Description and Analysis of Full-Scale Tracer Trials Conducted at the Northwest Wellfield Miami-Dade County Florida

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Table of Contents:

Figures

Tables

Appendix for Full Scale Tracer Trials

Title (With Description)

Summary

Full-scale dye tracer releases were conducted at the Northwest Wellfield area as part of the investigation on the adequacy of existing wellfield protection provisions.

This dye tracer study was undertaken to provide additional information on factors affecting groundwater flow, such as velocity, possible preferential flow paths and aquifer porosity. These factors are critical in understanding how groundwater contaminants would travel in the local aquifer. The results of the tracer investigations will be useful in performing more detailed computer modeling and risk evaluation pertaining to aquifer and groundwater contaminant transport characteristics in the vicinity of this wellfield.

Two types of tracer dye were released into injection wells at different depths and samples were collected from monitoring wells and the production wells along the travel path of the dye. The full-scale dye release trial was started on September 10, 1999 and continued throughout the remainder of the rainy season into the dry season. Two different dyes were injected at different depths into the wellfield production zone.

The wellfield operated at a flow of 90 MGD, only part of its capacity. Also, major changes in hydrologic conditions occurred during this trial, including Hurricane Irene that resulted in 15 inches of rainfall at the nearest available meteorological station over a 48 hour period on October 15 and 16, 1999. This rainfall event greatly affected water levels, recharge and groundwater velocity. Water level and canal level recorder data is available to quantify these changes.

Conclusions

- The dye traveled along the predicted flow path, behavior which more closely that of porous media rather than karst conditions
- Longitudinal dispersivity values in the range of 0.8 to 3.5 meters were calculated based on the full scale tracer test results
- Tracer travel times were determined based on the study data. These characteristics allow more detailed predictions of the movement of groundwater pollutants and a more thorough evaluation of contaminant risks.
- The amount of dye injected was adequate to accurately monitor concentrations at monitoring wells along the flow path. However, only trace amounts (near the analytical detection limits) could be measured at the production wells.
- Changes in hydrologic conditions affected the travel of tracer dye.
- Groundwater and dye movement were slow during wet season conditions, but increased greatly as dry season conditions set in.
- Dry season conditions allow more rapid movement of groundwater and represent more conservative criteria for protecting the wellfield.
- The time of first arrival of the two different types of dye used were similar
- More pronounced travel of tracer dye was noted at a depth interval of 40 to 50 feet – apparently due to more rapid groundwater flow at this depth.

Introduction

Miami-Dade County Department of Environmental Resources Management (DERM), in cooperation with the South Florida Water Management District, has initiated a hydrogeologic investigation in the vicinity of the Northwest wellfield. This effort is in support of the Phase II recommendation of the Lake Belt Committee to determine what modifications to the wellfield protection program are necessary to guarantee the protection of the watershed and urban water supplies as the Lake Belt Plan is developed.

The limestone in this area is a valuable resource; not only as raw material; it makes up the Biscayne aquifer, which stores and filters the water supply for Miami-Dade County. Removal of the aquifer material by rock mining leaves the remaining aquifer more vulnerable to contamination from the newly created surface water bodies.

The objective of this phase of the investigation is to assess contaminant transport characteristics by using the technique of dye tracing in this hydrogeologic environment. The technique has been used before in the Biscayne aquifer (Fennema)(14). However the trace conducted for that study covered a distance of only 30 to 40 feet under natural groundwater flow gradients. During the planning phase of this effort, it was agreed, by members of the interagency group planning the study, that these trials would need to cover substantially greater distances. Since estimates of transport properties vary greatly with the scale of the experiment (Demenico and Schwartz)(7), traces conducted on the order of 1000 feet would assure more representative measurements. .

