ECONOMICS OF SURFACE WATER RUNOFF STORAGE IN BRACKISH AQUIFERS IN SOUTH FLORIDA

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by

N. Khanal & Stan Winn

ABSTRACT

South Florida, in comparison to other areas, is water rich - receiving almost 60 inches of rainfall per year. Seventy (70) percent of the rain falls, however, during the period when the existing surface water reservoirs and the water table aquifers are full, and vast quantities of water must be discharged to the ocean.

The South Florida Water Management District is the regional water manager for the area. In order to meet future water requirements for agricultural, commercial, and industrial enterprises, as well as potable water requirements for one of the fastest growing Standard Metropolitan Statistical Areas (SMSA's) of the nation, the District is studying various water supply alternatives for the region.

One classical water supply alternative is to store excess runoff water in surface water impoundments; however, flat topography, high evaporation rates, percent experience with a dam failure, and in general the public's skepticism with additional surface water reservoirs, makes this alternative costly and unattractive.

In south Florida there exists a vast potential subsurface reservoir where the excess runoff can be stored during periods of abundance and retrieved during dry months. This subsurface reservoir presently contains brackish water which can not be used for any purpose without first removing

the salt by use of desalt techniques. The potential of storing excess runoff in this brackish water aquifer has been explored by the District, in a cooperative program with the U. S. Geological Survey, by use of three test wells at different locations. This paper will discuss the field results on the recovery of the injected fluid and the final predicted recovery efficiency from such wells by use of a digital model developed at Louisiana State University, as well as the economics of storing water in such formations.

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"Water, Water Everywhere; Not a Drop to Drink"

INTRODUCTION

As the population of south Florida continues to grow, the need for more and more fresh water manifests itself, with the reliability of supply being of paramount importance.

To meet the future water requirements of the region, the South Florida Water Management District (SFWMD) was delegated the total water management responsibility of the region and is studying various water supply alternatives to determine which are the most suitable and economical for the region.

This particular study focuses on one alternative way of supplying water to the region. In particular, this alternative is tested for feasibility purposes in the Upper East Coast Planning Area (UECPA). This planning area encompasses approximately 1,304 square miles in Martin, St. Lucie and eastern Okeechobee Counties on the east coast of Florida (Figure 1). Presently, this area has neither large surface storage facilities nor is it connected with the sole regional water storage facility - namely, Lake Okeechobee. Vast quantities of fresh water, generated from rainfall, are being discharged to the ocean annually due to lack of surface storage facilities.

The classical way of storing fresh water for water supply purposes is to store this fresh water in surface water impoundments during periods of abundance for use during dry months. Feasibility of surface impoundment of runoff water was explored by Tai (1975) for the area. He found this alternative to be uneconomical due to flat topography and the high evaporation rate of the area.

Another alternative, the so-called Martin County Plan, which would connect the lake with Canal 23, would enable the water managers to pump

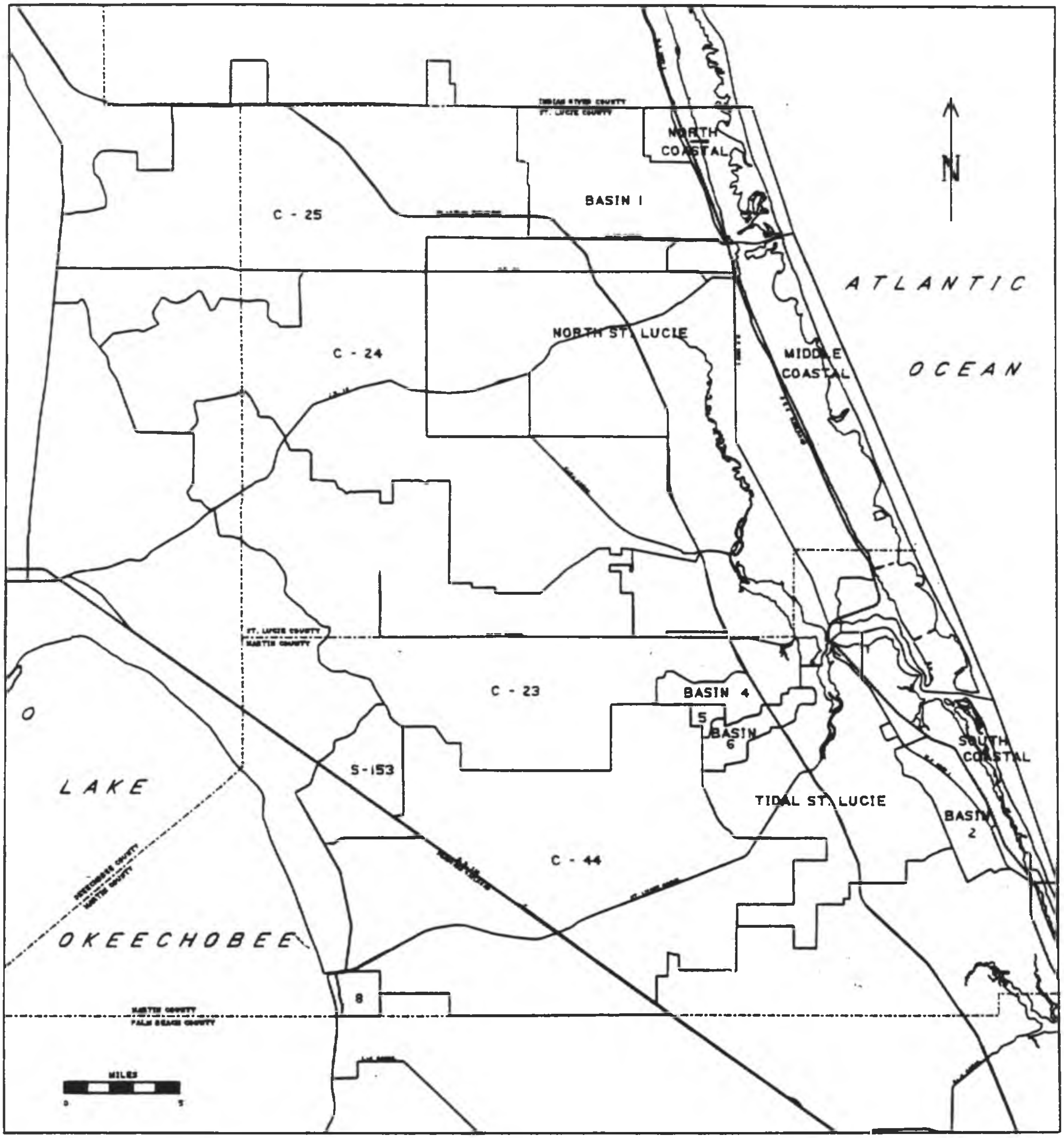


FIGURE 1. SURFACE WATER DRAINAGE BASINS
UPPER EAST COAST PLANNING AREA

excess runoff water to the lake from the area, and deliver water from the lake to the area via Canals 23, 24 and 25. This alternative is being studied by the U. S. Army Corps of Engineers.

