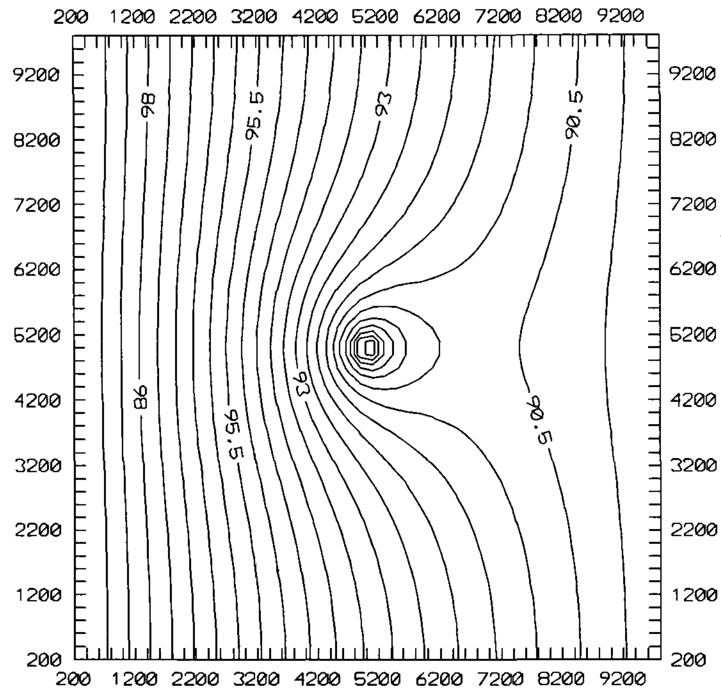


Figure 1. Comparison between WinFlow and MODFLOW for Test Case 1.

MODFLOW



WinFlow with Image Wells

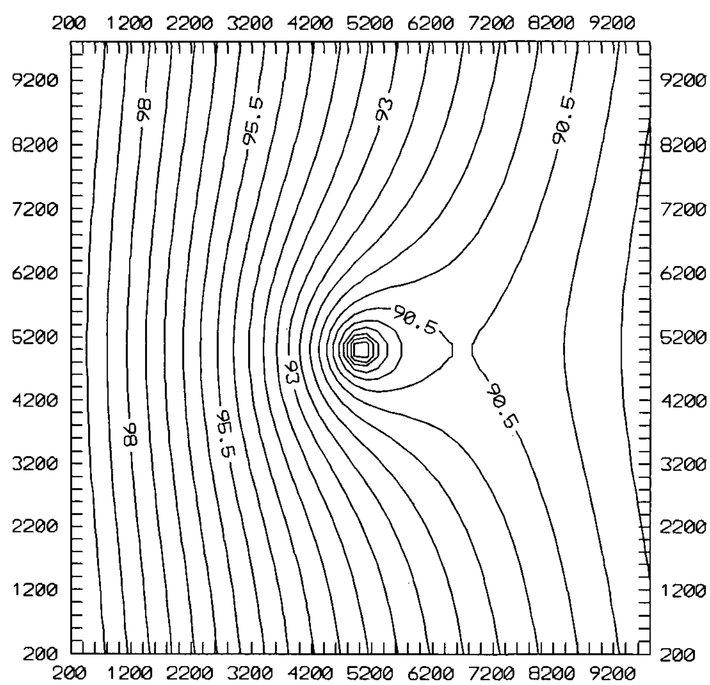


Figure 2. Comparison between WinFlow and MODFLOW for Test Case 2.

Transient Model

Three sets of verification problems are presented for the transient analytical functions used in WinFlow. In the first problem, drawdown is computed for a single well. In the second case, a uniform regional gradient is added to the problem. In each of the first two test cases, WinFlow calculations are compared to those performed with a calculator. The final test presents tables of the Theis (1935) and Hantush and Jacob (1955) well functions for comparison with published tables.

Case 1: Drawdown from a Single Well

The drawdown due to a single pumping well may be computed for any point in an aquifer using the following equation (Theis 1935):

$$s = \frac{Q}{4\pi T} W(u)$$

where

s	= drawdown [L],
Q	= well pumping rate [L^3/T],
T	= transmissivity [L^2/T],
u	= (r^2 S)/(4 T t),
r	= distance between well and calculation point,
S	= storage coefficient [dimensionless],
t	= time after start of pumping [T],
W(u)	= Theis well function.

In this example problem, we will choose the values of the parameters so that calculation is straightforward on a hand calculator and published tables of the Theis well function. The following parameters are used for Case 1:

T = 2500 ft^2/d

S = 0.01

t = 1.0 d

Q = 10,000 ft^3/d

WinFlow computed the same values of drawdown (s) as those computed using a calculator to four significant figures. The results of Case 1 are presented in Table 3.

Table 3 Comparison between WinFlow and calculator results for transient case 1.

Radius (ft)	u	W(u)	s (ft)	s (WinFlow)
1.0	10^{-6}	13.24	4.214	4.214
10.0	10^{-4}	8.633	2.748	2.748
20.0	4×10^{-4}	7.247	2.307	2.307
30.0	9×10^{-4}	6.437	2.049	2.049
40.0	1.6×10^{-3}	5.862	1.866	1.866
50.0	2.5×10^{-3}	5.417	1.724	1.724
60.0	3.6×10^{-3}	5.053	1.608	1.608
70.0	4.9×10^{-3}	4.746	1.511	1.511
80.0	6.4×10^{-3}	4.481	1.426	1.426
90.0	8.1×10^{-3}	4.247	1.352	1.352
100.0	0.01	4.038	1.285	1.285

Case 2: Drawdown from a Single Well in a Uniform Flow Field

The same parameters used in Case 1 above will be used in Case 2 and a uniform regional gradient will be added. Assume that the gradient is 0.001 ft/ft, with a reference head of 100 ft at the well. Because the transient model does not assume that the reference head is constant, the reference head may be specified anywhere (even at the well). We will also assume that the origin of the coordinate system (x=0, y=0) is at the well center.

The equation for a single well in a uniform flow field under transient conditions was given in the last chapter as

$$\phi(x, y, t) = C - G(x\cos\alpha + y\sin\alpha) - s$$

where

ϕ	= head [L],
G	= regional gradient [L/L],
α	= angle between regional gradient and x-axis,
(x,y)	= coordinates of calculation point,
t	= time since start of pumping,
s	= drawdown from well,
C	= constant.

The constant, C, is equal to the reference head in this case.

The heads computed by WinFlow and using a hand calculator are presented in Table 4. Again, WinFlow results and the calculator results are identical to six significant figures.

Table 4 Comparison between WinFlow and hand calculations for transient case 2.

X	Y	ϕ	ϕ (WinFlow)

1.0	0.0	95.786	95.786
10.0	0.0	97.152	97.152
20.0	0.0	97.493	97.493
30.0	0.0	97.651	97.651
40.0	0.0	97.734	97.734
50.0	0.0	97.776	97.776
60.0	0.0	97.792	97.792
70.0	0.0	97.789	97.789
80.0	0.0	97.774	97.774
90.0	0.0	97.748	97.748
100.0	0.0	97.715	97.715

Case 3: Calculation of Well Function Tables

The first two transient test cases tested the ability of WinFlow to compute drawdown with and without a regional gradient. These tests illustrated that WinFlow internal drawdown calculations are properly implemented. A further test of the software is calculation of well function tables, which tests WinFlow's ability to accurately compute drawdown over a wide range of conditions.

WinFlow uses two transient analytical functions: (1) the Theis (1935) equation for confined aquifers, and (2) the Hantush and Jacob (1955) equation for semi-confined (or leaky) aquifers. Values of the Theis well function, W(u), were computed using the numerical routines in WinFlow for a wide range of values of u. These calculations are shown in Table 5. These values can be compared to any published values, although the format of the table is identical to that published by Kruseman and deRidder (1990) in Annex 3.1, page 294. Table 5 and Annex 3.1 (Kruseman and deRidder 1990) are identical, illustrating that WinFlow can calculate the Theis well function accurately over a wide range in u.

Similarly, the Hantush and Jacob (1955) well function, W(u,r/L), was computed using the routines in WinFlow for a range of u and r/L values. These are shown in Tables 6, 7, and 8. Kruseman and deRidder (1990) have published similar tables in Annex 4.2 (pages 298 and 299). The Kruseman and deRidder (1990) tables and Tables 6, 7, and 8 are identical, confirming that WinFlow accurately computes values for the Hantush and Jacob leaky well function.

Table 5 Theis well function, W(u), computed using routines in WinFlow.

u	W(u)	W(u 10^{-1})	W(u 10^{-2})	W(u 10^{-3})	W(u 10^{-4})	W(u 10^{-5})	W(u 10^{-6})	W(u 10^{-7})	W(u 10^{-8})	W(u 10^{-9})	W(u 10^{-10})
1.0	2.194e-01	1.823e+00	4.038e+00	6.332e+00	8.633e+00	1.094e+01	1.324e+01	1.554e+01	1.784e+01	2.015e+01	2.245e+01
1.2	1.584e-01	1.660e+00	3.858e+00	6.149e+00	8.451e+00	1.075e+01	1.306e+01	1.536e+01	1.766e+01	1.996e+01	2.227e+01
1.5	1.000e-01	1.464e+00	3.637e+00	5.927e+00	8.228e+00	1.053e+01	1.283e+01	1.514e+01	1.744e+01	1.974e+01	2.204e+01
2.0	4.890e-02	1.223e+00	3.355e+00	5.639e+00	7.940e+00	1.024e+01	1.255e+01	1.485e+01	1.715e+01	1.945e+01	2.176e+01
2.5	2.491e-02	1.044e+00	3.137e+00	5.417e+00	7.717e+00	1.002e+01	1.232e+01	1.462e+01	1.693e+01	1.923e+01	2.153e+01
3.0	1.305e-02	9.057e-01	2.959e+00	5.235e+00	7.535e+00	9.837e+00	1.214e+01	1.444e+01	1.674e+01	1.905e+01	2.135e+01
3.5	6.970e-03	7.942e-01	2.810e+00	5.081e+00	7.381e+00	9.683e+00	1.199e+01	1.429e+01	1.659e+01	1.889e+01	2.120e+01
4.0	3.779e-03	7.024e-01	2.681e+00	4.948e+00	7.247e+00	9.549e+00	1.185e+01	1.415e+01	1.646e+01	1.876e+01	2.106e+01
4.5	2.073e-03	6.253e-01	2.568e+00	4.831e+00	7.129e+00	9.432e+00	1.173e+01	1.404e+01	1.634e+01	1.864e+01	2.094e+01
5.0	1.148e-03	5.598e-01	2.468e+00	4.726e+00	7.024e+00	9.326e+00	1.163e+01	1.393e+01	1.623e+01	1.854e+01	2.084e+01
6.0	3.601e-04	4.544e-01	2.295e+00	4.545e+00	6.842e+00	9.144e+00	1.145e+01	1.375e+01	1.605e+01	1.835e+01	2.066e+01
7.0	1.155e-04	3.738e-01	2.151e+00	4.392e+00	6.688e+00	8.990e+00	1.129e+01	1.359e+01	1.590e+01	1.820e+01	2.050e+01
8.0	3.767e-05	3.106e-01	2.027e+00	4.259e+00	6.554e+00	8.856e+00	1.116e+01	1.346e+01	1.576e+01	1.807e+01	2.037e+01
9.0	1.245e-05	2.602e-01	1.919e+00	4.142e+00	6.437e+00	8.739e+00	1.104e+01	1.334e+01	1.565e+01	1.795e+01	2.025e+01

Table 6 Hantush well function, W(u,r/L), computed using routines in WinFlow.