Currently, the wellfield protection program is based on the concept of groundwater travel times. Protection zones consist of concentric curves around the wellheads that represent equal travel time distances to the wellheads. These curves are created through a process that includes groundwater flow modeling coupled with an advective transport model that uses the solution provided by the groundwater flow model. Implicit in the creation of wellfield protection zones is the assumption that the hydrogeologic parameters do not vary in time. However, the very nature of rock mining, removing the geologic material, negates this assumption. There is a concern that existing and future rockmining excavations serve to expand the travel time contours beyond those used to define the existing wellfield protection area. In addition accurate transport modeling is heavily dependent on the porosity term chosen for the aquifer. In a porous media, such as a sandy aquifer, this approach is valid. However, in this area where the Biscayne aquifer is dominated by solution cavities and vugs, this approach may not be valid.

These two factors indicated that an empirical study of the aquifer system in this area would be the only way to prove conclusively whether the groundwater modeling with techniques for porous media was valid. Since measuring groundwater flow directly is very difficult, the tracer trial represents a useful empirical method of getting this measurement.

With the tracer method however, the groundwater velocity is actually measured by direct means. The tracer is introduced into the aquifer through an injection well with a known screened interval. Samples are collected from the monitoring wells and pumping wells and analyzed for the tracer. The time between the release and the first detection at the receptor wells will be referred to as the time for first arrival. The time between the release and the mean concentration of dye gives a travel time indicative of the groundwater velocity under the test conditions.

A tracer trial which involved injecting two different dyes at different depths was conducted during this phase of the investigation. The injection point was 3040 feet east of the wellfield and tracer concentrations were measured at monitoring wells along the flow path of the dye.

The study area for this tracer investigation is shown in Figure 1A. As shown in that figure, the water supply production wells are located two miles east of the Florida Turnpike Extension. The contours represent boundaries of existing wellfield protection zones. The generalized locations of production wells, the tracer injection location, monitoring points and other pertinent features in the study area are also shown in Figure 1A.

Figure 1B provides a more detailed view in which specific wells mentioned in this report are labeled.

Figure 1A

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Figure 1B

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Study Area and Hydrogeologic Setting

The Northwest Wellfield is part of a regional water supply system serving approximately 900,000 Miami-Dade County residents. This facility consists of 15 large supply wells located along a two-mile length of access road two miles west of the Turnpike Extension in northwestern Miami-Dade County. The southernmost well, Number 1, is located near theoretical NW 58 Street. The northernmost well, Number 15, is located near theoretical NW 90 Street. A map showing the location of the Lake Belt Area, the Northwest Wellfield and the West Wellfield is provided below.

Figure 2 Location Map

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This wellfield obtains water from the Biscayne Aquifer. Pertinent information about the hydrogeology is as follows.

Unconfined and located at or near the land surface, the Biscayne Aquifer is made up mainly of layers of limestone and sand. The Biscayne Aquifer underlies all of Dade County, much of Broward County and a small portion of southeastern Palm Beach County. The generally high hydraulic conductivity and the many passages through the solution-riddled limestone offer little resistance to flow. The result is one of the most permeable aquifers in the world, which quickly responds to slight differences in the water table. As a result:

- The water table is relatively flat
- Wells are generally capable of producing large amounts of water
- The direction and velocity of groundwater flow is strongly influenced by water levels in adjacent canals and other surface water bodies
- The water table reacts quickly as rainfall penetrates into the aquifer

In October 1979 EPA officially designated the Biscayne Aquifer to be “the sole or principal source of drinking water for all municipal water systems southeast Florida...”

In the Northwest Wellfield Area the strata consist of limestone of varying hydraulic conductivities along with mixtures of limestone and sand or limestone with shell. Hydraulic conductivities in the range of 5,000 to 15,000 feet per day can be expected. These values, together with an aquifer thickness of approximately 70 feet allow the wells to operate at the high pumping rates noted earlier.