The study here focuses on a relatively new technique of salvaging a portion of the fresh water which is presently discharged to the ocean via cyclic storage in subsurface reservoirs.

In south Florida, there exists a vast potential subsurface reservoir where the excess fresh water runoff may be stored during periods of abundance and retrieved during periods of need (dry season). This subsurface reservoir presently contains brackish water which cannot be used without first removing the salt by desalination techniques. The alternative being evaluated here is the feasibility of cyclic storage of fresh water in the brackish water formation in the UECPA. Field tests of this alternative have been carried out in other parts of the District area; however, in this study, the feasibility of cyclic storage and retrieval will be evaluated using mathematical models and hydrogeologic data obtained from other studies of the Upper East Coast Planning Area.

The objectives of this study, then, will be as follows:

1. To predict recovery efficiency (fresh water pumped out/fresh water pumped in) of the cyclic storage/retrieval system via mathematical modeling, without recourse to long, multiple cycle field evaluation.
2. To perform sensitivity analyses of the model parameters in order to (a) predict the effect of the change of a particular parameter on recovery efficiency, and (b) to be able to run the model for other planning areas where the hydrogeologic data are different than those of the UECPA.

THEORETICAL BACKGROUND

There are six primary parameters that affect recovery efficiency of stored fresh water in brackish aquifer, Kimbler (1975). They are as follows:

A. Mixing of two fluids due to molecular diffusion and convective dispersion

B. Segregation of the two fluids due to density difference

C. Viscous fingering due to the difference in viscosities between the injected fluid and the native fluid

D. Aquifer heterogeneities

E. Aquifer dip, and

F. Pre-existing groundwater movement in the aquifer.

Methods of mathematical development on the above parameters follow.

Mixing Due to Molecular Diffusion and Convective Dispersion

If two miscible fluids of different composition are in contact, a transfer of molecules will take place. As time progresses, a mixed zone will be created by the random movement of molecules, where the two fluids have diffused into one another.

When one fluid miscibly displaces another fluid in a porous medium, the mixed zone will be greater than that due to molecular diffusion alone. The additional mixing, as per Kimbler, et al., (1975) depends primarily on pore geometry, which results from variations in the velocity field, and the constant intermingling of flow paths as displacement progresses.

An equation as presented by Gardner, Downie, and Wyllie and modified by Kimbler, et al., (1975) which can be applied to successive injection and production half-cycles to compute the concentration at any radius (r) and for any injection or production half-cycle is given below:

$$\frac{Cn}{Co} = \frac{1}{2}\,\mathrm{erfc}\left[\frac{R^2 - r^2}{DNOM_{(I\ \mathrm{or}\ P),j}}\right]$$

C_i = Concentration of injected fluid at the radius r, and time t

r = radius (cm)

R = radius (cm) of injected fluid at time (t) with no mixing or gravitational segregation

erfc( ) = complementary error function of

$$f_{I,j(tk)} = \frac{4}{3} \propto (2\alpha_{I,J}tk)^{3/2} + D \frac{(2\alpha_{I,J}tk)^2}{\alpha_{I,j}}$$

$$f_{P,j(tk)} = \frac{4}{3} \propto (2\alpha_{P,j}tk)^{3/2} + D \frac{(2\alpha_{P,j}tk)^2}{\alpha_{P,j}}$$

First Injection Half-cycle

$$DNOM_{I,1} = 2(f_{I,1}(t_1))^{1/2}$$

First Production Half-cycle

$$DNOM_{P,2} = 2\left[f_{P,2}(t_2) - f_{P,2}(t_1) + f_{I,1}(t_1)\right]^{1/2}$$

Second Injection Half-cycle

$$DNOM_{I,3} = 2\left[f_{L,3}(t_3 - f_{I,3}(t_2) + f_{P,2}(t_2) - f_{P,2}(t_1) + f_{I,1}(t_1)\right]^{1/2}$$

Second Production Half-cycle

$$DNOM_{P,4} = 2\Big[f_{P,4}(t_4) - f_{P,4}(t_3) + f_{I,3}(t_3) - f_{I,3}(t_2) + f_{P,2}(t_2) - f_{P,2}(t_1) + f_{I,1}(t_1)\Big]^{1/2}.$$

where,

$\propto$ = longitudinal dispersivity coefficient of porous medium (cm)

D = coefficient of molecular diffusion of fluids in porous medium (cm)

Q = $q/2\pi h\phi)$ cm^2/sec

q = volumetric flow rate (cm^3/sec)

h = aquifer thickness (cm)

ϕ = aquifer porosity (fraction)

$t_1, t_2, t_3 \ldots$ = time measured from start of first injection half-cycle (sec)

I,P = subscripts for Injection and production

j,k = integers

In Figure 2 a schematic representation of the displacement process during an injection half-cycle is presented.

As can be noticed, the injected fresh water displaces the native brackish water away from the source. As the interphase between the fresh water and brackish water moves in the aquifer, the mixing between the two fluids will generate a transition, or mixed zone, in which the composition of either fluid will vary from 0 to 100 percent. The length of the mixed zone, as it moves in the aquifer, is dependent on the total distance travelled by the interface, the velocity of the interface, the total time of contact between the liquids, the properties of the liquids, and the properties of the porous medium.

In the schematic diagram, R is the radius of the injected fluid at any time, t. Please refer to Kimbler (1975) for the calculations of Ci/Co and the length of the mixed zone at any time (t) and about any radius (R).