u	r/L = 0	0.005	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
1.0e-06	1.32e+01	1.08e+01	9.44e+00	8.06e+00	7.25e+00	6.67e+00	6.23e+00	5.87e+00	5.56e+00	5.29e+00	5.06e+00
2.0e-06	1.25e+01	1.08e+01	9.44e+00	8.06e+00	7.25e+00	6.67e+00	6.23e+00	5.87e+00	5.56e+00	5.29e+00	5.06e+00
4.0e-06	1.19e+01	1.07e+01	9.44e+00	8.06e+00	7.25e+00	6.67e+00	6.23e+00	5.87e+00	5.56e+00	5.29e+00	5.06e+00
6.0e-06	1.14e+01	1.06e+01	9.44e+00	8.06e+00	7.25e+00	6.67e+00	6.23e+00	5.87e+00	5.56e+00	5.29e+00	5.06e+00
8.0e-06	1.12e+01	1.05e+01	9.43e+00	8.06e+00	7.25e+00	6.67e+00	6.23e+00	5.87e+00	5.56e+00	5.29e+00	5.06e+00
1.0e-05	1.09e+01	1.04e+01	9.42e+00	8.06e+00	7.25e+00	6.67e+00	6.23e+00	5.87e+00	5.56e+00	5.29e+00	5.06e+00
2.0e-05	1.02e+01	9.95e+00	9.30e+00	8.06e+00	7.25e+00	6.67e+00	6.23e+00	5.87e+00	5.56e+00	5.29e+00	5.06e+00
4.0e-05	9.55e+00	9.40e+00	9.01e+00	8.03e+00	7.25e+00	6.67e+00	6.23e+00	5.87e+00	5.56e+00	5.29e+00	5.06e+00
6.0e-05	9.14e+00	9.04e+00	8.77e+00	7.98e+00	7.24e+00	6.67e+00	6.23e+00	5.87e+00	5.56e+00	5.29e+00	5.06e+00
8.0e-05	8.86e+00	8.78e+00	8.57e+00	7.91e+00	7.23e+00	6.67e+00	6.23e+00	5.87e+00	5.56e+00	5.29e+00	5.06e+00
1.0e-04	8.63e+00	8.57e+00	8.40e+00	7.84e+00	7.21e+00	6.67e+00	6.23e+00	5.87e+00	5.56e+00	5.29e+00	5.06e+00
2.0e-04	7.94e+00	7.91e+00	7.82e+00	7.50e+00	7.07e+00	6.62e+00	6.22e+00	5.86e+00	5.56e+00	5.29e+00	5.06e+00
4.0e-04	7.25e+00	7.23e+00	7.19e+00	7.01e+00	6.76e+00	6.45e+00	6.14e+00	5.83e+00	5.55e+00	5.29e+00	5.06e+00
6.0e-04	6.84e+00	6.83e+00	6.80e+00	6.68e+00	6.50e+00	6.27e+00	6.02e+00	5.77e+00	5.51e+00	5.27e+00	5.05e+00
8.0e-04	6.55e+00	6.55e+00	6.52e+00	6.43e+00	6.29e+00	6.11e+00	5.91e+00	5.69e+00	5.46e+00	5.25e+00	5.04e+00
1.0e-03	6.33e+00	6.33e+00	6.31e+00	6.23e+00	6.12e+00	5.97e+00	5.80e+00	5.61e+00	5.41e+00	5.21e+00	5.01e+00
2.0e-03	5.64e+00	5.64e+00	5.63e+00	5.59e+00	5.53e+00	5.45e+00	5.35e+00	5.24e+00	5.12e+00	4.98e+00	4.85e+00
4.0e-03	4.95e+00	4.95e+00	4.94e+00	4.92e+00	4.89e+00	4.85e+00	4.80e+00	4.74e+00	4.67e+00	4.59e+00	4.51e+00
6.0e-03	4.54e+00	4.54e+00	4.54e+00	4.53e+00	4.51e+00	4.48e+00	4.45e+00	4.41e+00	4.36e+00	4.30e+00	4.24e+00
8.0e-03	4.26e+00	4.26e+00	4.26e+00	4.25e+00	4.23e+00	4.21e+00	4.19e+00	4.15e+00	4.12e+00	4.08e+00	4.03e+00
1.0e-02	4.04e+00	4.04e+00	4.04e+00	4.03e+00	4.02e+00	4.00e+00	3.98e+00	3.95e+00	3.93e+00	3.89e+00	3.86e+00
2.0e-02	3.35e+00	3.35e+00	3.35e+00	3.35e+00	3.34e+00	3.34e+00	3.33e+00	3.31e+00	3.30e+00	3.28e+00	3.26e+00
4.0e-02	2.68e+00	2.68e+00	2.68e+00	2.68e+00	2.68e+00	2.67e+00	2.67e+00	2.66e+00	2.66e+00	2.65e+00	2.64e+00
6.0e-02	2.30e+00	2.30e+00	2.29e+00	2.29e+00	2.29e+00	2.29e+00	2.29e+00	2.28e+00	2.28e+00	2.27e+00	2.27e+00
8.0e-02	2.03e+00	2.03e+00	2.03e+00	2.03e+00	2.02e+00	2.02e+00	2.02e+00	2.02e+00	2.02e+00	2.01e+00	2.01e+00
1.0e-01	1.82e+00	1.82e+00	1.82e+00	1.82e+00	1.82e+00	1.82e+00	1.82e+00	1.82e+00	1.81e+00	1.81e+00	1.81e+00
2.0e-01	1.22e+00	1.22e+00	1.22e+00	1.22e+00	1.22e+00	1.22e+00	1.22e+00	1.22e+00	1.22e+00	1.22e+00	1.22e+00
4.0e-01	7.02e-01	7.02e-01	7.02e-01	7.02e-01	7.02e-01	7.02e-01	7.02e-01	7.02e-01	7.01e-01	7.01e-01	7.00e-01
6.0e-01	4.54e-01	4.54e-01	4.54e-01	4.54e-01	4.54e-01	4.54e-01	4.54e-01	4.54e-01	4.54e-01	4.54e-01	4.53e-01
8.0e-01	3.11e-01	3.11e-01	3.11e-01	3.11e-01	3.11e-01	3.10e-01	3.10e-01	3.10e-01	3.10e-01	3.10e-01	3.10e-01

Table 7 Hantush well function, W(u,r/L), computed using routines in WinFlow.

u	r/L = 0	0.1	0.2	0.3	0.4	0.6	0.8
1.0e- 04	8.63e+00	4.85e+00	3.51e+00	2.74e+00	2.23e+00	1.56e+00	1.13e+00
2.0e- 04	7.94e+00	4.85e+00	3.51e+00	2.74e+00	2.23e+00	1.56e+00	1.13e+00
4.0e- 04	7.25e+00	4.85e+00	3.51e+00	2.74e+00	2.23e+00	1.56e+00	1.13e+00
6.0e- 04	6.84e+00	4.85e+00	3.51e+00	2.74e+00	2.23e+00	1.56e+00	1.13e+00
8.0e- 04	6.55e+00	4.84e+00	3.51e+00	2.74e+00	2.23e+00	1.56e+00	1.13e+00
1.0e- 03	6.33e+00	4.83e+00	3.51e+00	2.74e+00	2.23e+00	1.56e+00	1.13e+00
2.0e- 03	5.64e+00	4.71e+00	3.50e+00	2.74e+00	2.23e+00	1.56e+00	1.13e+00
4.0e- 03	4.95e+00	4.42e+00	3.48e+00	2.74e+00	2.23e+00	1.56e+00	1.13e+00
6.0e- 03	4.54e+00	4.18e+00	3.43e+00	2.74e+00	2.23e+00	1.56e+00	1.13e+00
8.0e- 03	4.26e+00	3.98e+00	3.36e+00	2.73e+00	2.23e+00	1.56e+00	1.13e+00
1.0e- 02	4.04e+00	3.82e+00	3.29e+00	2.71e+00	2.23e+00	1.56e+00	1.13e+00
2.0e- 02	3.35e+00	3.24e+00	2.95e+00	2.57e+00	2.18e+00	1.55e+00	1.13e+00
4.0e- 02	2.68e+00	2.63e+00	2.48e+00	2.27e+00	2.02e+00	1.52e+00	1.13e+00
6.0e- 02	2.30e+00	2.26e+00	2.17e+00	2.02e+00	1.85e+00	1.46e+00	1.11e+00
8.0e- 02	2.03e+00	2.00e+00	1.94e+00	1.83e+00	1.69e+00	1.39e+00	1.08e+00
1.0e- 01	1.82e+00	1.80e+00	1.75e+00	1.67e+00	1.56e+00	1.31e+00	1.05e+00
2.0e- 01	1.22e+00	1.22e+00	1.19e+00	1.16e+00	1.11e+00	9.96e- 01	8.58e- 01
4.0e- 01	7.02e- 01	7.00e- 01	6.93e- 01	6.81e- 01	6.65e- 01	6.21e- 01	5.65e- 01
6.0e- 01	4.54e- 01	4.53e- 01	4.50e- 01	4.44e- 01	4.36e- 01	4.15e- 01	3.87e- 01
8.0e- 01	3.11e- 01	3.10e- 01	3.08e- 01	3.05e- 01	3.01e- 01	2.89e- 01	2.73e- 01
1.0e+00	2.19e- 01	2.19e- 01	2.18e- 01	2.16e- 01	2.14e- 01	2.06e- 01	1.97e- 01
2.0e+00	4.89e- 02	4.89e- 02	4.87e- 02	4.85e- 02	4.82e- 02	4.72e- 02	4.60e- 02

Table 8 Hantush well function, W(u,r/L), computed using routines in WinFlow.

u	r/L = 0	1.0	2.0	3.0	4.0	5.0	6.0
1.0e-02	4.04e+00	8.42e-01	2.28e-01	6.95e-02	2.23e-02	7.38e-03	2.49e-03
2.0e-02	3.35e+00	8.42e-01	2.28e-01	6.95e-02	2.23e-02	7.38e-03	2.49e-03
4.0e-02	2.68e+00	8.42e-01	2.28e-01	6.95e-02	2.23e-02	7.38e-03	2.49e-03
6.0e-02	2.30e+00	8.39e-01	2.28e-01	6.95e-02	2.23e-02	7.38e-03	2.49e-03
8.0e-02	2.03e+00	8.32e-01	2.28e-01	6.95e-02	2.23e-02	7.38e-03	2.49e-03
1.0e-01	1.82e+00	8.19e-01	2.28e-01	6.95e-02	2.23e-02	7.38e-03	2.49e-03
2.0e-01	1.22e+00	7.15e-01	2.27e-01	6.95e-02	2.23e-02	7.38e-03	2.49e-03
4.0e-01	7.02e-01	5.02e-01	2.10e-01	6.91e-02	2.23e-02	7.38e-03	2.49e-03
6.0e-01	4.54e-01	3.54e-01	1.77e-01	6.64e-02	2.22e-02	7.38e-03	2.49e-03
8.0e-01	3.11e-01	2.54e-01	1.44e-01	6.07e-02	2.17e-02	7.36e-03	2.49e-03
1.0e+00	2.19e-01	1.85e-01	1.14e-01	5.34e-02	2.07e-02	7.27e-03	2.49e-03
2.0e+00	4.89e-02	4.44e-02	3.34e-02	2.10e-02	1.12e-02	5.13e-03	2.10e-03
4.0e+00	3.78e-03	3.58e-03	3.06e-03	2.35e-03	1.63e-03	1.03e-03	5.86e-04

Transport Model

Introduction

The finite-element transport model in WinTran is verified through comparison with an analytical solution from Wexler (1992) and with another finite-element transport model called SEFTRAN (Huyakorn et al., 1984). The Wexler analytical solution models transport of a dissolved contaminant from a point source in a two-dimensional uniform flow field. Six test cases were investigated with SEFTRAN for the three different source configurations (injection well, pond, and linesink) in both uniform flow and in non-uniform flow fields.

Comparison to an Analytical Solution

Wexler (1992) presents a series of analytical solutions to the partial differential equations of dissolved contaminant transport in porous media. WinTran was compared to the solution for a continuous point source in an aquifer of infinite extent (see page 26 of Wexler, 1992). The analytical solution was implemented by Wexler in a FORTRAN program called POINT2.

The data for the test problem are presented in Table 1. Concentration is plotted versus time at two locations downgradient of the source for both WinTran and SEFTRAN (see Figure 1). These curves show that WinTran results are virtually identical to those of the analytical solution. Contours for both WinTran results and POINT2 results are shown in Figure 2. Again, these contours are almost identical for the two solutions. The largest difference is at the source, where WinTran slightly underpredicts the source concentration. This is probably caused by dilution of the source concentration in the finite-element cell. The majority of the plume, however, matches quite well between WinTran and POINT2.

Comparison of WinTran to an analytical solution confirms that the basic transport model has been coded properly. The analytical solution, however, assumes that the flow field is uniform and the source is a single point and continuous over time. The next section presents a series of tests that illustrate that WinTran performs properly for more complex scenarios.

Table 1. Model Parameters for the Analytical Solution Comparison

Parameter	Value
Hydraulic conductivity	100 ft/d
Top Elevation	-75 ft
Bottom Elevation	-100 ft
Porosity	0.2
Hydraulic Gradient	0.01 to the East
Groundwater Velocity	5 ft/d
Longitudinal Dispersivity	30 ft
Transverse Dispersivity	3 ft
Retardation Coefficient	1
X coordinate of source	212.32 ft
Y coordinate of source	230.87 ft
Source fluid flow rate	-1 ft^3/d
Source concentration	100
Number of X nodes	70
Number of Y nodes	70
Minimum X coordinate	50.0 ft
Minimum Y coordinate	50.0 ft
Nodal Spacing in X	8.116 ft
Nodal Spacing in Y	5.652 ft
Number of time steps	50
Minimum time step size	0.5 day
Maximum time step size	10 days
Time step multiplier	1.1
Final time value	280.569 days

Figure 1. Time-series comparison between WinTran and an analytical solution at two downgradient nodes