Hoffmeister (1) and USGS documents (Fish)(2) contain the following additional information about the aquifer materials:

Formation	*Approximate thickness at Southwest Wellfield Site*	*Description*
Miami Oolite	Upper 10 feet	Soft, white to yellowish, containing streaks or thin layers of calcite, massive to crossbedded and stratified; generally perforated with vertical solution holes
Fort Thompson	Approximately 60 feet total – located above and below the fingers of the Anastasia and Key Largo formations	Alternating marine, brackish-water and fresh-water marls, limestones and sandstone. A major component of the highly permeable Biscayne Aquifer

A major factor affecting groundwater flow and levels in this study area is the pumping and cone of influence of the Northwest Wellfield. This wellfield consists of 15 wells originally designed for a pumping rate of 15 million gallons per day (MGD) each. These wells were originally constructed with 48-inch diameter casings extending to a depth of 46 feet and 34 feet of uncased hole extending below the casing. One of these wells, Number 10, was modified so that a 40-inch casing extended 64 feet below grade with an additional 40 feet of uncased hole below this casing. This modification of Well Number 10 was completed in September 1998. Additional modifications on three other Northwest production wells, Numbers 13, 14 and 15, have also been completed. After modification, these three wells have a 40-inch casing extending 62 feet below the pump house slab, with an additional 18 to 60 feet of uncased hole. During this full scale tracer release the wellfield was operating at a total pumping rate of approximately 95 MGD.

The following factors also influence the groundwater levels and flows:

- Surface water during wet season conditions, which provides recharge and reduces the wellfields cone of influence.
- The Snapper Creek Canal Extension located two miles east of Wellfield (constructed in the late 1980's in order to recharge the adjacent groundwater -- reducing the eastern extent of the wellfield's cone of influence in order to prevent groundwater contaminants from areas further east from being pulled toward the wellfield)
- Interaction of groundwater with other adjacent surface water bodies – including rockmining pits and the Dade Broward Levee Canal located two miles west of the wellfield
- General movement of groundwater from the Everglades eastward to the coast
- Rainfall
- Evaporation

A tabulation of hydrologic conditions defined by water level measurements in the vicinity of the wellfield is as follows:

Table 1 – Hydrologic Conditions (Water Level Summary)

Full Scale Tracer Trial
Water Level Data for Respective Monitoring Points

Tracer Release 9/10/99

Date	G-3253 (feet NGVD)(1) [located near center of wellfield]	G-3259A (feet NGVD)(1) [located 5100' east of G-3253]	Snapper Creek Extension Canal (feet NGVD)(1)	Groundwater Head Difference (feet)	Average Groundwater Gradient (ft/ft) between G-3253 and G-3259A
9/1/99	6.14	6.39	5.62	0.25	4.90E-05
9/15/99	6.03	6.30	5.46	0.27	5.29E-05
10/1/99	6.17	6.43	5.57	0.26	5.10E-05
10/15/99	7.23	7.48	6.51	0.25	4.90E-05
11/3/99	6.89	7.17	6.27	0.28	5.49E-05
11/15/99	6.36	6.68	5.67	0.32	6.27E-05
12/1/99	5.92	6.10	5.22	0.18	3.53E-05
12/15/99	5.42	5.74	5.02	0.32	6.27E-05
1/1/00	4.75	5.17	4.63	0.42	8.24E-05
1/14/00	4.05	4.56	4.38	0.51	1.00E-04
2/1/00	2.20	3.67	4.18	1.47	2.88E-04
2/15/00	1.32	3.03	4.15	1.71	3.35E-04
2/27/00	-0.08	2.81	4.14	2.89	5.67E-04
3/14/00	1.13	2.82	4.01	1.69	3.31E-04
3/31/00	0.77	2.67	4.02	1.90	3.73E-04
4/13/00	1.02	2.86	4.10	1.84	3.61E-04
4/30/00	1.8	3.14		1.34	2.63E-04
5/15/00	-0.95	2.23		3.18	6.24E-04
5/25/00	-1.08	1.78		2.86	5.61E-04
Average	*3.43*	*4.58*		*1.15*	*2.26E-04*

Notes

(1) denotes USGS provisional data subject to review

The table above shows head differences varying from 0.25 to 3.81 feet over the 5100 foot distance between the two USGS wells. Based on Darcy's Law, a correspondingly large variation in groundwater velocity can be expected.