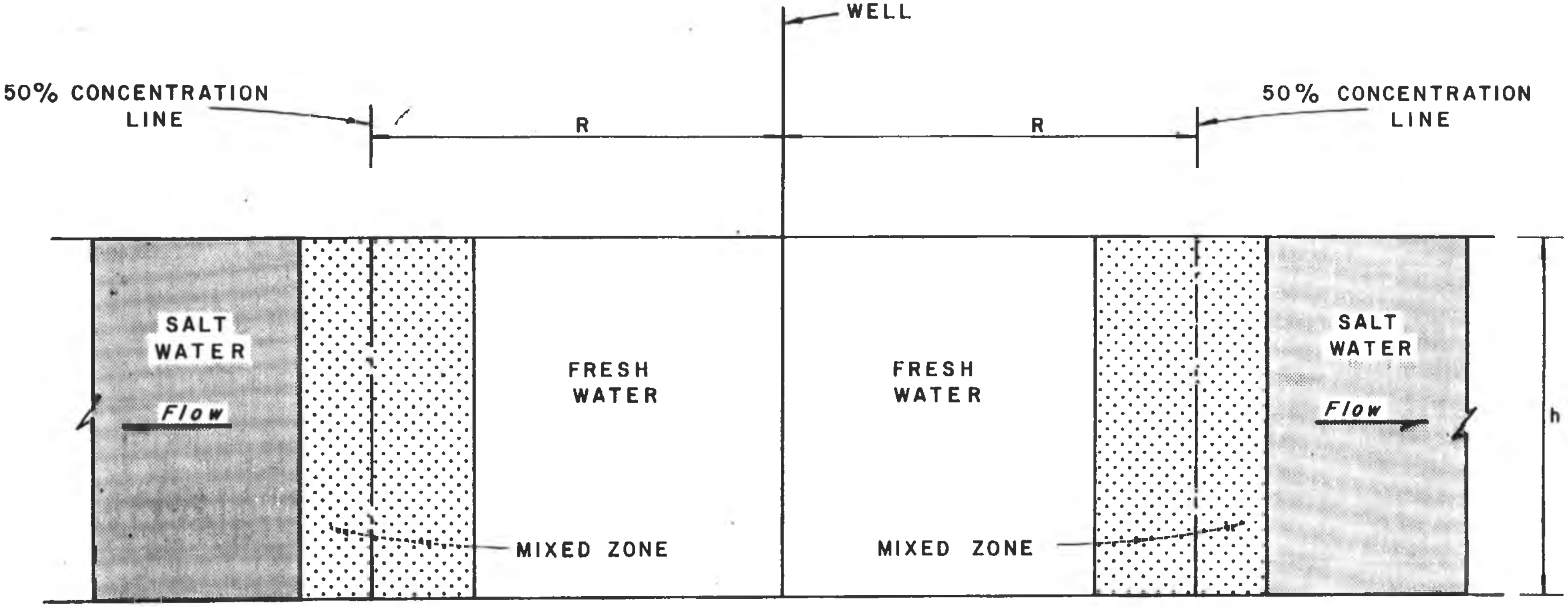


Figure 2 SCHEMATIC REPRESENTATION OF THE DISPLACEMENT PROCESS DURING AN INJECTION HALF-CYCLE (NO DENSITY DIFFERENCE) AFTER KIMBLER ET. AL.

Calculation of Gravitational Segregation Due to Density Difference

Figure 3 shows schematically the inclination of the mixed zone due to density differences between the two liquids. The less dense water will rise over the more dense brackish water. The gravitational segretation between the two fluids, at any time, can be represented by the tangent of the angle θ, that the 50-percent concentration lines makes with the vertical ($\tan \theta = 2xR/h$). Readers are referred to a publication by Kimbler (1975) concerning the theoretical development and the procedure for calculating the value of gravitational segregation before approximation to radial geometry.

The equation describing gravitational segregation, as proposed by Esmail (Kimbler, 1975) is as follows:

$$\frac{2xL}{h} = f(\psi)$$

where,

$$\psi = \left[\frac{k \cdot g \cdot \Delta\rho \cdot t}{h}\right]\left[\frac{\bar{\mu}^{2/3} \cdot s}{(\Delta\rho)^{5/3}(g)^{1/3}}\right]$$

where,

$2xL$ = projection of the interface on the horizontal surface (cm)

h = aquifer thickness (cm)

t = time (secs.)

ϕ = porosity

$\bar{\mu}$ = average viscosity of the two fluids (poises)

g = acceleration due to gravity (cm/sec^2)

$\Delta\rho$ = density difference between two fluids (gm/cm)

A detailed description of the above equation can be found in (Kimbler, 1975).

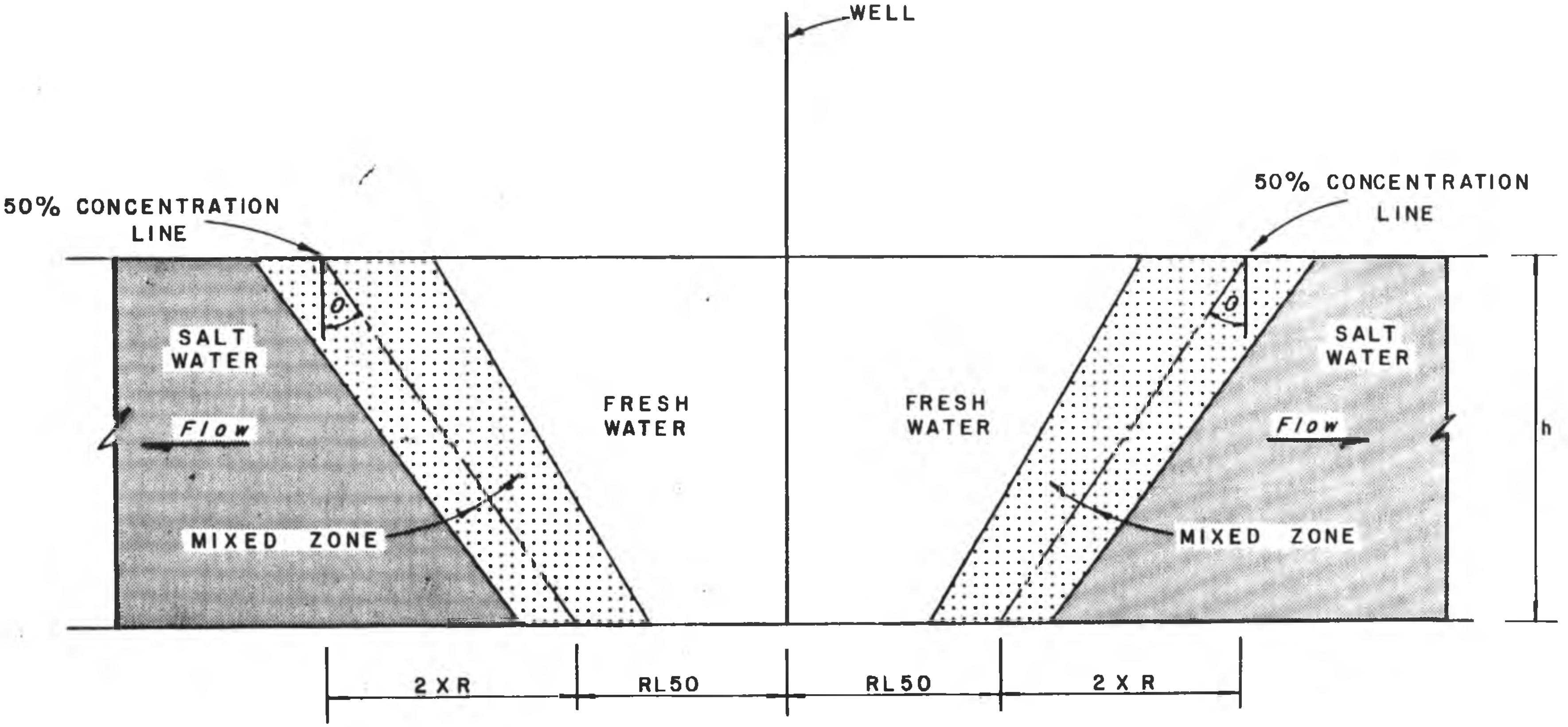


Figure 3 SCHEMATIC REPRESENTATION OF THE DISPLACEMENT PROCESS DURING AN INJECTION HALF-CYCLE DUE TO BOTH MIXING AND DENSITY DIFFERENCE AFTER KIMBLER ET. AL.