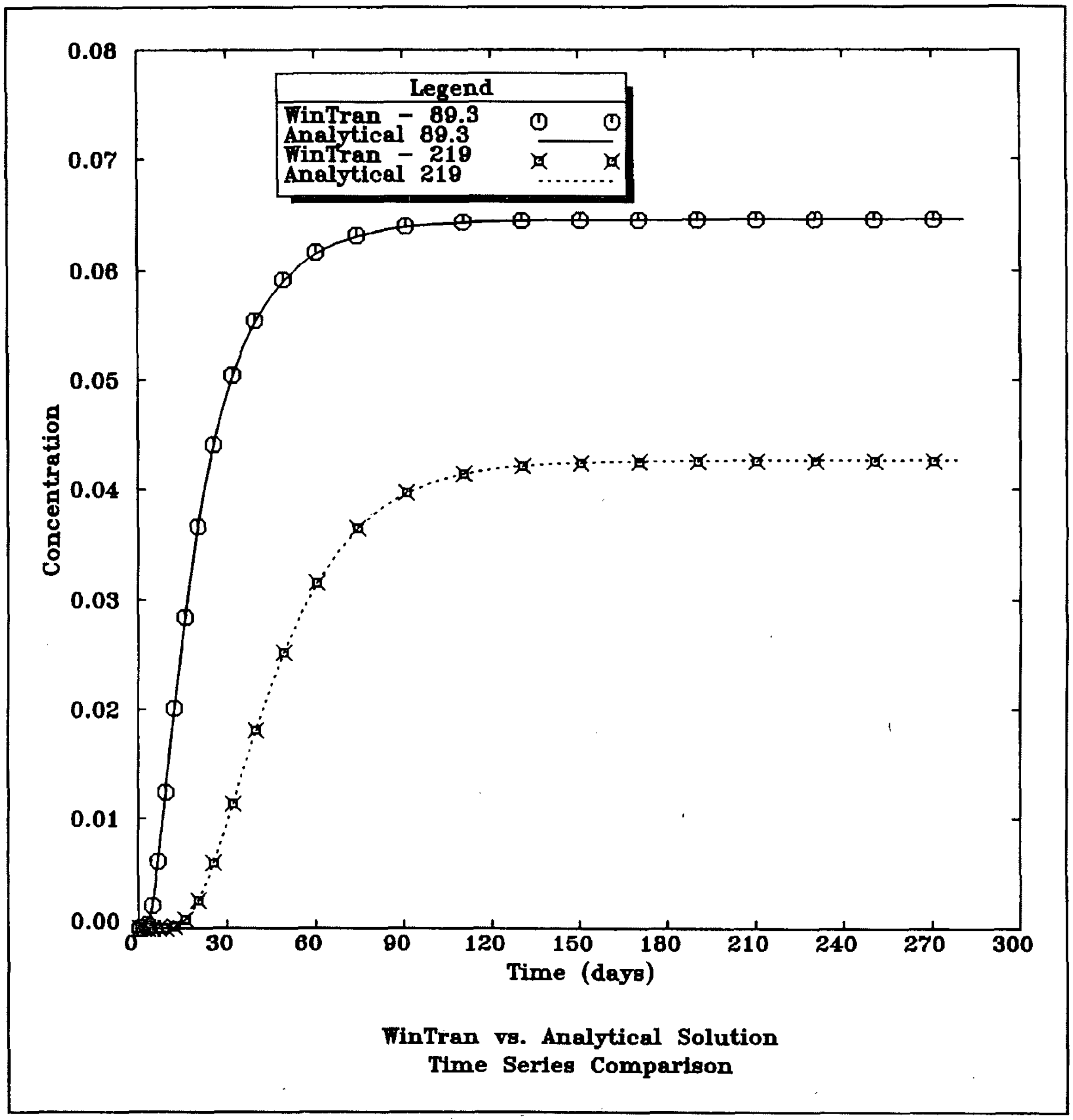
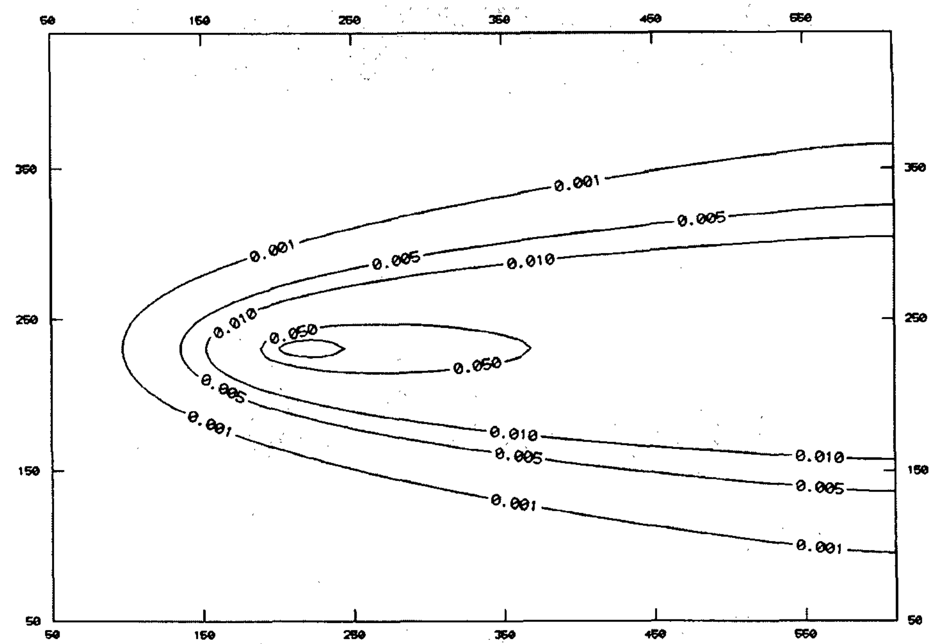
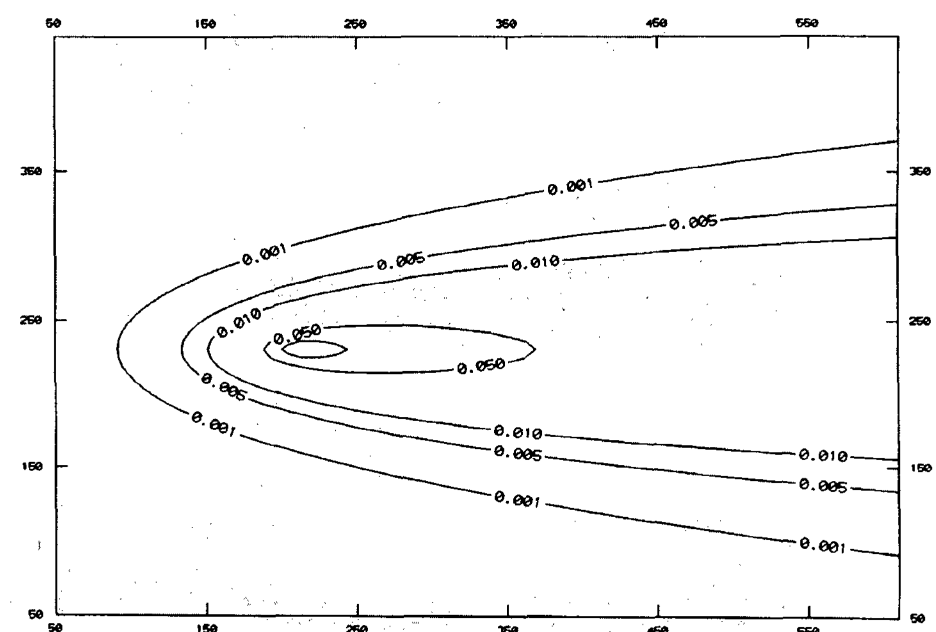


Figure 2. Concentration contours for WinTran and the analytical solution at time=260.569 days.

WinTran



Analytical Model



Benchmarking with SEFTRAN

SEFTRAN (Huyakorn et al., 1984) was chosen for the majority of testing because it uses the same finite-element techniques that are employed by WinTran. SEFTRAN also makes a good choice for benchmark testing because it has undergone a significant amount of testing at the International Ground Water Modeling Center (Huyakorn et al., 1984).

To facilitate this testing, a special option has been added to the WinTran Export menu allowing WinTran to create SEFTRAN data input files. Three files are created, (1) a SEFTRAN flow data set (always called FLOW.IN), (2) a SEFTRAN transport data set (you specify the name in the dialog), and (3) a velocity file with analytically-computed velocities (always called FLOW.VEL).

A series of six simulations were performed to test the three different source configurations (point source using an injection well, pond infiltration, and linesink injection). Each of the three source terms was tested in both a uniform flow field and a non-uniform flow field. The non-uniform flow field was produced by adding a pumping well downgradient from the source. The results for the six simulations are summarized in Table 2 and Table 2b. Data for the simulations are shown in Table 3.

The benchmark simulations are evaluated by presenting the following in Table 2: (1) maximum source concentration computed by WinTran and SEFTRAN, (2) the mean and maximum differences (errors) when SEFTRAN uses WinTran-computed velocities, (3) the mean and maximum differences when SEFTRAN uses SEFTRAN-computed velocities, and (4) mass balance errors for the two models. The source concentrations were scaled to a value of 1.0 in WinTran. The mass balance errors are in percent.

The mean and maximum differences between the two codes are very low for the case when each code uses velocities computed by WinTran. This tests the WinTran transport model because both codes are using the same velocity field. The tests illustrate that the transport model in WinTran is functioning properly for all cases. The mass balance error for each code is comparable for all cases and the source concentrations are accurate to the fourth decimal place.

The second set of errors (differences) presented in Table 2 are for SEFTRAN results computed using velocities computed by the SEFTRAN flow model. In the first set of differences described in the previous paragraph, the SEFTRAN transport model read velocity data computed by WinTran. The second set of comparisons, therefore, are used to evaluate the hybrid modeling approach. The results show that for uniform flow conditions, WinTran and SEFTRAN velocities produce virtually the same results. In a non-uniform flow field, however, the differences are larger. This indicates that the analytically-computed velocities are slightly in error.

Table 2b presents the differences between SEFTRAN and WinTran when velocities in WinTran are computed using finite elements (rather than the analytical model). In this case, the differences are very minor. Thus, for complex flow fields, you may want to consider using the finite-element flow model to compute velocities. You may select this option using the **Model->Flow Model Type** menu.

Figures 3 through 8 present concentration contour maps created by WinTran and SEFTRAN. These figures further substantiate that the two models are producing the same results.

Table 2. Comparison Between WinTran and SEFTRAN for Six Simulations.

Description	Maximum Conc. WinTran	Maximum Conc. Seftran	WinTran Velocities Mean Error	WinTran Velocities Maximum Error	Seftran Velocities Mean Error	Seftran Velocities Maximum Error	Mass Balance Error WinTran	Mass Balance Error Seftran
Test 1 Point Source Uniform Flow	1.0	1.000052	-1.1e-05	7.5e-05	3.8e-05	7.0e-05	0.0129	0.00082
Test 2 Pond Source Uniform Flow	1.0	1.00024	-4.2e-05	2.4e-04	4.9e-05	1.99e-04	0.00758	0.0069
Test 3 Line Source Uniform Flow	1.0	0.99992	1.66e-05	2.04e-04	1.47e-04	2.4e-03	0.00438	0.018
Test 4 Point Source Nonuniform Flow	1.0	1.00005	-9.8e-06	7.3e-05	7.5e-06	5.8e-03	0.2057	0.195
Test 5 Pond Source Nonuniform Flow	1.0	0.99996	7.5e-06	7.23e-05	2.0e-05	0.045	0.147	0.136
Test 6 Line Source Nonuniform Flow	1.0	0.99991	1.06e-05	1.4e-04	4.2e-05	0.025	0.056	0.046

Table 2b. Comparison Between WinTran (Using the Finite Element Flow Model) and SEFTRAN for the Nonuniform Flow Test Cases.

Description	Mean Error	Maximum Error	WinTran Mass Balance Error
Test 4	-6.33e-06	6.78e-05	0.145
Test 5	1.3e-06	1.4e-04	0.161
Test 6	2.6e-05	2.7e-04	0.20

Table 3. Model Parameters for the SEFTRAN Benckmarking

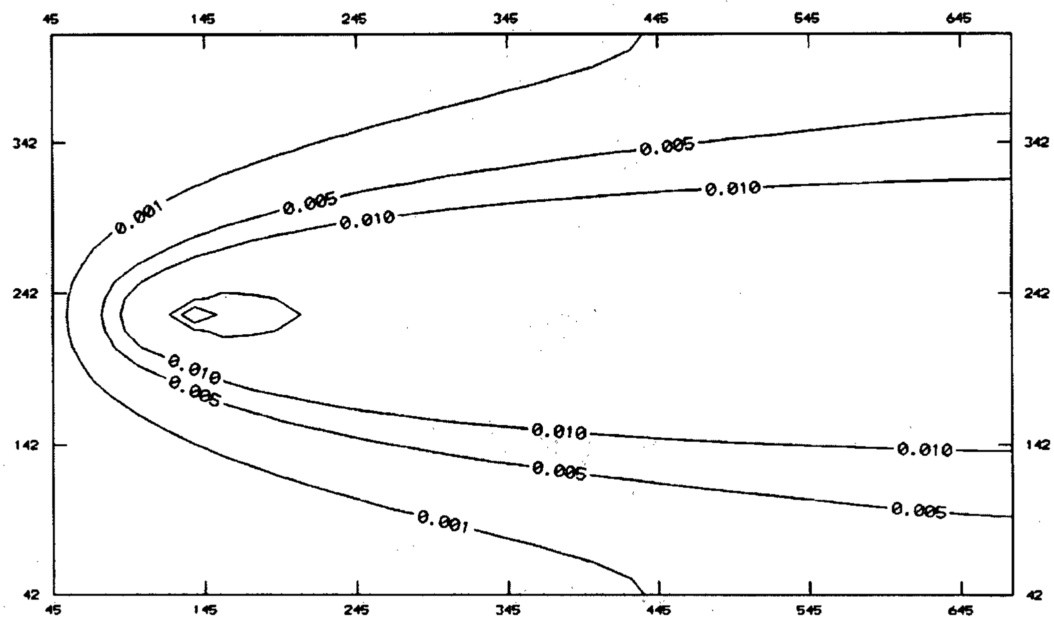
Parameter	Value
Hydraulic conductivity	100 ft/d
Top Elevation	100 ft
Bottom Elevation	0 ft
Reference Head	25 ft at (75,65)
Porosity	0.2
Hydraulic Gradient	0.01 to the East
Longitudinal Dispersivity	30 ft
Transverse Dispersivity	6 ft
Retardation Coefficient	1
Number of X nodes	35
Number of Y nodes	35
Minimum X coordinate	45.03 ft
Minimum Y coordinate	42.29 ft
Maximum X coordinate	678.81 ft
Maximum Y coordinate	413.66 ft
Number of time steps	30
Minimum time step size	1 day
Maximum time step size	100 days
Time step multiplier	1.2
Point Source Information (Simulation 1 and 4)	
Fluid Injection Rate	-1.0 ft^3/d
Concentration in fluid	100
Coordinates of Well (x,y)	(138.23,227.98)
Pumping Well Information (Simulations 4 through 6)	
Pumping Rate	10,000 ft^3/d
Coordinates of Well (x,y)	(604.25,315.36)

Table 3 (continued). Model Parameters for the SEFTRAN Benckmarking

<u>Linesink Source Information (Simulations 3 and 6)</u>	
Linesink Injection Rate	-1 ft^2/d
Concentration in fluid	100
Beginning Coordinates of line (x,y)	(145.27,275.11)
Ending Coordinates of line (x,y)	(143.65,167.59)
<u>Pond Source Information (Simulations 2 and 5)</u>	
Pond Infiltration Rate	0.0015 ft/d
Concentration in fluid	100
Pond Radius	24.68 ft
Coordinates of pond center (x,y)	(137.99,227.41)

Figure 3. Concentration contours for WinTran and SEFTRAN at the final time step for Test Case 1.