Description of Full-Scale Tracer Trial and Results

Table 2 – Dye Tracer Well and Monitoring Well Construction

Well Identification	*Casing (feet; measured from natural grade to bottom of casing)*	*Screen Interval (feet; measured from top to bottom of screen)*	*Total Depth (feet: measured from top of casing)*	*Slot Size in Screen (inches)*
NW Tracer Well 1	0 to 20	20 to 50	50	0.02
NW Tracer Well 2A	0 to 60	60 to 80	80	0.06
NW Tracer Well 2B	0 to 40	40 to 50	50	0.06
NW Tracer Well 3A	0 to 60	60 to 80	80	0.06
NW Tracer Well 3B	0 to 40	40 to 50	50	0.06
NW Tracer Well 4A	0 to 60	60 to 80	80	0.06
NW Tracer Well 4B	0 to 40	40 to 50	50	0.06
DERM Monitoring Well 7C	0 to 20	20 to 25	25	
DERM Monitoring Well 7D	0 to 55	55 to 60	60	

General Methodology:

After the dye releases, dye concentrations were measured at the respective monitoring points by two methods:

- *Collecting water samples for laboratory analysis with a baler*
- *Suspending activated carbon packs at 10-foot intervals and retrieving these packs for lab analysis.*

These samples were retrieved at one-week intervals during the period up to April 4. Samples were retrieved at two-week intervals after that date.

Table 3A – Descriptive Summary of Flourescein Dye Release

The dye was introduced into the deeper of the two injection wells into a zone 60 to 80 feet below grade. After injection of the dye, 500 gallons of water was also injected at a controlled rate.

Date of Injection	9/10/99
Point of Injection	NW Tracer Well 2A
Screen Interval of Injection Well (feet from top of casing)	60 to 80
Type of Dye	Fluorescein (15174 Uranine C) powder
Amount of Dye (pounds of dye)	30

Sampling Points Along Longitudinal Flow Path

Well	Distance From Injection Point (feet)	Screen Interval (feet from top of casing)
NW Tracer Well 3A	530	60 to 80
DERM Monitoring Well 7D	1180	55 to 60
NW Tracer Well 1	2170	20 to 50
Production Well #9	3040	40 to 80*

* denotes borehole interval

Table 3B – Summary of Results for Fluoroscein Dye Release

Receptor Well	NWTr 3A	MW 7D
Distance from release point (meters)	162	360
Time to leading edge (days)	158	186
Time to peak concentration (days)	207	202
Peak dye concentration (ug/l)	6.4	2.8
Time to mean concentration (days)	229	199
Std deviation of time for mean concentration (days)	31.5	13
Mean tracer velocity (meters/day)	0.7	1.8

Notes:

- *The travel times were based on results for water samples.*
- *The mean and peak tracer travel times indicated above reflect extrapolations.*
- *The above results indicate more rapid dye movement during the latter part of the trial as water conditions changed.*

Table 4A – Descriptive Summary of Rhodamine Dye Release

The dye was introduced into the shallower of the two injection wells into a zone 40 to 50 feet below grade.

Date of Injection	9/10/99
Point of Injection	NW Tracer Well 2B
Screen Interval of Injection Well (feet from top of casing)	40 to 50
Type of Dye	Rhodamine WT 20% solution
Amount of Dye solution (pounds of solution)	50
Amount of Dye (pounds of dye)	10

Sampling Points Along Longitudinal Flow Path

Well	Distance From Injection Point (feet)	Screen Interval (feet from top of casing)
NW Tracer Well 3B	530	40 to 50
DERM Monitoring Well 7D	1180	55 to 60
NW Tracer Well 1	2170	20 to 50
Production Well #9	3040	40 to 80*