Difference in Viscosities

In the model, the viscosities of the injected and the native fluids are assumed to be the same.

Aquifer Heterogeneities

The model assumes that the aquifer is not inclined but is horizontal, homogeneous, or isotropic and is of infinite areal extent.

Pre-existing Groundwater Movement

If the potentiometric gradient is found to be high (not in south Florida where the gradient is less than 1 foot/mile), groundwater movement will take place at a faster rate. This movement can be slowed or counteracted through the use of boundary wells, to retard the groundwater movement.

Recovery Efficiency

When the leading edge of the mixed zone reaches the breakthrough radius (RBT, See Figure 4), stored freshwater production is stopped. For a single well system, the breakthrough radius would be the wellbore radius. For a multiple well system, it would be the radius from the center of the well pattern to the outer ring of wells. The volume of water contained in the frustrum of the cone, having a height, h, and upper and lower radii of RU50/RL50, respectively, is the volume of the lost fresh water.

The cumulative recovery efficiency (CRE) is the difference between the volume of fresh water injected (V_{IN}) minus the volume of lost fresh water V_{LOST} divided by the total volume of fresh water injected (V_{TOTAL})

$$CRE = \frac{V_{IN} - V_{LOST}}{V_{TOTAL}}$$

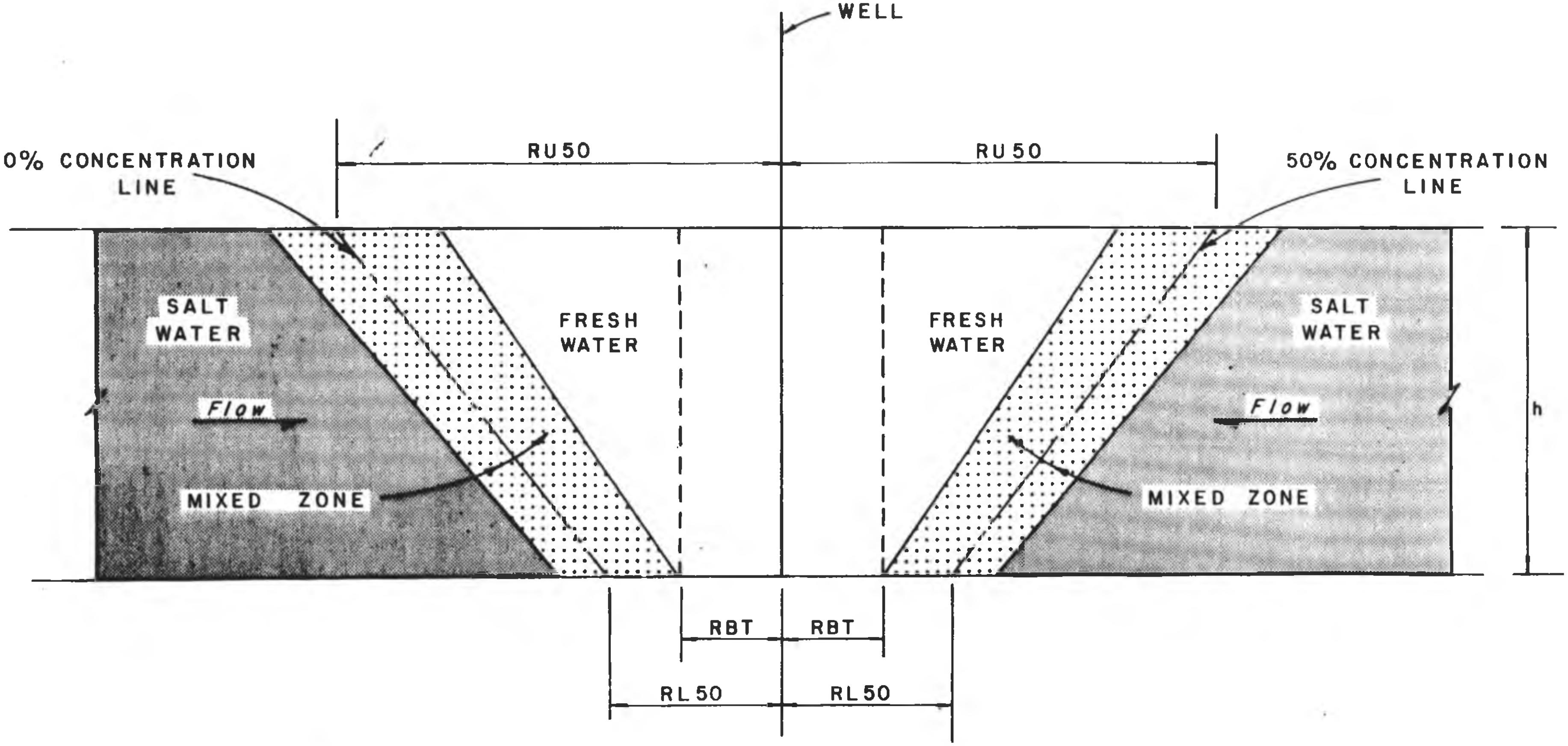


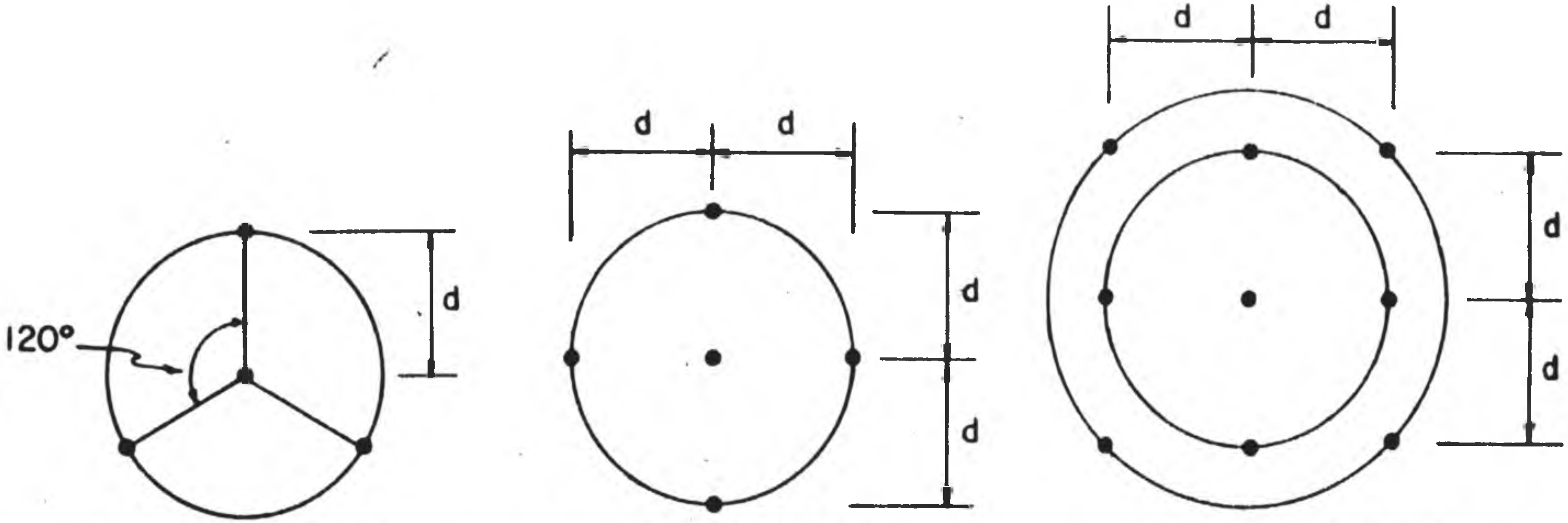
Figure 4 SCHEMATIC DIAGRAM ILLUSTRATING THE CALCULATION OF RECOVERY EFFICIENCY. AFTER KIMBLER ET. AL.

Multiple Well System

If large quantities of runoff water are available for storage, then a wellfield rather than a single well will be needed. In Figure 5 some possible injection wellfields are presented. The operating procedure for a wellfield, such as shown in (c) would be (Kimbler, 1975):

1) Inject into the center well until the lagging edge of the mixed zone passes the inner ring of wells.
2) Start injection in the inner wells (with injection continuing in the center well) until the lagging edge of the mixed zone passes the outer ring of wells.
3) Inject into all nine wells until the desired quantity is injected.
4) Allow the injected water to stand until needed.
5) Produce all nine wells until breakthrough occurs at the outer ring of wells, at which time production from the wellfield is stopped.
6) Subsequent cycles are made with injection beginning in all nine wells.

Detailed computer programs for computing recovery efficiencies from single and multiple injection wells have been developed at Louisiana State University. These programs have been modified to a certain extent to fit the District's need and the computer capability will be applied for the computation of recovery efficiency from such wells in the Upper East Coast Planning Area.



FOUR WELL PATTERN
(a)

FIVE WELL PATTERN
(b)

NINE WELL PATTERN
(c)

Figure 5 SOME POSSIBLE WELL FIELD PATTERNS AFTER KIMBLER ET. AL.

STUDY AREA