WinTran Results



SEFTRAN Results

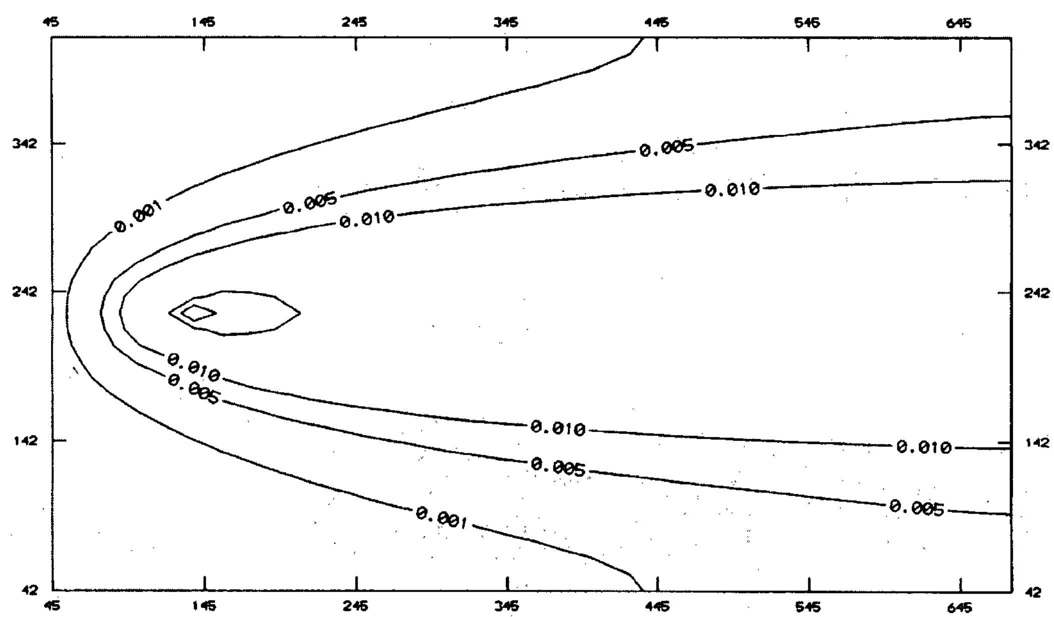
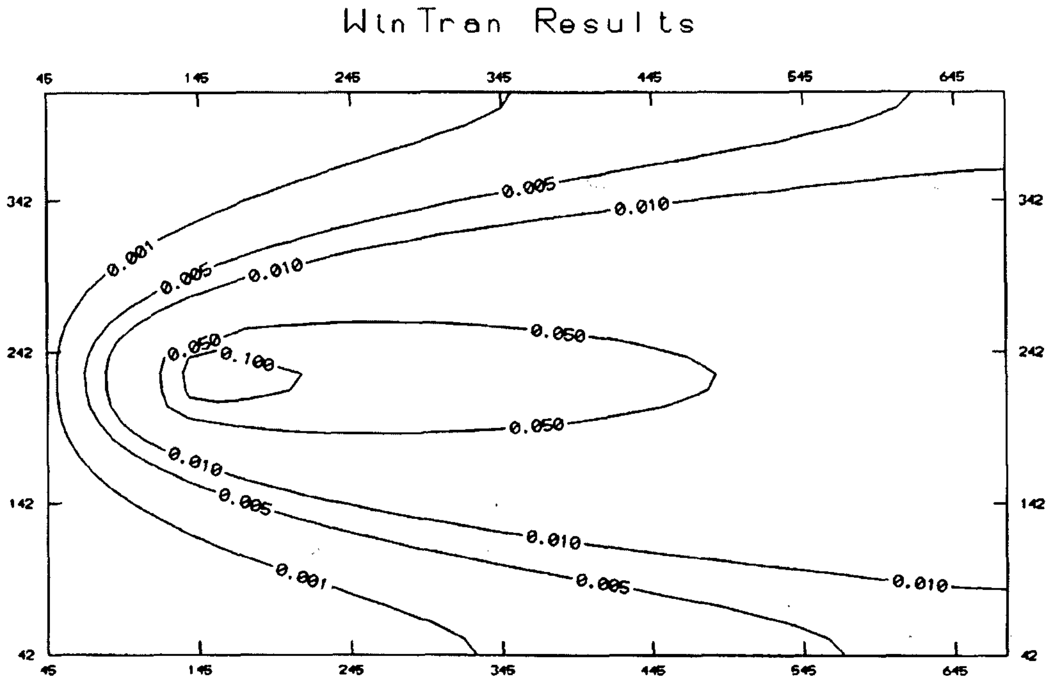
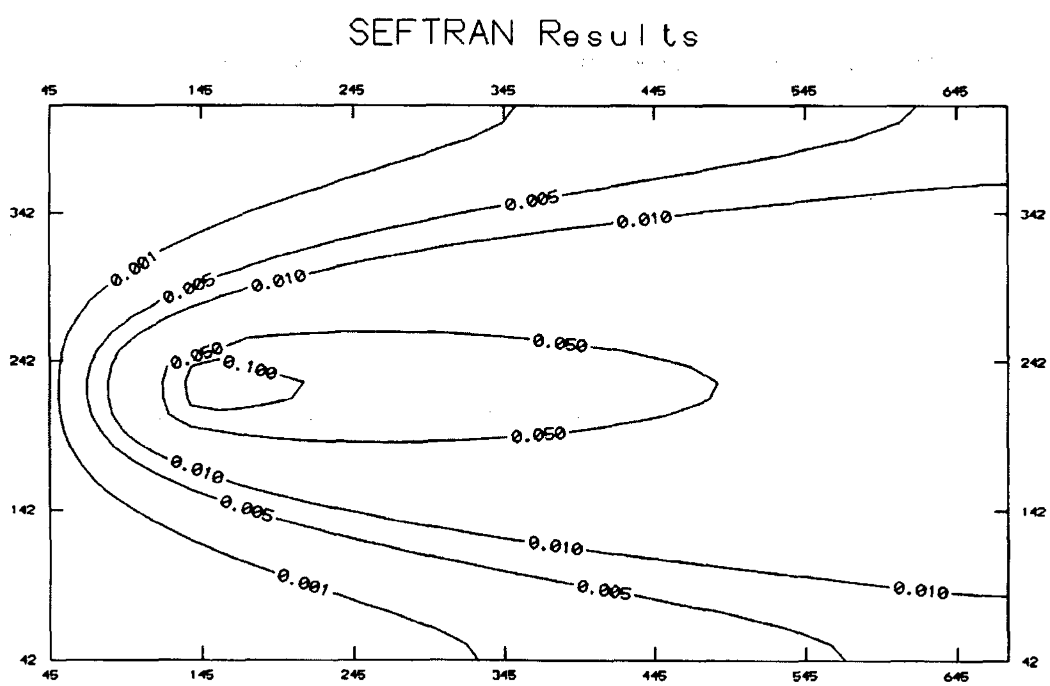


Figure 4. Concentration contours for WinTran and SEFTRAN at the final time step for Test Case 2.



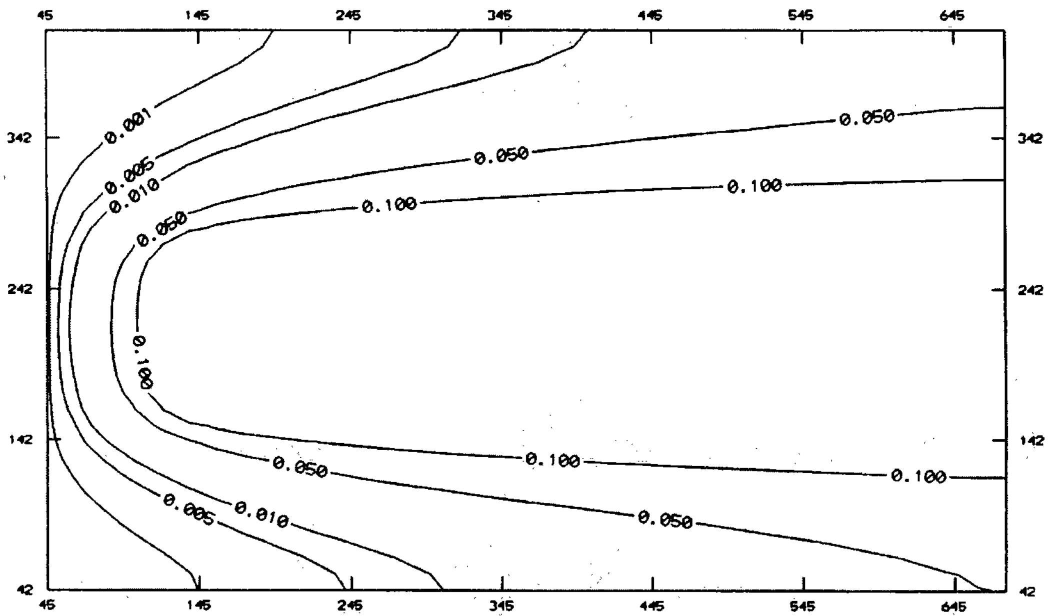
WinTran Results
45
145
245
345
445
545
645
342
242
142
42
0.001
0.005
0.010
0.050
0.100



SEFTRAN Results
45
145
245
345
445
545
645
342
242
142
42
0.001
0.005
0.010
0.050
0.100

Figure 5. Concentration contours for WinTran and SEFTRAN at the final time step for Test Case 3.

WinTran Results



SEFTRAN Results

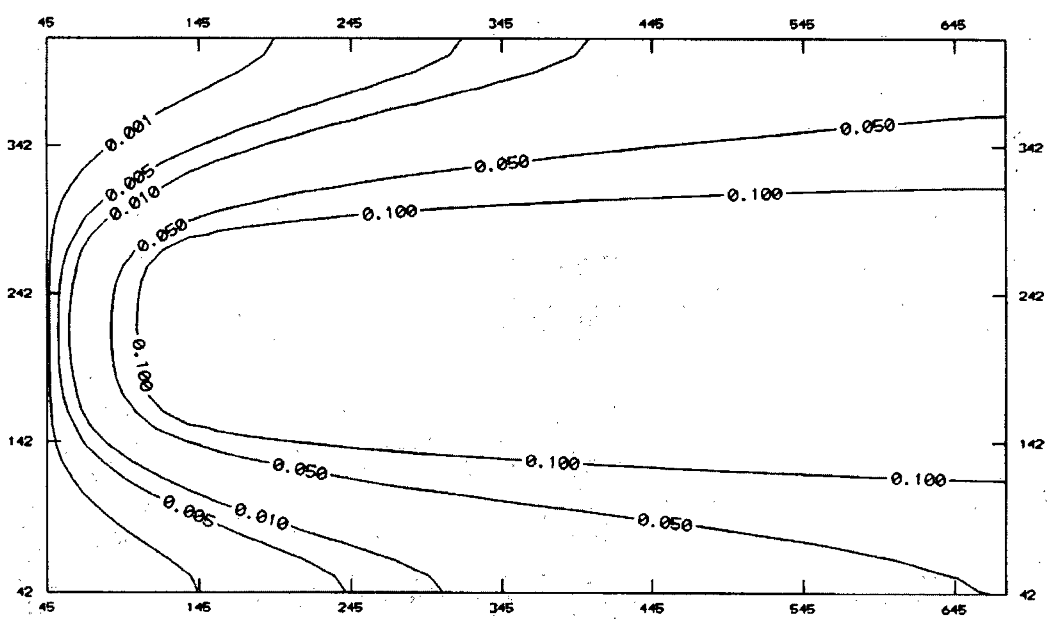
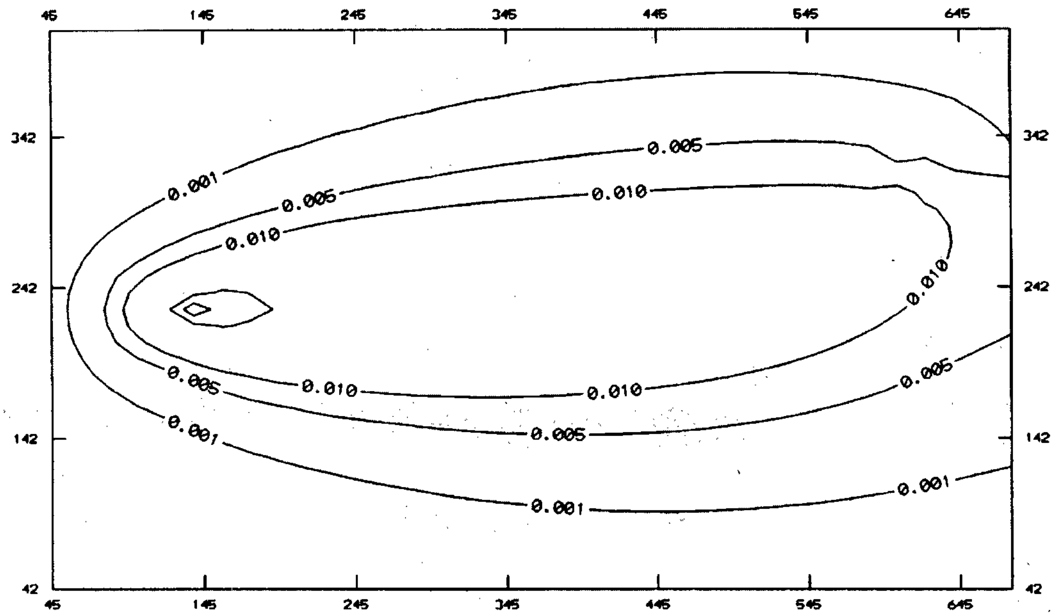


Figure 6. Concentration contours for WinTran and SEFTRAN at the final time step for Test Case 4.