* denotes borehole interval

Table 4B – Summary of Results for Rhodamine Dye Release

Receptor Well	NWTr 3A	MW 7D	NWTr 1
Distance from release point (meters)	162	360	661
Time to leading edge (days)	151	186	192
Time to peak concentration (days)	173	202	192
Peak dye concentration (ug/l)	48.3	13.2	2.04
Time to mean concentration (days)	197	200	224
Std deviation of time for mean concentration (days)	33.1	13.0	23.2
Mean tracer velocity (meters/day)	0.8	1.8	3.0

Notes:

- *The travel times were based on results for water samples.*
- *The mean and peak tracer travel times indicated above reflect extrapolations.*
- *Only a 14% increase in mean travel time was needed to travel a 408% greater distance during this trial. This result reflects a large increase in groundwater velocity as water conditions changed during the trial.*

Abbreviations Used:

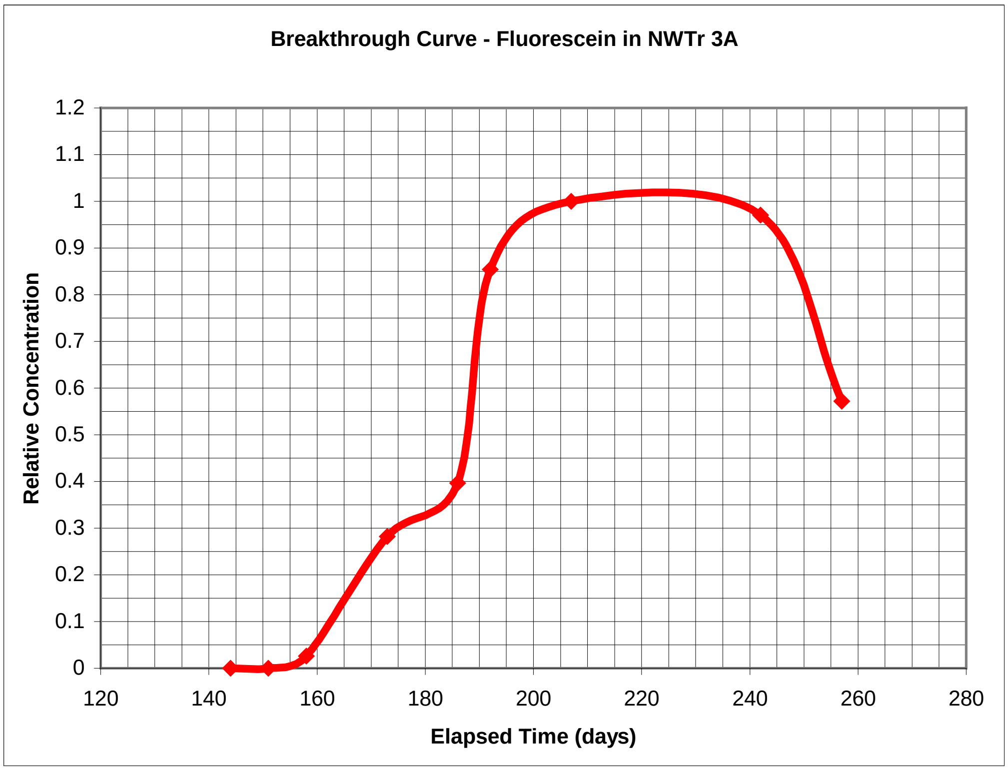
NWTr Tracer Monitoring or Injection Wells (constructed for tracer investigation)
MW Monitoring Well (constructed prior to tracer study for wellfield protection monitoring)
PW Production Well (water supply well operated by MDWSD)

Breakthrough Curves

Plots of dye concentrations detected at different times are referred to as breakthrough curves. For an ideal solute traveling under ideal conditions, these plots would be a symmetrical normal distribution or 'bell curve' (Domenico & Schwartz (7). However, in actual tracer tests, deviations from ideal breakthrough curves are common.

The curve presented below is an example of the breakthrough curves found in the Appendix of this report.

Figure 3 Sample Breakthrough Curve



Figure

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Additional Observations about Movement of Dye

Suspending activated carbon packs at 10-foot intervals in the monitoring wells allowed comparison of dye movement at different depths.