The study area is the Upper East Coast Planning Area of the South Florida Water Management District (see Figure 1). The area encompasses approximately 1304 square miles in Martin, St. Lucie, and eastern Okeechobee counties. Climate of the area is humid-subtropical with warm wet summers and mild dry winters. The northern portion of the area is drained by SFWMD primary Canals 23, 24, and 25 with many interconnected secondary and tertiary canals.

Water Resources - Supply Aspects

The volume of surface water which is potentially available for beneficial use in St. Lucie County consists solely of the runoff generated from rainfall over the basin (SFWMD, 1974). Runoff during the rainy period, due to lack of surface storage facilities has to be discharged to the ocean. Presented in Tabular form (Tables 1a, 1b, and 1c) are the discharge records for Canals 23, 24, and 25. During the months of April-October (10-yr. period) 34,890 million gallons of water was discharged to the ocean from C-23, 22,298 million gallons from C-24, and 27,991 million gallons from C-25.

The average yearly discharge to the ocean from the basin during the 10 year period was approximately 85 billion gallons.

Various alternatives are being studied to save this 85 billion gallons of water. One of the alternatives being studied by the Corps of Engineers is the Martin County Plan which will connect C-23 with Lake Okeechobee. This plan will enable the excess water to be stored in the Lake during the period of excess and to be released during dry months.

The plan being studied here is to see whether a portion of the surface runoff can be injected into the upper zone of the brackish aquifer, allowed to remain in storage for some time and retrieved, when required, during critical dry months.

TABLE 1a. C-23 AT S-48 DISCHARGE CFS-DAYS

YEAR	JAN.	FEB.	MAR.	APRIL	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	SEASONAL TOTALS	NOV.	DEC.	YEARLY TOTALS
1963								390	1,865	3,800		1,335	2,810	
1964	(2,030)	(4,580)	1,256	803	1,118	820	5,309	13,083	13,557	8,011	42,701	3,349	940	54,857
1965	180	3,209	2,184	476	71	612	3,298	3,714	4,720	11,611	24,502	5,516	731	36,322
1966	14,878	10,320	3,904	1,468	1,799	13,748	23,226	14,399	9,156	22,420	86,216	2,620	1,089	119,027
1967	699	1,192	905	258	99	2,761	8,917	5,811	1,807	7,930	27,583	904	275	31,558
1968	213	196	166	166	2,939	29,451	29,677	6,234	2,131	3,054	73,652	3,782	878	78,887
1969	1,008	941	7,389	1,345	7,730	11,706	6,535	21,938	12,798	27,148	89,200	14,833	11,584	124,955
1970	(4,500)	8,341	22,969	4,880	2,190	6,761	9,511	(13,606)	8,540	18,645	64,133	1,833	573	102,349
1971	463	468	551	595	589	3,061	6,868	5,224	9,880	9,473	35,690	8,189	1,210	46,571
1972	401	1,229	343	1,477	7,418	18,210	5,372	4,349	1,174	379	38,379	251	491	41,094
1973	1,496	1,753	1,220	778	368	6,790	11,018	10,282	19,270	9,539	58,045	1,233	1,144	64,891
MEAN SEASONAL											54,010			

( ) estimated by rainfall-discharge relationship.

NOTE: For the purpose of this study, discharges at S-97 are assumed equivalent to discharges at S-48.