WinTran Results



SEFTRAN Results

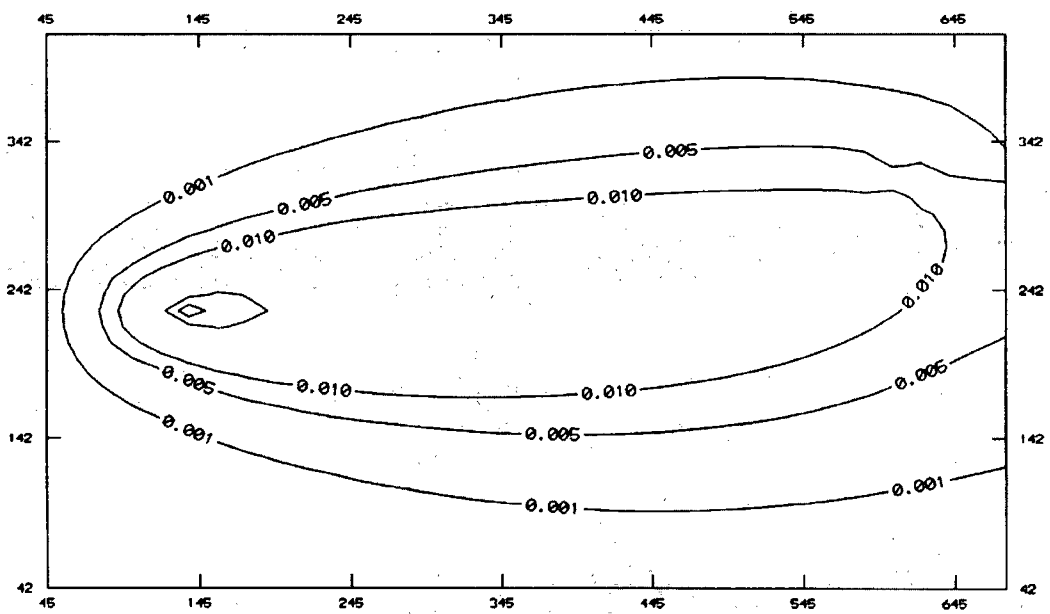
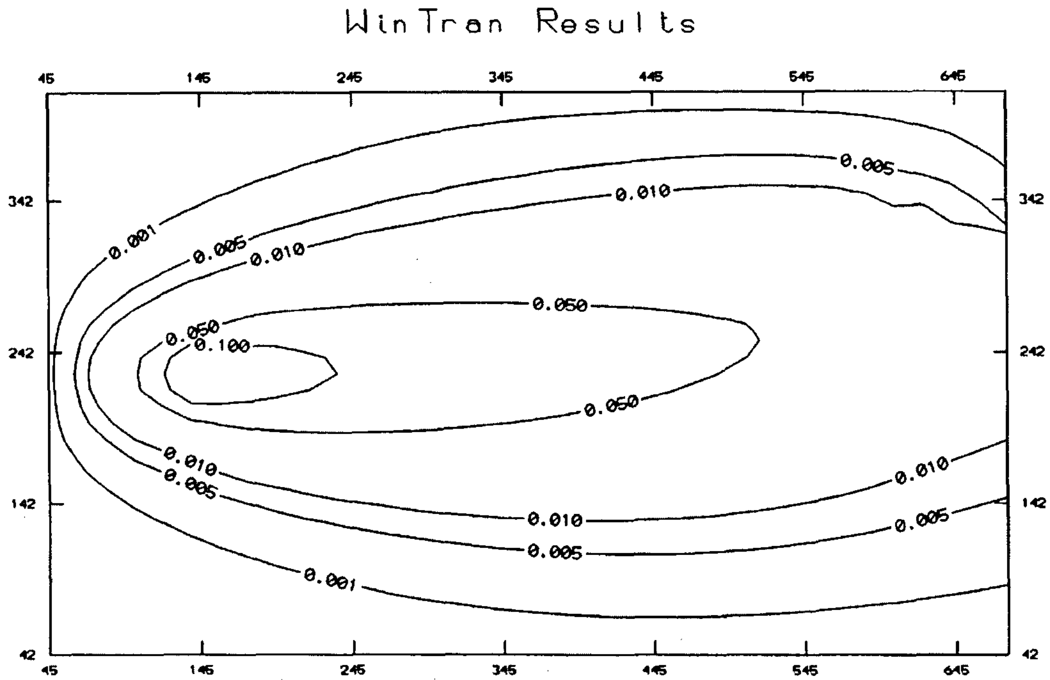
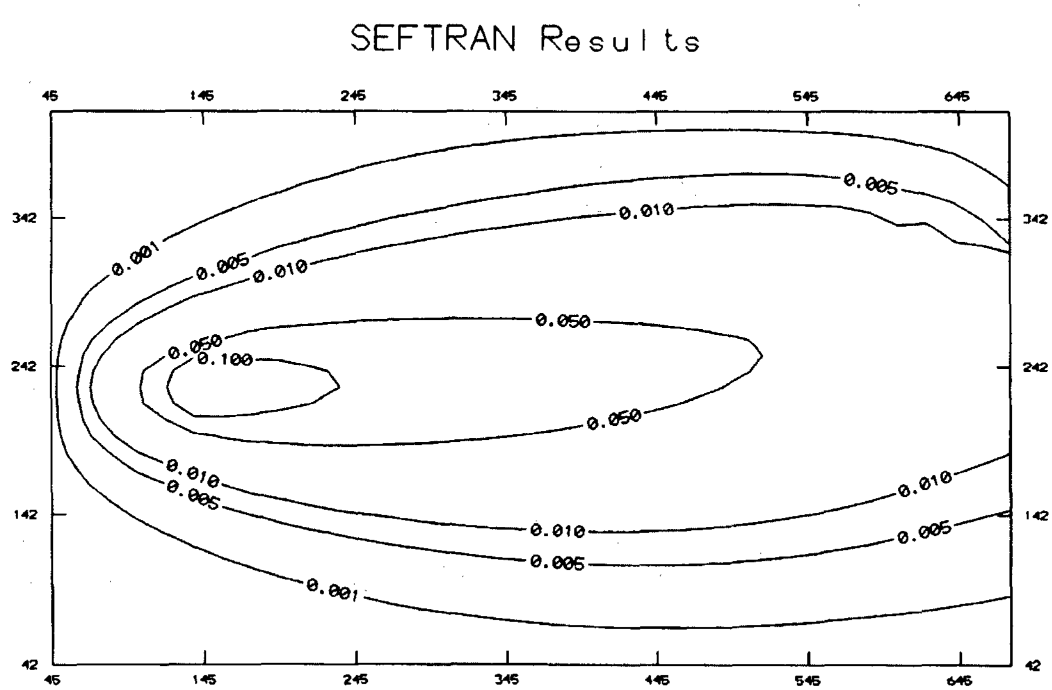


Figure 7. Concentration contours for WinTran and SEFTRAN at the final time step for Test Case 5.



WinTran Results
45
145
245
345
445
545
645
342
242
142
42
0.001
0.005
0.010
0.050
0.100



SEFTRAN Results
45
145
245
345
445
545
645
342
242
142
42
0.001
0.005
0.010
0.050
0.100

Figure 8. Concentration contours for WinTran and SEFTRAN at the final time step for Test Case 6.

WinFlow Application Guide

WinFlow Assumptions

It is important to understand the many simplifying assumptions inherent in an analytical model before the model can be applied to a real-world problem. Chapter 5 described the equations that are solved in WinFlow. Chapter 6 verified that these equations are properly implemented in the WinFlow software. This chapter presents potential applications of WinFlow to the solution of ground-water problems. First, however, some important assumptions are discussed as they apply to the practical application of WinFlow. For easy identification, the primary assumptions are underlined.

WinFlow is designed to solve two-dimensional ground-water flow problems in a horizontal plane. It is not designed for two-dimensional cross-sections (2D vertical plane). The two primary assumptions are that ground-water flow is horizontal and occurs in an infinite aquifer. WinFlow should not be applied to aquifers exhibiting strong vertical gradients unless the scale of the problem is such that horizontal flow can still be considered dominant. WinFlow can be used even in cases where there are significant vertical gradients if the horizontal scale of the model is much larger than the vertical scale, such as in regional studies.

Another assumption is that the aquifer hydraulic conductivity is assumed to be isotropic and homogeneous. The base of the aquifer is horizontal and fixed at a given elevation. In the steady-state and transient models, the top of the aquifer is also horizontal and fixed at a given elevation. In the steady-state model, however, unconfined conditions are simulated when the hydraulic head is below the top of the aquifer. In the transient model, the aquifer is always confined, even when the head falls below the top of the aquifer.

The reference head in the steady-state model is constant throughout all calculations. The reference head is analogous to a constant head boundary condition in a numerical model. It is therefore very important to keep the reference head far from the area of interest so that model predictions are not impacted.

The reference head in the transient model is only used in combination with the uniform gradient to compute an initial planar potentiometric surface. Drawdowns computed by either the Theis (1935) or the Hantush and Jacob (1955) methods are then subtracted from the planar potentiometric surface to obtain the resulting flow field. Drawdowns are also subtracted from the reference head in the transient model; however, there is an option that allows the user to keep the reference head constant in the transient model. This option should only be used when trying to compare the transient model to the steady-state model.

All pumping rates, linesink fluxes, pond recharge, and elliptical recharge rates are constant through time. In the transient model, all wells start pumping or injecting water at time zero.

All wells are assumed to fully penetrate the aquifer. Wells are assumed to be perfectly efficient and linesinks are in perfect hydraulic communication with the aquifer. Both assumptions are rarely encountered in practice. There is often head loss around the well screen or stream bottom caused by clogging of the pore-space by fine-grained material (clay). There are two important consequences of imperfect hydraulic communication.

(1) Pumping rates predicted by WinFlow to achieve a desired response may not be attainable because more drawdown will be encountered in the actual well. The increased drawdown encountered in the field is caused by inefficiency around the well screen. The same effect will happen using linesinks to simulate trenches or drains.

(2) The amount of water produced or injected by a linesink to maintain a specified head in the linesink will be overestimated if the actual drain has less than 100 percent efficiency.

Particle traces and streamlines are two-dimensional. In cases where the aquifer receives recharge, the capture zone of a pumping well will be large enough to capture the amount of recharge equaling the pumping rate of the well (Larson et al., 1987). In two-dimensional analyses, such as in WinFlow, the capture zone extends upgradient until encountering a ground-water divide or infinity. This is an important consideration in designing a containment system.

Analysis of Remedial Actions

WinFlow can provide valuable guidance in designing a ground-water remediation system. The most obvious remedial action that WinFlow can simulate is "pump & treat" where the goal is to contain a volume of contaminated aquifer. WinFlow can simulate the effects of both pumping and injection wells. To illustrate the capture zone of a well, use reverse particle-tracking and start the particles in a circle around the well.

WinFlow can simulate trenches and drains using linesinks. There are two options in simulating drains: (1) specify a head to be maintained in the drain and WinFlow will compute the discharge rate necessary to achieve the given head; or (2) specify the discharge rate and compute the resulting head in the drain. To illustrate the capture zone of the drain, use reverse particle-tracking and start the particles along two lines on either side of the linesink.

WinFlow can simulate a lagoon closure by using ponds. To do this, set up the initial analytical model with ponds that simulate the lagoon. Adjust the pond recharge rate to match field-measured heads. Finally, remove the pond (or set the pond recharge equal to zero) to simulate the effects of closure.

The effects of capping can be simulated with a combination of elliptical recharge and circular ponds. Set up the initial analytical model using recharge to match field-measured heads. A circular cap can then be simulated with a pond that has a recharge rate equivalent to the regional recharge rate but opposite in sign (e.g. negative).

Pumping Test Analysis and Design

WinFlow's transient model can simulate the effects of a pumping test to facilitate interpreting test results or designing a future test. Pumping test results can be interpreted by contouring drawdown at a specified time after the start of the test. To contour drawdown, set the reference head equal to zero and the gradient equal to zero. Make sure that the top of the aquifer is less than zero if the steady-state model is used.

Drawdowns computed by WinFlow can be compared to drawdown contours from the pumping test. Hydraulic conductivity and storage can be adjusted until a reasonable match between observed and computed drawdown is achieved. Image wells can be added to the model to simulate boundary effects. Use calibration targets to provide a quantitative match between the results of your aquifer test and the model calculations.

When designing an aquifer test, WinFlow estimates the drawdown likely to occur at selected times and at various distances from the pumping well. Time and drawdown estimates can help select appropriate wells to monitor and determine the length of the test.

Regional Modeling

Strack (1989) advocates the use of "analytic element models" (his term for the superposition of analytical functions) in regional flow system modeling. At a regional scale, most aquifers are very thin compared to the distance across the aquifer in the horizontal plane. Thus, the z-axis (vertical dimension) becomes quite small and vertical gradients are negligible compared to horizontal gradients. In this case, the problem becomes two-dimensional and can be easily simulated with analytical functions.

The regional model is constructed using linesinks to simulate rivers and streams. Recharge from precipitation is applied in a large ellipse covering the area of interest. Circular recharge areas (ponds) simulate lakes. Obviously, wells represent areas of ground-water extraction, such as wellfields.

Strack (1989) has developed many complex analytical functions or analytic elements to facilitate regional modeling. The Single-Layer Analytic Element Model (SLAEM) developed by Strack contains these advanced functions not available in WinFlow. SLAEM is available from Dr. Strack.

Well Head Protection

Many states are requiring water companies to model the ground-water flow system around all public supply wells to determine the "zone of contribution" for each well. Small water companies will find it difficult to pay for expensive numerical modeling studies. WinFlow is ideally suited for these small wellfields, because a simple regional model can be constructed to comply with wellhead protection regulations at little cost. WinFlow can also be useful for preliminary studies at larger wellfields prior to numerical modeling.

To determine the zone of contribution for a particular time of travel, use reverse particle-tracking. Start the particles in a circle around each well and set the maximum travel time to the desired value.

WinTran Application Guide

Introduction

This chapter presents the major assumptions inherent in WinTran and guidelines for the use of the transport model. These guidelines include estimating memory requirements, dealing with model instabilities, and suggestions for simulating various transport scenarios.

WinTran Assumptions

It is important to understand the many simplifying assumptions inherent in any model before the model can be applied to a real-world problem. This chapter presents potential applications of WinTran to the solution of contaminant fate and transport problems. First, however, some important assumptions are discussed as they apply to practical application of WinTran. For easy identification, the primary assumptions are underlined.

WinTran is designed to solve two-dimensional ground-water flow and transport problems in a horizontal plane. It is not designed for two-dimensional cross-sections (2D vertical plane). <u>The two primary assumptions are that ground-water flow is horizontal and contaminant concentrations are the same throughout the entire aquifer thickness</u>. WinTran should not be applied to aquifers exhibiting strong vertical gradients unless the scale of the problem is such that horizontal flow can still be considered dominant. WinTran can be used even in cases where there are significant vertical gradients if the horizontal scale of the model is much larger than the vertical scale, such as in regional studies.