The sampling at NWTr 3A and 3B indicated that more dye of both types traveled at a 50-foot depth than at other depths in the 40 to 80-foot range. This conclusion is supported by:

- The concentrations which showed at the time of the dye's first arrival on February 8, 2000
- The higher concentrations found at that depth during the period between February 8 and March 28.

However, this pattern of higher concentrations did not hold true after March 28.

A comparison of concentrations found during the period between February 8 and March 28, 2000 is contained in the following table:

Table 5 – Dye Adsorbed at Different Depths

Rhodamine WT

Depth (feet)	*40*	*50*	*60*	*70*	*80*
PPB/day -- averaged concentration on date indicated					
2/8/00	0.3	18.1	0.0	0.0	0.0
2/15/00	38.4	113.3	0.7	1.9	2.3
3/1/00	134.0	156.0	6.2	63.4	23.2
3/14/00	105.4	238.5	17.0	154.6	94.6
3/20/00	50.3	154.0	16.0	102.2	85.2
3/28/00	22.9	95.5	14.1	82.3	108.6

Fluorescein

Depth (feet)	*40*	*50*	*60*	*70*	*80*
2/8/00	0.1	1.8	0.0	0.0	0.0
2/15/00	5.7	17.3	0.5	1.1	1.0
3/1/00	17.5	24.5	1.8	20.2	10.1
3/14/00	2.1	71.1	2.4	59.8	33.1
3/20/00	25.3	116.5	5.8	105.7	75.5
3/28/00	5.6	67.1	4.4	58.5	55.1

The 50-foot depth corresponds to a zone where cavities were noted in the lithological data (2).

The greater transport of dye at 50 feet apparently reflects a higher hydraulic conductivity at that depth. Therefore, a larger volume of water and a greater amount of dye would travel at that zone.

Comparison with Previous Preliminary Tracer Trials

Two successful and two unsuccessful preliminary trials were carried out earlier. This earlier work was intended to develop the methodology for the full-scale trials. Preliminary Trials 1 and 4 also provided additional information about contaminant transport. A Summary of the information from these trials is as follows:

Table 6 – Summary of Preliminary Tracer Trials

Trial	1	2	3	4
Date of Dye Release	1/28/98	1/28/98	7/13/98	12/17/98
Amount of Dye (grams)	186	302	1260	1635
Type of Dye	RWT	F	F	RWT
Injection Point	by G3253	NW 7C	NW 7C	NWT #1
Amt of Water Injected After Dye (gal)	500	50	500	1500
Nearest Output Point	NWP #8	NWP #9	NWP #9	NWP #9
Travel Distance (feet)	450	1800	1800	870
Travel Distance (meters)	137	549	549	265
Time of First Dye Detection (days)	1.3	ND	ND	5.3
Time of Peak Dye Concentration	1.9	ND	ND	9.5
Mean Dye Travel Time **	2.3	ND	ND	13.2
Mean Tracer Velocity (meters/day)	196			65.9
Mean Dye Travel Time **	2.3	ND	ND	13.2

Notes:
NWP denotes Northwest production well
NWT #1 denotes new well constructed for tracer injection
RWT denoted Rhodamine WT
F denotes Fluorescein
ND denotes no dye detection for unsuccessful trial
** The mean travel time for Trial 4 varied from 13.2 to 17 days depending on the QTRACER model extrapolation method

The preliminary trials differed from the full-scale tracer work in the following respects:
The production wells were used as receptor wells
The injection points were located closer to the wellfield where the effect of well pumping is more pronounced
The two successful Trials, 1 and 4, reflected dry season conditions during the entire period involved.

Because of the dry season conditions and the nearness to the production wells, tracer travel velocity was much higher during these preliminary trials. Velocities of 196 and 65.9 meters/day are noted in Table 6. By comparison, the mean velocities ranged from 0.7 to 3.0 meters/day during the full-scale trial.