TABLE 1b. C-24 AT S-49 DISCHARGE CFS-DAYS

YEAR	JAN.	FEB.	MAR.	APRIL	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	SEASONAL TOTALS	NOV.	DEC.	YEARLY TOTALS
1962				120	260	1,960	5,640	18,510	38,320	15,170	79,980	930	240	
1963	0	0	0	0	800	30	1,670	0	8,020	5,050	15,578	1,720	2,610	19,740
1964	3,960	6,320	280	880	940	310	3,820	15,010	11,630	2,700	35,290	1,070	550	47,085
1965	0	1,740	340	0	0	0	2,980	430	4,090	7,050	14,550	2,750	270	19,480
1966	9,420	8,050	3,800	340	3,610	8,730	11,040	8,070	3,120	14,670	46,772	0	0	70,270
1967	0	590	0	0	0	4,431	4,753	249	3,834	5,839	19,106	399	0	20,095
1968	0	0	0	0	3,728	40,348	13,856	892	3,916	6,170	68,910	1,792	0	70,752
1969	1,712	0	9,464	384	7,310	5,991	2,796	25,792	15,989	21,336	79,598	19,302	9,755	119,821
1970	18,515	8,759	11,491	3,575	0	1,172	5,872	5,909	5,702	18,802	41,032	1,876	0	81,673
1971	0	380	2,657	0	55	5,965	10,704	5,220	10,073	13,211	45,228	8,222	3,556	60,043
1972	6,302	3,209	1,676	6,635	5,537	13,432	1,826	2,892	1,604	786	32,712	990	8,598	53,487
1973	4,157	3,009	1,972	1,896	1,442	7,006	5,667	5,407	11,002	8,804	41,224	1,340	433	52,135
MEAN SEASONAL											43,331			

PROVISIONAL DATA
TABLE 1c. C-25 AT S-99 DISCHARGE CFS-DAYS

YEAR	JAN.	FEB.	MAR.	APRIL	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	SEASONAL TOTALS	NOV.	DEC.	YEARLY TOTALS
1964			0	42	709	1,091		7,009	15,667	12,614		636	1,042	
1965	97	1,566	4,174	74	0	0	6,478	4,914	1,781	5,492	18,739	7,836	992	33,404
1966	7,517	8,259	5,238	1,691	3,697	12,207	12,202	16,746	11,197	18,555	76,295	6,754	0	104,063
1967	0	334	86	0	0	4,286	10,881	6,066	3,579	5,622	30,434	850	14	31,718
1968	603	310	339	0	1,982	18,975	13,694	3,738	5,439	9,410	53,288	7,423	6,586	68,499
1969	1,919	735	13,540	458	11,388	1,149	2,112	11,566	9,799	10,534	47,006	10,959	6,707	80,866
1970	4,875	5,226	16,907	4,838	3,198	1,135	1,186	5,104	4,616	15,578	35,655	1,647	0	64,310
1971	0	923	918	0	24	5,925	8,595	8,768	7,654	7,463	38,429	4,362	2,446	47,078
1972	985	4,086	2,020	1,820	2,982	11,378	7,326	1,666	2,015	0	27,097	0	0	34,278
1973	5,343	8,702	2,392	1,990	411	14,750	8,596	10,017	8,381	8,173	52,318	6,823	1,418	76,996
MEAN SEASONAL											34,519			

NOTE: These discharges have been reduced 20% from those calculated by the theoretical rating curve on the basis of two flow measurements.

Water Resources - Demand Aspects

A recent memorandum report released by the District (Woehlcke and Loving, 1979), shows the 1978 water use of St. Lucie County to be 11,866,300 gallons for a population of 77,477. In terms of per capita use, this translates to a per capita consumption of 153 gallons. For Martin County, the per capita use is 179 gallons with 85 gallons for the portion of Okeechobee County within the planning basin (Table 2).

TABLE 2. PROJECTED POPULATION FOR THE UPPER EAST COAST PLANNING BASIN (Smith, 1978)

YEARS (POPULATION)

County	1985	1990	1995	2000	2010	2020	GPCD
Martin	72,800	80,400	87,000	93,339	104,371	115,036	180
St. Lucie	96,600	106,700	115,500	123,941	138,500	152,653	160
Okeechobee (within P.Area)	7,530	8,310	9,000	9,654	10,788	11,891	90

These per capita consumption rates, together with the projected population (Table 2), were used to estimate future water requirements of the planning basin. These are presented in Table 3. For the year 2000, the table shows that St. Lucie County will require an additional 8 million gallons of water on a daily basis.

TABLE 3. PROJECTED WATER REQUIREMENTS FOR THE UPPER EAST COAST

WATER REQUIREMENT (MGD)

County	1985	1990	1995	2000	2010	2020
Martin	13.10	14.47	15.66	16.80	18.78	20.70
St. Lucie	15.45	17.07	18.48	19.83	22.16	24.42
Okeechobee (within P.Area)	.67	.74	.81	.86	.97	1.07

FIELD DATA FOR CYCLIC STORAGE

In order to evaluate the capability of the brackish aquifer to act as a storage reservoir for fresh water, a hydrogeological survey of the area was conducted. In this study use was made of the results of surveys conducted by Brown and Reece (1979) and Brown (1980) on the potential of the Floridan aquifer of the area.

The field survey was conducted to determine the potentiometric gradient, transmissivity, storage coefficient, porosity and the dispersivity of the fluid medium for the feasibility of deep well storage. Schematics of deep well storage are shown in Figure 6.

The following hydrogeologic parameters were supplied by Brown (1980) for a typical Floridan aquifer well in St. Lucie County (SLF-14 - Figure 7).

Thickness of the 1st water bearing zone = 75'
Transmissivity = 412,800 g/ft/day
Porosity of the medium = .30
Viscosity of the injected fluid = 1.00
Viscosity of the native fluid = 1.00
Density of the injected fluid = 1.0
Density of the native fluid = 1.0015
Total dissolved solids (native fluid) = 1600 mg/l

However, in addition to the above parameters, one needs to know 1) the longitudinal dispersivity of the medium as well as 2) the coefficient of molecular diffusion.

Longitudinal Dispersivity: This is a relatively new parameter in groundwater hydrology. The value of longitudinal dispersivity coefficient is a characteristic of the porous medium and increases as the uniformity coefficient increases. Most experimental data indicates that it has an upper limit of 1.2 for engineering work. Kimbler (1975) suggests a value