Another assumption is that the <u>aquifer hydraulic conductivity is assumed to be isotropic and homogeneous.</u> The base of the aquifer is horizontal and fixed at a given elevation. The top of the aquifer is also horizontal and fixed at a given elevation. Unconfined conditions are simulated when the hydraulic head is below the top of the aquifer.

<u>The reference head in the flow model is constant throughout all calculations</u>. The reference head is analogous to a constant head boundary condition in a numerical model. It is therefore very important to keep the reference head far from the area of interest so that model predictions are not impacted.

<u>All pumping rates, linesink fluxes, pond recharge, and elliptical recharge rates are constant through time</u>. The transport model simulates transient movement of the contaminant in this steady-state velocity field.

All wells are assumed to fully penetrate the aquifer. Wells are assumed to be perfectly efficient and linesinks are in perfect hydraulic communication with the aquifer. Both assumptions are rarely encountered in practice. There is often head loss around the well screen or stream bottom caused by clogging of the pore-space by fine-grained material (clay). There are two important consequences of imperfect hydraulic communication.

(1) Pumping rates predicted by WinTran to achieve a desired response may not be attainable because more drawdown will be encountered in the actual well. The increased drawdown encountered in the field is caused by inefficiency around the well screen. The same effect will happen using linesinks to simulate trenches or drains.

(2) The amount of water produced or injected by a linesink to maintain a specified head in the linesink will be overestimated if the actual drain has less than 100 percent efficiency.

Particle traces and streamlines are two-dimensional. In cases where the aquifer receives recharge, the capture zone of a pumping well will be large enough to capture the amount of recharge equaling the pumping rate of the well (Larson et al. 1987). In two-dimensional analyses, such as in WinTran, the capture zone extends upgradient until encountering a ground-water divide or infinity. This is an important consideration in designing a containment system.

Chemical reactions are reduced to two types, (1) linear, fully-reversible sorption using a retardation coefficient, and (2) first-order decay. WinTran can be used to simulate biological decay of organic compounds only if the biological reactions can be reduced to a first-order decay reaction. That is, a contaminant half-life is estimated for the compound.

Memory Requirements

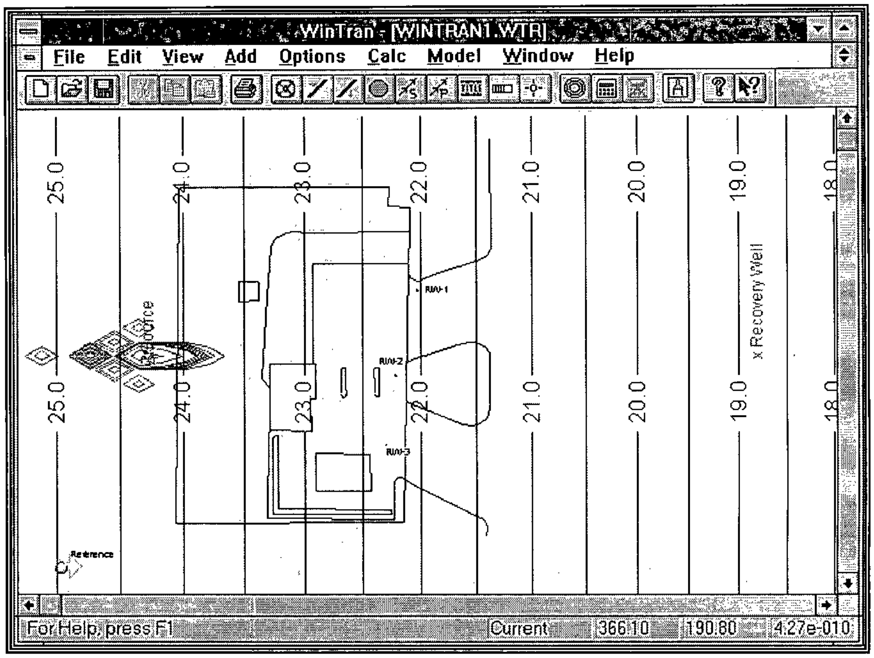
WinTran uses a substantial amount of computer memory to solve the finite-element transport model. The amount of memory required for each model is determined by the size of the contour matrix. The default size of the contour matrix is 35 x 35 (35 nodes in both the X- and Y-directions). In this case, the model requires about 1 megabyte of memory. The maximum matrix size allowed in WinTran is 100 x 100, requiring about 18 megabytes of memory. Other matrix sizes and memory requirements are shown below:

Matrix Size	Memory Required
35 x 35	1 megabyte
50 x 50	2.6 megabytes
75 x 75	8 megabytes
100 x 100	18 megabytes

Problems with Model Stability

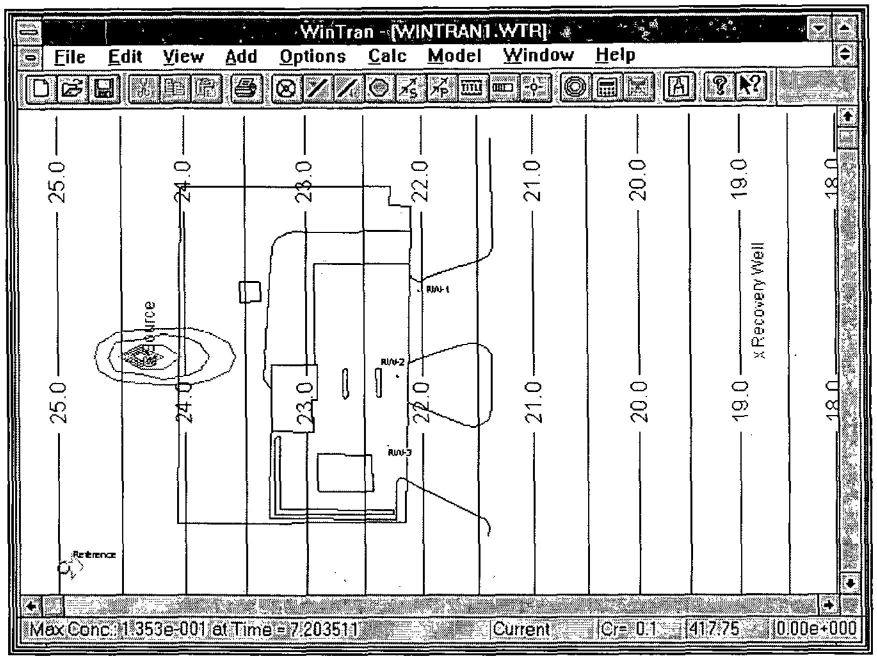
Numerical transport models require the user to carefully evaluate each simulation for potential errors. WinTran assists you in evaluating model error by displaying the mass balance error on the status bar when the transport model is running. The mass balance error is expressed as a percentage and should be less than 10 percent for a valid simulation. Usually, the mass balance error is less than 1 percent.

Even if the mass balance error is below 10 percent, there can be oscillations in the transport solution. Oscillations are indicated by negative concentrations computed by WinTran. In extreme cases, alternating nodes will have positive and negative concentrations producing diamond-shaped contours. The following screen shows a contour pattern that is typical of numerical oscillations:



Note the diamond shaped contours upgradient of the source. These contours are produced because alternating nodes are positive and negative. The contouring routine draws "bulls-eyes" around these high and low points producing the diamond-shaped contours. This is very typical of oscillating solutions and is probably the most common problem you will run into with WinTran.

The pattern above was produced in the tutorial model by lowering the time-step size to 0.1 days, using centered-in-time, and reducing the longitudinal dispersivity to 3 ft. This produces a Peclet number of 6.2, which is above the recommended limit of 2. In the screen shown below, the dispersivity value was increased to 30 ft, dropping the Peclet number to 0.62. This was enough to remove the oscillations.



When the transport solution oscillates, check the following:

(1) The Peclet number is displayed on the status bar as "Pe=" and is computed by dividing the nodal spacing (the distance between nodes in the contour matrix) by the longitudinal dispersivity. The Peclet number should generally be less than 2 for a stable solution. If you are experiencing mass balance problems or oscillations, increase dispersivity until the Peclet number is less than 2, as described above.

(2) The Courant number is another criterion used to judge the stability of a transport simulation. The Courant number is computed as the velocity times time-step size divided by nodal spacing. This criterion is displayed as "Cr=" on the status bar and should generally be less than 1. Again, if you are experiencing mass balance or oscillation problems, try decreasing the initial and maximum time-step sizes.

There are also times when the Courant number is too low. In cases where the Courant number is less than 0.1, there can be round-off errors in the matrix solver. In this case, you should increase the initial and maximum time-step sizes until the Courant number is close to 1.

There are two other WinTran options that can aid in model stability. These include the time discretization method (backward and centered in time) and upstream weighting. The time discretization methods are selected using the **Edit->Time Stepping** menu. Backward in time is unconditionally stable but is only first-order accurate, while centered in time is second-order accurate but may be subject to instability (Javandel et al., 1984). It is usually best to start with backward in time.

Upstream weighting factors in the X- and Y-directions are edited from the **Edit->Transport Parameters** menu. Upstream weighting factors of 1.0 indicate full upstream weighting, while a weighting factor of 0.0 turns off upstream weighting. Upstream weighting adds stability to the solution (helps eliminate oscillations) at the expense of added numerical dispersion. Numerical dispersion is artificial dispersion that produces similar results to an increase in the dispersivity coefficient.

Analysis of Remedial Actions

Setting Up the Flow Model

WinTran can provide valuable guidance in designing a ground-water remediation system. The most obvious remedial action that WinTran can simulate is "pump & treat" where the goal is to contain a volume of contaminated aquifer. WinTran can simulate the effects of both pumping and injection wells.

WinTran can simulate trenches and drains using linesinks. There are two options in simulating drains: (1) specify a head to be maintained in the drain and WinTran will compute the discharge rate necessary to achieve the given head; or (2) specify the discharge rate and compute the resulting head in the drain. To illustrate the capture zone of the drain, use reverse particle-tracking and start the particles along two lines on either side of the linesink.

WinTran can simulate a lagoon closure by using ponds. To do this, set up the initial analytical model with ponds that simulate the lagoon. Adjust the pond recharge rate to match field-measured heads. Finally, remove the pond (or set the pond recharge equal to zero) to simulate the effects of closure.

The effects of capping can be simulated with a combination of elliptical recharge and circular ponds. Set up the initial analytical model using recharge to match field-measured heads. A circular cap can then be simulated with a pond that has a recharge rate equivalent to the regional recharge rate but opposite in sign (e.g. negative).

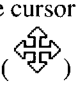
Setting Up the Transport Model

Remedial alternatives are usually simulated in several stages, as described below:

(1) Calibrate the transport model to the observed contaminant plume. This is accomplished by adding source terms to the model (injection wells, infiltrating ponds, or injecting linesinks) and adjusting the source concentration until the desired plume is simulated. The length of the simulation should be chosen to approximate the length of time that the source of contamination has been effecting the groundwater system.

An alternative approach to calibrating the plume configuration is to import a SURFER grid file (e.g. test.grd) containing the contaminant distribution data (use **File->Import** from the main menu). The contoured concentrations are then used as initial conditions for the remedial simulation.

(2) Save the calibrated concentrations as initial conditions using the **Calc->Restart** option on the main menu. Skip this step if you have imported a SURFER grid file for initial conditions.

(3) Add the remediation system (pumping wells or linesinks, etc.) and rerun the transport model. To simulate source removal, delete the source terms added in State 1 above. This is accomplished by moving the cursor over the source element (well, pond, or linesink) until the four-arrow cursor () is displayed. Click the left mouse button to select the element and then press the delete key or select **Edit->Delete** from the main menu. Now, rerun the transport model to simulate source removal.

At any time during the simulations, you may save concentrations for later restart using the **File->Export** menu. Exporting concentration as a restart file (*.rst) will allow you to **Import** these concentrations in later simulations.

Simulating Biodegradation

Simulating the biodegradation of organic compounds is a popular modeling scenario, especially for dissolved hydrocarbons. WinTran does not simulate these complex degradation processes; however, the decay term in WinTran can be used to approximate biodecay. The biodegradation process is reduced to specifying a half-life for the compound. The half-life is the time required to remove half of the original mass. While the half-life is most often used for radioactive elements, such as uranium, it can also be used to express the decay of organic compounds through biodecay. The *Handbook of Environmental Degradation Rates* (Howard et al., 1991) is a good reference for contaminant half-life data.

Performing Risk Assessments

WinTran is not a risk assessment model but can be useful in risk assessments by providing concentration data over time at receptor locations. To obtain the concentration over time at these receptor locations, you must add a well at the receptor. Specify the flow rate as zero (0.0) and check the "Observation well" option on the well dialog. These concentration-time data may then be saved to a file for use in other programs. To save these data, select **File->Export** and choose the file time **Conc-Time** (*.cvt). The file is a DOS text file delimited by commas. The first line contains the well names and subsequent lines list the time and concentration for each well.

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D 4105 Test Method (Analytical Procedure) for Determining Transmissivity and Storage Coefficient of Nonleaky Confined Aquifers by the Modified Theis Nonequilibrium Method, ASTM, 5 p.

D 4106 Test Method (Analytical Procedure) for Determining Transmissivity and Storage Coefficient of Nonleaky Confined Aquifers by the Theis Nonequilibrium Method, ASTM, 5 p.

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APPENDIX C

Aquifer Test Procedures and Output

Description of Aquifer Test

Hydraulic conductivity is one of the most critical parameters used for any fate and transport modeling effort, and the various published values researched range widely over two orders of magnitude, from less than 2 ft/day to 200 ft/day. Therefore, an aquifer test at two nearby industrial water supply wells (WW-1 and WW-5) was performed on November 22, 2006, to determine site-specific hydraulic conductivity. There were several advantages in using these wells as follows:

- Each well is fully penetrating (screened across entire thickness of the aquifer)
- The wells had been reportedly running continuously for over 16-20 hours prior to recording the recovery drawdown data.
- The wells are located nearby the Jct. J-26 site thus available for site-specific testing.
- The wells were constructed efficiently as they are designed to provide maximum yields for supply to the Eunice Gas Plant.
- The wells play a useful role in abatement of chlorides and TDS in the area.