Dispersion Parameter Calculations

Various methods for determining contaminant transport parameters are mentioned in Campbell (15), as well as in Domenico and Schwartz (7). Campbell mentions two modeling programs for providing solutions for solute transport for continuous or slug injection of the solute or dye. In addition, Campbell describes a graphical technique involving log scale plots of concentration versus time, which are matched to empirical data by eye or computer.

The method applied to the data in this report uses equations from Domenico and Schwartz as described below. This technique applies two relatively simple equations and does not provide a sophisticated method for correcting for the apparent changes in groundwater velocity during the full-scale tracer trial. At this time, the dispersion coefficient and dispersivity estimates are presented as provisional values subject to verification by more rigorous methods.

Equations Used for Calculation of Longitudinal Dispersion Characteristics

$$D_L = \frac{v^2 \sigma_t^2}{2t}$$

(Equation 10.17 page 225 in Domenico & Schwartz Physical and Chemical Hydrogeology 2nd Edition)

$$\alpha_L = \frac{D_L}{v}$$

(Derived from Equation 10.10 page 221 in Domenico & Schwartz Physical and Chemical Hydrogeology 2nd Edition)

Table 7 – Contaminant Transport Parameters

Full Scale Tracer Trials

Dye	Well	**v** Velocity (m/day) *	**t** Time (days)*	σ_L Std Dev (days)*	$\mathbf{D}_L$ Longitudinal Dispersion Coefficient ** (meters^2/day)	α_L Longitudinal Dispersivity** (meters)
Fluorescein	NWTr 3B	0.82	197	33.1	1.9	2.3
	MW 7D	1.81	199	13	1.4	0.8
	NWTr 1	2.95	224	23.2	10.5	3.5
Rhodamine	NWTr 3A	0.71	229	31.5	1.1	1.5
	MW 7D	1.81	199	13.3	1.5	0.8

Preliminary Tracer Trials

Dye	Well	**v** Velocity (m/day) *	**t** Time (days)*	σ_L Std Dev (days)*	$\mathbf{D}_L$ Longitudinal Dispersion Coefficient ** (meters^2/day)	α_L Longitunal Dispersivity** (meters)
Rhodamine	PW #9	59.5	2.3	0.187	26.9	0.5
Rhodamine	PW #9	15.6	17	2.08	30.9	2.0

* Qtracer Output
** Calculated from Eq 10.13 Domenico & Schwartz 2ed (7)

Surface Dye Release Trial on December 8, 1999

A third type of dye, Eosine, was used to obtain information about surface water flow in an area adjacent to Production Wells 8 and 9. Observations indicated a rapid spread of dye in the surface water with dye reaching the edge of the ponded area within two days. This surface travel placed the dye within a 100-foot horizontal distance of the production wells.

Samples from the nearest production well, Number 9, showed arrival of dye five days after the release. However, the dye detected at that production well did not have characteristics which matched the Eosine dye that was released. Also, the vertical travel path for the dye was not known.

Assuming the arrival of dye after five days, the results indicate comparatively slow vertical movement of contaminants. It is noted that the Production Well Number 9 is cased to a depth of 46 feet (14 meters). Therefore a travel time of at least 5 days would represent vertical velocity of less than 9.2 feet per day (2.8 meters per day). The apparent vertical travel is much slower than the horizontal movement measured near the wells during the preliminary tracer trials. Specifically, an average horizontal velocity of 643 feet per day (196 meters per day) was noted over a 450-foot (137-meter) interval during the first preliminary tracer trial in January 1998.

More detailed information about this surface release is Found in Appendix I.

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- Staff from Miami-Dade Water and Sewer Department installed sinks and piping to facilitate tracer sampling at the production wells and cooperated in operating the wellfield at nearly constant flow conditions during the first 120 days of the full scale trial.
- Ozark Underground Laboratories served as the consulting lab for the tracer analyses. This laboratory also supplied the tracer dye and performed the necessary quality assurance pertaining these materials.