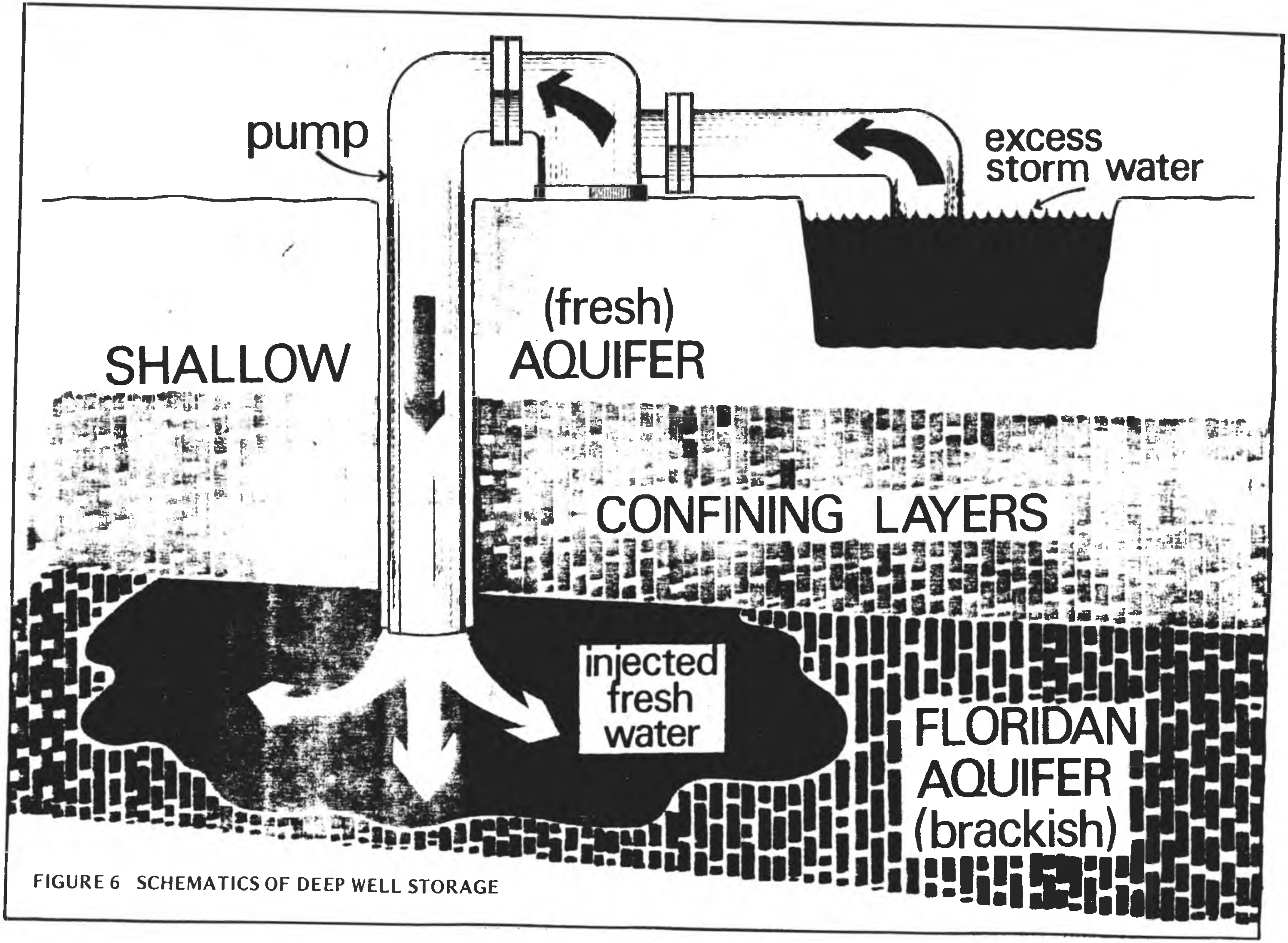


FIGURE 6 SCHEMATICS OF DEEP WELL STORAGE

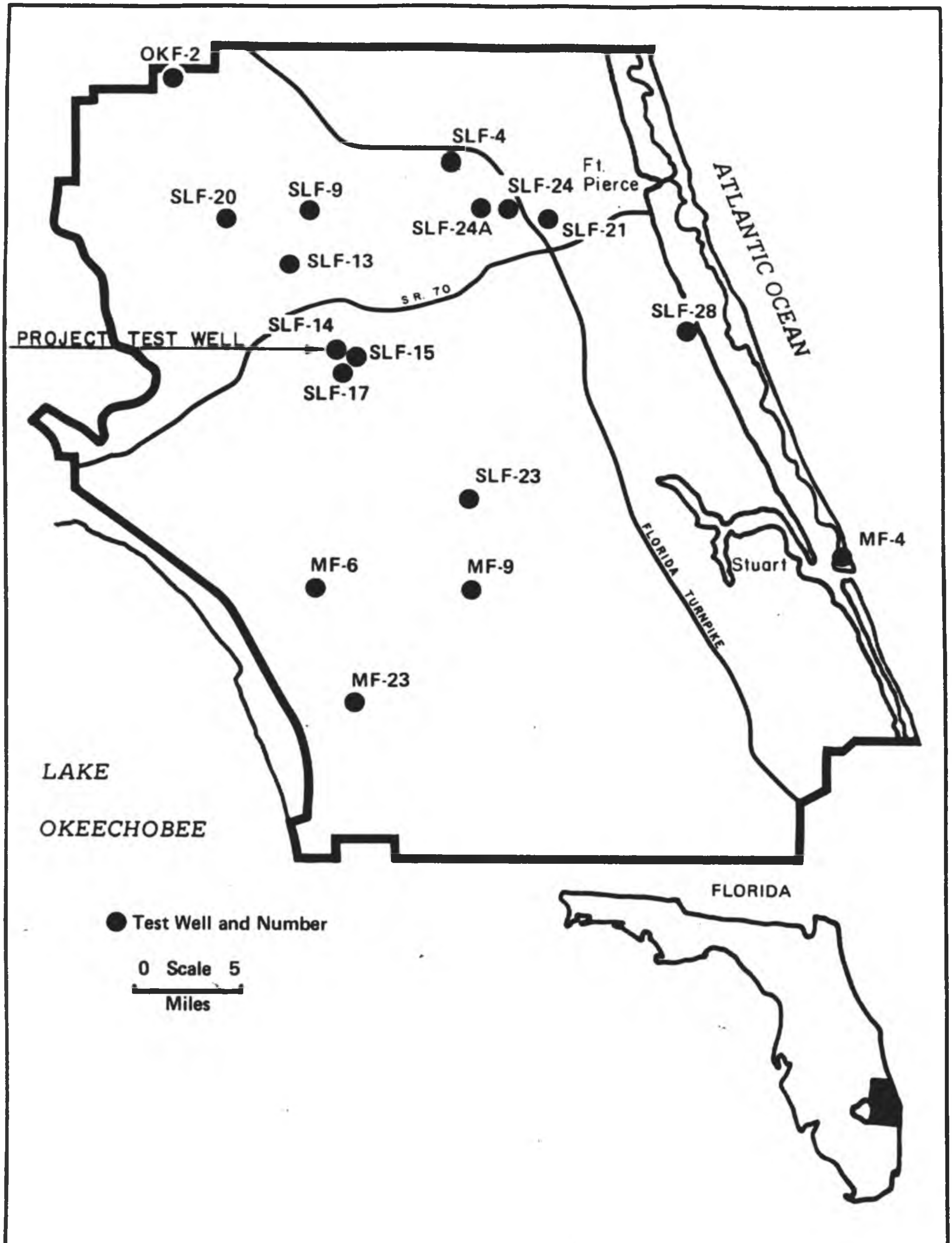


Figure 7 PROJECT TEST WELL LOCATION

of 1.0 which will be used in this study. For additional detail refer to Kimbler (1975, page 13).