The wells had been running continuously for about 16-20 hrs according to the Eunice Gas Plant personnel who graciously allowed access to their wells for aquifer testing. Immediately prior to turning off the pump in each well, depth to groundwater was measured using an electronic water level indicator. A 10 psi pressure transducer and Hermit 2000 Data logger were then used to capture and record the recovery drawdown data. This instrumentation made it possible to obtain many data points early on in the test (first few minutes) which was essential for subsequent analysis and interpretation of the results. Data was recorded immediately after the water well pump was turned off to provide recovery drawdown data. Collection of data was terminated after the water table equilibrated to near static conditions; consequently the tests were of relatively short duration (less than 1 hour).

Hydraulic conductivity values were determined using a Cooper-Jacob analysis of the recovery data, and a program from USGS Open-File 02-197 (Keith Halford, 2002, documentation attached in Appendix C). The USGS program uses Thiem's equation and the Cooper-Jacob plotting methods for determining hydraulic conductivity. Results of the aquifer test analysis are shown on the following graphs and tables attached herein. The slope near the earlier time drawdown data (within the first few minutes of the test) provided the best estimation. Note that the time axis is plotted as t/t' so time increases from right to left. This is the preferred method to analyze recovery data from a pumping well.

Hydraulic conductivity values of 3.4 ft/day and 4.4 ft/day were calculated from water supply wells WW-1 and WW-5, respectively. Results from water supply well WW-1 probably provided better data because that well was pumping at a rate that stressed the aquifer, that is, the pumping water level was over 9 feet below the static level, whereas with WW-5 the pumping level was less than 2 feet from static. Either way the results from both tests are consistent with each other. The higher hydraulic conductivity value of 4.4 ft/day was used in the fate and transport modeling because it provided a more conservative value.

WELL ID: WW-1

Local ID: T21S-R37E-Section 26-J
Date: 11/22/06
Time: 2:00 PM

INPUT

Construction:	
Casing dia. (d_c)	8 Inch
Annulus dia. (d_w)	8 Inch
Screen Length (L)	40 Feet
Depths to:	
water level (DTW)	45 Feet
Top of Aquifer	45 Feet
Base of Aquifer	85 Feet
Annular Fill:	
across screen --	Gravel
above screen --	Cement
Aquifer Material --	Fine Sand
FLOW RATE	53 GPM

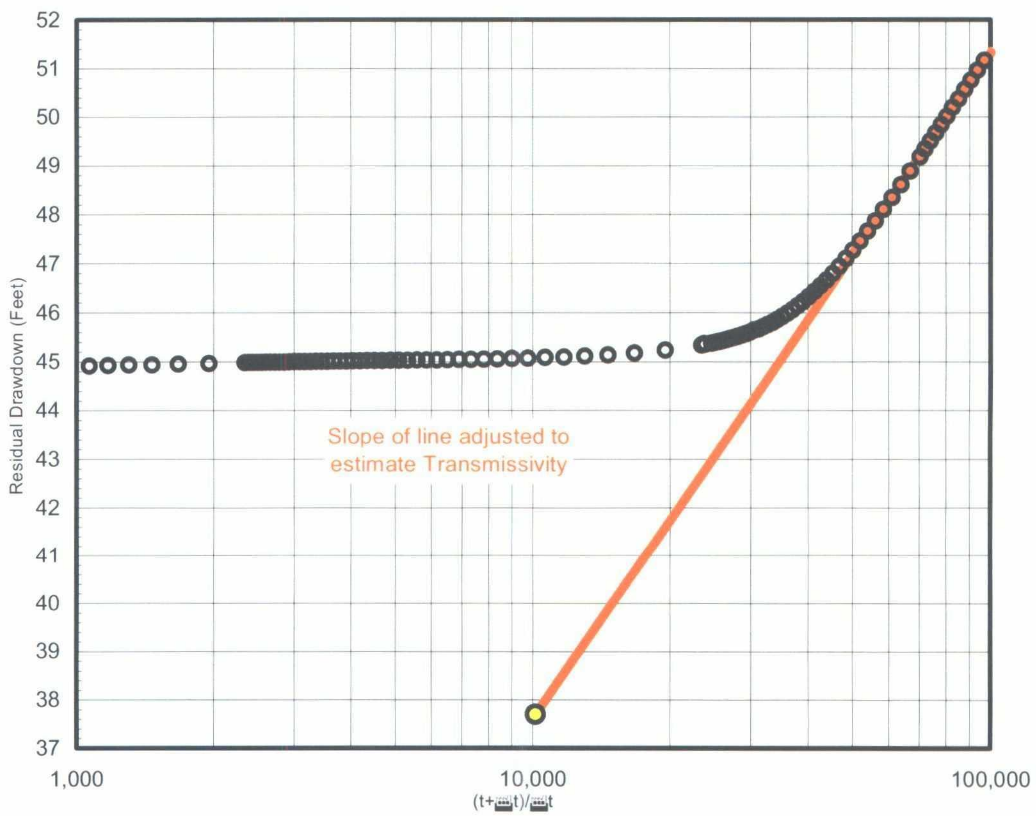
COMPUTED

Aquifer thickness = 40 Feet

Slope = 13.708543 Feet/log10

Input is consistent.

K =	3.4 Feet/Day
T =	140 Feet²/Day



REMARKS: Cooper-Jacob recovery analysis of single-well aquifer test

This recovery test was done on a water supply well (WW-1) that had been running continuously at ~53 gpm for 16-20 hours. A Hermit 2000 data logger was used to record the water level data for the length of the test (~50 minutes).

Depth to water before shutting off pump 54.09 ft (t = 0 min).

Depth to water at end of recovery test 44.84 ft (t = 50 min).

Raw input recovery data for water supply well WW-1

Entry	Reduced Data Time, Date Hr:Min:Sec	Water Level Feet	Entry	Time, Date Hr:Min:Sec	Water Level Feet	Entry	Time, Date Hr:Min:Sec	Water Level Feet
1	1/0/00 0:00:00	0.00	51	11/22/06 14:00:44	45.71	101	11/22/06 14:07:48	45.00
2	11/22/06 14:00:00	54.09	52	11/22/06 14:00:45	45.67	102	11/22/06 14:08:00	45.00
3	11/22/06 14:00:08	54.09	53	11/22/06 14:00:46	45.65	103	11/22/06 14:08:12	44.99
4	11/22/06 14:00:08	53.99	54	11/22/06 14:00:47	45.61	104	11/22/06 14:08:24	44.99
5	11/22/06 14:00:09	53.74	55	11/22/06 14:00:48	45.57	105	11/22/06 14:08:36	44.99
6	11/22/06 14:00:09	53.47	56	11/22/06 14:00:49	45.55	106	11/22/06 14:08:48	44.99
7	11/22/06 14:00:10	53.22	57	11/22/06 14:00:50	45.52	107	11/22/06 14:09:00	44.99
8	11/22/06 14:00:11	52.96	58	11/22/06 14:00:51	45.50	108	11/22/06 14:09:12	44.99
9	11/22/06 14:00:11	52.72	59	11/22/06 14:00:52	45.47	109	11/22/06 14:09:24	44.99
10	11/22/06 14:00:11	52.48	60	11/22/06 14:00:53	45.45	110	11/22/06 14:09:36	44.99
11	11/22/06 14:00:12	52.25	61	11/22/06 14:00:54	45.43	111	11/22/06 14:09:48	44.99
12	11/22/06 14:00:12	52.02	62	11/22/06 14:00:55	45.42	112	11/22/06 14:10:00	44.98
13	11/22/06 14:00:13	51.80	63	11/22/06 14:00:56	45.40	113	11/22/06 14:12:00	44.96
14	11/22/06 14:00:14	51.59	64	11/22/06 14:00:57	45.38	114	11/22/06 14:14:00	44.96
15	11/22/06 14:00:14	51.37	65	11/22/06 14:00:59	45.36	115	11/22/06 14:16:00	44.94
16	11/22/06 14:00:14	51.16	66	11/22/06 14:00:59	45.37	116	11/22/06 14:18:00	44.94
17	11/22/06 14:00:15	50.96	67	11/22/06 14:01:00	45.34	117	11/22/06 14:20:00	44.93
18	11/22/06 14:00:15	50.76	68	11/22/06 14:01:12	45.24	118	11/22/06 14:22:00	44.92
19	11/22/06 14:00:16	50.56	69	11/22/06 14:01:24	45.18	119	11/22/06 14:24:00	44.91
20	11/22/06 14:00:17	50.37	70	11/22/06 14:01:36	45.14	120	11/22/06 14:26:00	44.90
21	11/22/06 14:00:17	50.19	71	11/22/06 14:01:48	45.12	121	11/22/06 14:28:00	44.89
22	11/22/06 14:00:17	50.01	72	11/22/06 14:02:00	45.10	122	11/22/06 14:30:00	44.89
23	11/22/06 14:00:18	49.84	73	11/22/06 14:02:12	45.09	123	11/22/06 14:34:00	44.88
24	11/22/06 14:00:18	49.67	74	11/22/06 14:02:24	45.08	124	11/22/06 14:36:00	44.87
25	11/22/06 14:00:19	49.50	75	11/22/06 14:02:36	45.07	125	11/22/06 14:38:00	44.86
26	11/22/06 14:00:20	49.34	76	11/22/06 14:02:48	45.06	126	11/22/06 14:40:00	44.86
27	11/22/06 14:00:20	49.18	77	11/22/06 14:03:00	45.05	127	11/22/06 14:42:00	44.86
28	11/22/06 14:00:21	48.89	78	11/22/06 14:03:12	45.05	128	11/22/06 14:44:00	44.85
29	11/22/06 14:00:22	48.61	79	11/22/06 14:03:24	45.05	129	11/22/06 14:46:00	44.84
30	11/22/06 14:00:23	48.34	80	11/22/06 14:03:36	45.04	130	11/22/06 14:48:00	44.84
31	11/22/06 14:00:24	48.10	81	11/22/06 14:03:48	45.04	131	11/22/06 14:50:00	44.84
32	11/22/06 14:00:25	47.87	82	11/22/06 14:04:00	45.04			
33	11/22/06 14:00:26	47.66	83	11/22/06 14:04:12	45.04			
34	11/22/06 14:00:27	47.46	84	11/22/06 14:04:24	45.03			
35	11/22/06 14:00:28	47.27	85	11/22/06 14:04:36	45.03			
36	11/22/06 14:00:29	47.10	86	11/22/06 14:04:48	45.03			
37	11/22/06 14:00:30	46.94	87	11/22/06 14:05:00	45.03			
38	11/22/06 14:00:31	46.80	88	11/22/06 14:05:12	45.02			
39	11/22/06 14:00:32	46.66	89	11/22/06 14:05:24	45.02			
40	11/22/06 14:00:33	46.55	90	11/22/06 14:05:36	45.02			
41	11/22/06 14:00:34	46.43	91	11/22/06 14:05:48	45.02			
42	11/22/06 14:00:35	46.32	92	11/22/06 14:06:00	45.02			
43	11/22/06 14:00:36	46.23	93	11/22/06 14:06:12	45.02			
44	11/22/06 14:00:37	46.14	94	11/22/06 14:06:24	45.01			
45	11/22/06 14:00:38	46.06	95	11/22/06 14:06:36	45.01			
46	11/22/06 14:00:39	45.99	96	11/22/06 14:06:48	45.01			
47	11/22/06 14:00:40	45.92	97	11/22/06 14:07:00	45.01			
48	11/22/06 14:00:41	45.86	98	11/22/06 14:07:12	45.00			
49	11/22/06 14:00:42	45.81	99	11/22/06 14:07:24	45.00			
50	11/22/06 14:00:43	45.76	100	11/22/06 14:07:36	45.00			

WELL ID: WW-5

Local ID: T21S-R37E-Section 26-J

Date: 11/22/06

Time: 11:00 AM

INPUT

Construction:

Casing dia. (d_c)	8 Inch
Annulus dia. (d_a)	8 Inch
Screen Length (L)	34 Feet

Depths to:

water level (DTW)	46 Feet
Top of Aquifer	46 Feet
Base of Aquifer	80 Feet

Annular Fill:

across screen --	Gravel
above screen --	Cement
Aquifer Material --	Fine Sand

FLOW RATE 20 GPM

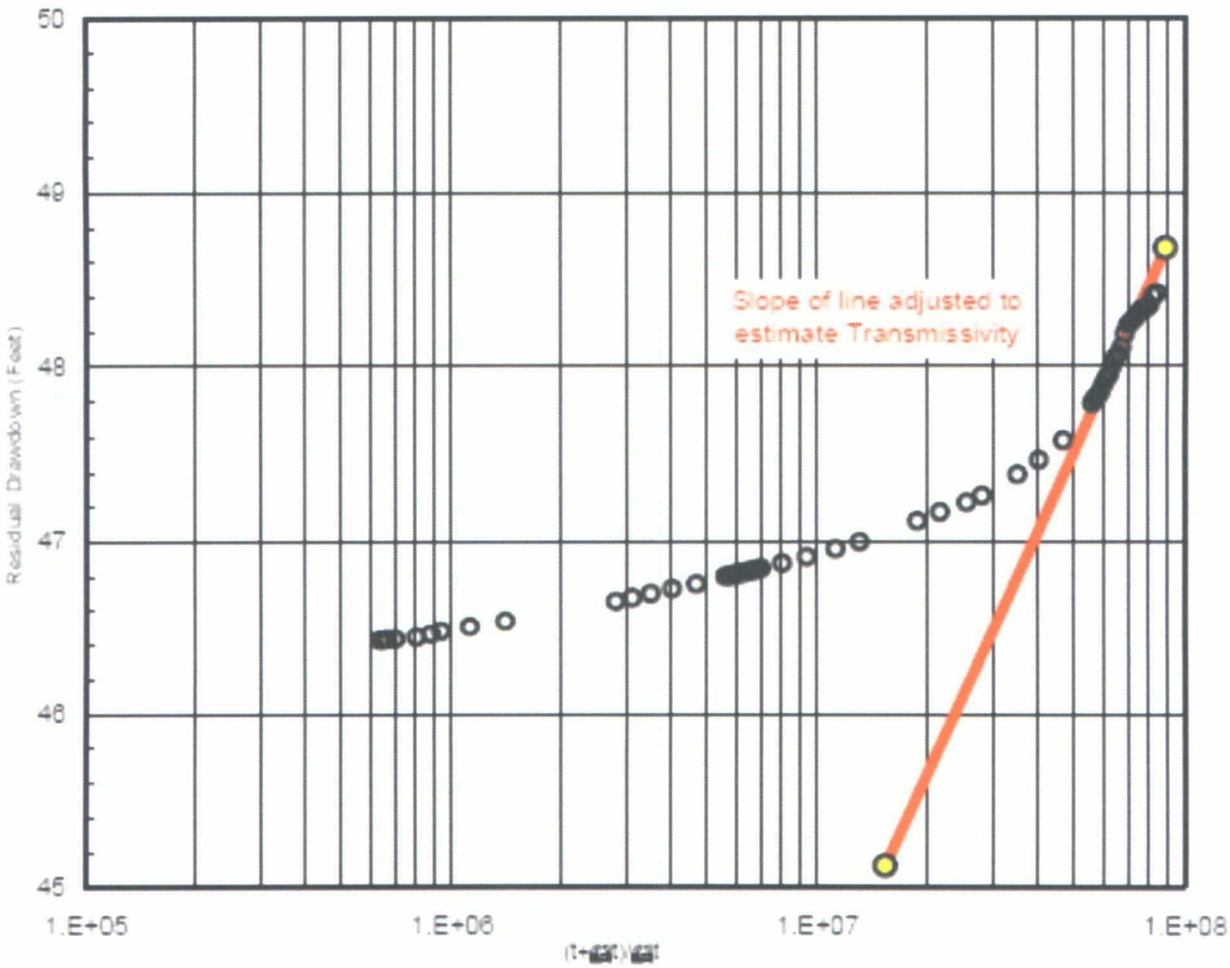
COMPUTED

Aquifer thickness = 34 Feet

Slope = 4.6657929 Feet/log10

Input is consistent

K =	4.4 Feet/Day
T =	150 $Feet^2$/Day



REMARKS: Cooper-Jacob recovery analysis of single-well aquifer test

This recovery test was done on a water supply well (WW-5) that had been running continuously at ~20 gpm for 16-20 hours. A Hermit 2000 data logger was used to record the water level data for the length of the test (~58 minutes).

Depth to water before shutting off pump 48.42 ft (t = 0 min).

Depth to water at end of recovery test 46.43 ft (t = 58 min).

Raw input recovery data for water supply well WW-5

Entry	Reduced Data Time, Date Hr:Min:Sec	Water Level Feet	Entry	Time, Date Hr:Min:Sec	Water Level Feet
1	11/22/06 11:00:00	0.00	31	11/22/06 11:05:00	47.00
2	11/22/06 11:00:40	48.42	32	11/22/06 11:06:00	46.96
3	11/22/06 11:00:41	48.42	33	11/22/06 11:07:00	46.92
4	11/22/06 11:00:42	48.40	34	11/22/06 11:08:00	46.88
5	11/22/06 11:00:43	48.35	35	11/22/06 11:08:12	46.85
6	11/22/06 11:00:44	48.33	36	11/22/06 11:08:24	46.84
7	11/22/06 11:00:45	48.32	37	11/22/06 11:08:36	46.84
8	11/22/06 11:00:46	48.31	38	11/22/06 11:08:48	46.83
9	11/22/06 11:00:47	48.28	39	11/22/06 11:09:00	46.83
10	11/22/06 11:00:48	48.25	40	11/22/06 11:09:12	46.82
11	11/22/06 11:00:49	48.24	41	11/22/06 11:09:24	46.82
12	11/22/06 11:00:50	48.18	42	11/22/06 11:09:36	46.81
13	11/22/06 11:00:51	48.11	43	11/22/06 11:09:48	46.81
14	11/22/06 11:00:52	48.07	44	11/22/06 11:10:00	46.80
15	11/22/06 11:00:53	48.05	45	11/22/06 11:12:00	46.80
16	11/22/06 11:00:54	48.00	46	11/22/06 11:14:00	46.76
17	11/22/06 11:00:55	47.95	47	11/22/06 11:16:00	46.73
18	11/22/06 11:00:56	47.93	48	11/22/06 11:18:00	46.70
19	11/22/06 11:00:57	47.89	49	11/22/06 11:20:00	46.68
20	11/22/06 11:00:58	47.85	50	11/22/06 11:40:00	46.66
21	11/22/06 11:00:59	47.83	51	11/22/06 11:50:00	46.54
22	11/22/06 11:01:00	47.81	52	11/22/06 12:00:00	46.51
23	11/22/06 11:01:12	47.79	53	11/22/06 12:04:00	46.48
24	11/22/06 11:01:24	47.58	54	11/22/06 12:10:00	46.47
25	11/22/06 11:01:36	47.47	55	11/22/06 12:20:00	46.45
26	11/22/06 11:02:00	47.39	56	11/22/06 12:24:00	46.44
27	11/22/06 11:02:12	47.27	57	11/22/06 12:26:00	46.44
28	11/22/06 11:02:36	47.23	58	11/22/06 12:28:00	46.43
29	11/22/06 11:03:00	47.17			
30	11/22/06 11:04:18	47.12			

APPENDIX D

Laboratory Analytical Reports

And

Chain of Custody Documentation

CARDINAL LABORATORIES

PHONE (575) 393-2326 • 101 E. MARLAND • HOBBS, NM 88240

ANALYTICAL RESULTS FOR
RICE OPERATING COMPANY
ATTN: HACK CONDER
122 WEST TAYLOR
HOBBS, NM 88240
FAX TO: (575) 397-1471

Receiving Date: 01/18/10
Reporting Date: 01/22/10
Project Number: NOT GIVEN
Project Name: BD JUNCTION J-26
Project Location: T21S R37E SEC26 J~ LEA CO., N.M.

Sampling Date: 01/14/10
Sample Type: WATER
Sample Condition: COOL & INTACT
Sample Received By: CK
Analyzed By: HM

LAB NO.	SAMPLE ID	Cl^- (mg/L)	SO_4 (mg/L)	TDS (mg/L)
Analysis Date:		01/19/10	01/22/10	01/19/10
H19086-1	MONITOR WELL #1	144	130	891
H19086-2	MONITOR WELL #2	740	327	2,000
H19086-3	MONITOR WELL #3	144	122	865
Quality Control		510	37.7	NR
True Value QC		500	40.0	NR
% Recovery		102	94.2	NR
Relative Percent Difference		< 0.1	3.6	2.4

METHOD: Standard Methods, EPA	4500-Cl⁻B	375.4	160.1

Not accredited for Chloride, Sulfate and TDS.

Chemist

Date 01/25/10

H19086 RICE

Page 1 of 1

101 East Marland ~ Hobbs, New Mexico 88240
Tel (575) 393-2326
Fax (575) 393-2476

Cardinal Laboratories, Inc.

CHAIN-OF-CUSTODY AND ANALYSIS REQUEST

LAB Order ID # ____________

Company Name: RICE Operating Company	BILL TO Company: RICE Operating Company PO#
Project Manager: Hack Conder	Address: (Street, City, Zip) 122 W Taylor Street ~ Hobbs, New Mexico 88240
Address: (Street, City, Zip) 122 W Taylor Street ~ Hobbs, New Mexico 88240	Phone#: (575) 393-9174 Fax#: (575)397-1471
Phone #: (575) 393-9174	Fax #: (575) 397-1471
Project #:	Project Name: BD Junction J-26
Project Location: T21S R37E Sec26 J ~ Lea County New Mexico	Sampler Signature: Rozanne Johnson (575)631-9310 rozanne@valornet.com

LAB # (LAB USE ONLY) H19086	FIELD CODE	(G)rab or (C)omp	# CONTAINERS	MATRIX: WATER	SOIL	AIR	SLUDGE	PRESERVATIVE METHOD: HCL	HNO_3	$NaHSO_4$	H_2SO_4	ICE (1-Liter HDPE)	NONE	SAMPLING: DATE (2010)	TIME
1	Monitor Well #1	G	1	X								1		1-14	10:10
2	Monitor Well #2	G	1	X								1		1-14	11:15
3	Monitor Well #3	G	1	X								1		1-14	9:15

ANALYSIS REQUEST
(Circle or Specify Method No.)

FIELD CODE	MTBE 8021B/602	BTEX 8021B/602	TPH 418.1/TX1005 / TX1005 Extended (C35)	PAH 8270C	Total Metals Ag As Ba Cd Cr Pb Se Hg 6010B/200.7	TCLP Metals Ag As Ba Cd Cr Pb Se Hg	TCLP Volatiles	TCLP Semi Volatiles	TCLP Pesticides	RCI	GC/MS Vol. 8260B/624	GC/MS Semi. Vol. 8270C/625	PCB's 8082/608	Pesticides 8081A/608	BOD, TSS, pH	Moisture Content	Cations (Ca, Mg, Na, K)	Anions (Cl, SO4, CO3, HCO3)	Sulfates	Total Dissolved Solids	Chlorides	Turn Around Time ~ 24 Hours
Monitor Well #1																			X	X	X	
Monitor Well #2																			X	X	X	
Monitor Well #3																			X	X	X	

Relinquished by: Rozanne Johnson Date: 1-18-2010 Time: 9:45	Received by: Date: 1-18-2010 Time: 9:46	Phone Results [ ] Yes [ ] No
		Fax Results [ ] Yes [ ] No Additional Fax Number:
Relinquished by: Date: 1-18-2010 Time: 12:40	Received By: (Laboratory Staff) Date: 1/18/10 Time: 12:40	REMARKS:
Delivered By: (Circle One) Sampler - UPS - Bus - Other:	Sample Condition: Cool Yes ✓ No; Intact Yes ✓ No. CHECKED BY: (Initials)	Email Results to: hconder@riceswd.com lweinheimer@riceswd.com rozanne@valornet.com

#26

APPENDIX E

NMOCD Correspondence

Gil Van Deventer

From: "Hansen, Edward J., EMNRD" <edwardj.hansen@state.nm.us>
To: "Kristin Pope" <kpope@riceswd.com>
Cc: "Price, Wayne, EMNRD" <wayne.price@state.nm.us>; "Gil Van Deventer" <gilbertvandeventer@suddenlink.net>
Sent: Wednesday, February 13, 2008 12:32 PM
Subject: Completion Report for AP-75 (1R0426-40) (Rice BD Jct. J-26 Site)

Dear Ms. Pope:

The NMOCD has reviewed the submitted Stage 2 Final Investigation and Abatement Completion Report (**AP-75**) (1R0426-40), dated November 20, 2007, for the above referenced site. The NMOCD cannot approve of the Report at this time. To expedite the approval process, the NMOCD recommends that the following amendments are made to the Abatement Plan:

1. The Corrective Action to the Groundwater must include that at least two additional groundwater monitoring wells will be installed downgradient of MW-2 at the Rice BD Jct. J-26 Site. In addition, one of the additional groundwater monitoring wells must be nested so that the well(s) is screened at the upper portion of the aquifer and at the lower portion of the aquifer. Two separate wells may be installed for this purpose for a total of three additional groundwater monitoring wells.
2. The Corrective Action to the Groundwater must include that a groundwater recovery well will be installed downgradient of the Rice BD Jct. J-26 Site (near MW-2). An existing groundwater monitoring well may be used for this purpose. Also, please propose a treatment and / or disposal method of the recovered groundwater.

If you have questions regarding this matter, please contact me at 505-476-3489.

Edward J. Hansen
Hydrologist
Environmental Bureau

P.S.: Please use the referenced OCD case # on future correspondence regarding the site listed above.

Gil Van Deventer

From: "Hansen, Edward J., EMNRD" <edwardj.hansen@state.nm.us>
To: "Kristin Pope" <kpope@riceswd.com>
Cc: "Marvin Burrows" <mburrows@riceswd.com>; "Gil Van Deventer" <gilbertvandeventer@suddenlink.net>
Sent: Tuesday, April 29, 2008 2:19 PM
Subject: RE: Request for extension

Dear Ms. Pope:

The New Mexico Oil Conservation Division (NMOCD) has reviewed your request for the extension of the submittal date of the amended abatement plans for the below referenced sites. The NMOCD hereby approves the extension for the amended plan submittal date. The amended plans for the three EME sites must be submitted the NMOCD by Monday, June 16, 2008. However, the amended plan for the BD Jct J-26 (AP-75) must be submitted by Tuesday, May 27, 2008.

Please be advised that NMOCD approval of this extension does not relieve the owner/operator of responsibility should operations pose a threat to ground water, surface water, human health or the environment. In addition, NMOCD approval does not relieve the owner/operator of responsibility for compliance with any NMOCD, federal, state, or local laws and/or regulations.

If you have any questions regarding this matter, please contact me at 505-476-3489.

Edward J. Hansen
Hydrologist
Environmental Bureau

From: Gil Van Deventer [mailto:gilbertvandeventer@suddenlink.net]
Sent: Monday, April 28, 2008 1:20 PM
To: Hansen, Edward J., EMNRD
Cc: Marvin Burrows; Kristin Pope
Subject: Request for extension

Subject sites:

- EME P-6 Release (AP-45)
- EME Jct K-6 (AP-46)
- EME Jct. N-5 (AP-66)
- BD Jct J-26 (AP-75)

Hello Edward:

In reference to the subject sites listed above which have amended abatement plans coming due, and on behalf of Rice Operating Company (ROC), I would like to request an extension to June 16, 2008, for the following reasons:

- Ongoing review of draft reports still in progress
- Change of management at ROC (Kristin's departure end of May and Marvin's recent hiring)
- Gil's vacation (May 12-19 for son's wedding)
- Gil's scheduled fieldwork (May 2, 6,7,8, 27-30, and June 2-6)

We will likely submit amended plans one by one before this date in no particular order. Please accept my apologies if this is not convenient for NMOCD and let me know if you accept our request for extension.

Thank you!
Gil

Gilbert J. Van Deventer, PG, REM
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Home: 432-682-0727