Coefficient of Molecular Diffusion: Stoessel (Kimbler, 1975) recommends a value of 10^{-6} cm^2/sec for engineering work. This value will be used in this study.

Sizing of Wellfields

Assumptions:

1. Water will be available for injection for 150 days (May - Sept.)
2. Injected water will remain in storage for 95 days
3. Period of critical demand will be 120 days

Water requirements from deep well storage

$8 \frac{mg}{day}$ X 120 days = 960 million gallons

30% recovery loss (288 million gallons) = 1248 million gallons

Assume injection rate of 100 gpm/well

$1000 \frac{gal}{min}$ X $\frac{1440 \text{ min}}{day}$ X 150 days = 216 million gallons per well

To meet the water requirement including the recovery loss (assume 30%), one requires 1248 million gallons. This translates to 6 injection wells.

Concerning recovery, one needs 8 million gallons of produced water on a daily basis. If one uses the same withdrawal rates, more than 7.2 million but not more than 8 million gallons (1440 x 1000 gpm x 6 x 120) can be withdrawan on a daily basis during critical months.

In the model, the following figures will be used.

Injection Rate - 1000 gallons/min/well

Production Rate - 1000 gallons/min/well

Volume of Fluid injected - 1000 x 1440 x 150 days

= 216,000,000 gallons

RESULTS

One Well (SLF-14), One Cycle

A computer run was made on the feasibility of cyclic storage of fresh water through well SLF-14. The input parameters for the model are presented as data in Table 4. In addition to the computer printed data, two more parameters were input into the model. First, the radius at which breakthrough is computed. As the test was run for a single well, a 24" diameter well was assumed. For this well, the value of the radius at which breakthrough is computed is taken as the well bore radius which is 12 inches.

The second parameter input into the model was the allowable concentration of native brackish water in produced stream (a volume fraction). The figure used in the model was .025.

Using the second parameter, the model computed the volume of fluid that can be produced in the first production half-cycle. Of the 216,000,000 gallons of water injected, during the first half-cycle production a volume of 111,335,000 gallons of water can be produced. In addition, the computer model also calculates the cycle recovery efficiency (RCEFF) and the cumulative recovery efficiency.

For one cycle operation, the cycle recovery efficiency and the cumulative recovery efficiency would be the same. For well SLF-14, the recovery efficiency, using the data as shown, is calculated to be 51.5%. In other words, 51.5% of the total water which was injected can be recovered.

Table 4. SLF-14, ONE CYCLE DATA

```
POROUS MEDIUM

    THICKNESS OF THE MEDIUM (FT)                                          75.000000
    PERMEABILITY OF THE MEDIUM (MEINZERS)                               5504.000000
    POROSITY OF THE MEDIUM (FRACTION)                                       .300000
    LONGITUDINAL DISPERSIVITY OF THE MEDIUM (CM)                           1.000000
    COEFFICIENT OF MOLECULAR DIFFUSION (SQ CM/SEC)                          .000001


FLUID PROPERTIES

   VISCOSITY OF THE FLUIDS (CP)
    VISCOSITY OF THE INJECTED FLUID                                        1.000000
    VISCOSITY OF THE NATIVE FLUID                                          1.000000
    MEAN VISCOSITY OF THE TWO FLUIDS                                       1.000000

   DENSITY OF THE FLUIDS (GM/CC)
    DENSITY OF THE INJECTED FLUID                                          1.000000
    DENSITY OF THE NATIVE FLUID                                            1.001600
    DENSITY DIFF. BETWEEN THE FLUIDS                                        .001600


OPERATING CONDITIONS

   INJECTION AND PRODUCTION RATES (GAL/MIN)
    INJECTION  RATE FOR FIRST  INJECTION HALF-CYCLE                    1000.000000
    PRODUCTION RATE FOR FIRST  PRODUCTION HALF-CYCLE                   1000.000000

   VOLUME OF FLUID INJECTED OR PRODUCED (GALLONS)
    FLUID INJECTED IN FIRST  INJECTION  HALF-CYCLE              216000000.

   TIME OF STATIC STORAGE (DAYS)
    AT THE END OF FIRST INJECTION HALF-CYCLE                          180.000000



                         CALCULATION OF RECOVERY EFFICIENCY
                         -----------------------------------


FLPRGZ=  .111335E+09       CYLRDG=  .111335E+09      I= 76
 RCEFF=  .515441E+00       CRCEFF=  .515441E+00      X=   .597050E+00
TILIFT=  .500000E+02       TILPFT=  .300000E+01
```

One Well (SLF-14), Two Cycles

It has been stated by various researchers (Kimbler, 1975) and also verified by field tests, that recovery efficiency gets better as more and more injection retrieval cycles are performed. A test was run to check this (see Table 5). In addition to the data required for the first cycle, another 216,000,000 gallons of water was injected into the aquifer for two cycle operation. The model shows that during the second cycle, 143,211,000 gallons of water, in lieu of 111,335,000, can be recovered, volumewise. In terms of recovery efficiency of this particular cycle, efficiency increased from 51.5% to 66.3%. The cumulative recovery efficiency for the two cycle operation goes up to 59%.

In addition to the volume of water that can be produced in one and two cycle operations, the model can also compute the position of front at the end of the injection period (Table 6 and Figure 8). For injection well SLF-14, the front has moved to 686 feet at the top and 553 feet at the bottom.

Table 5. SLF-14, TWO CYCLE DATA

```
POROUS MEDIUM

   THICKNESS OF THE MEDIUM (FT)                                          75.000000
   PERMEABILITY OF THE MEDIUM (MEINZERS)                               5504.000000
   POROSITY OF THE MEDIUM (FRACTION)                                       .300000
   LONGITUDINAL DISPERSIVITY OF THE MEDIUM (CM)                           1.000000
   COEFFICIENT OF MOLECULAR DIFFUSION (SQ CM/SEC)                          .000001


FLUID PROPERTIES

  VISCOSITY OF THE FLUIDS (CP)
   VISCOSITY OF THE INJECTED FLUID                                        1.000000
   VISCOSITY OF THE NATIVE FLUID                                          1.000000
   MEAN VISCOSITY OF THE TWO FLUIDS                                       1.000000

  DENSITY OF THE FLUIDS (GM/CC)
   DENSITY OF THE INJECTED FLUID                                          1.000000
   DENSITY OF THE NATIVE FLUID                                            1.001500
   DENSITY DIFF. BETWEEN THE FLUIDS                                        .001500


OPERATING CONDITIONS

  INJECTION AND PRODUCTION RATES (GAL/MIN)
   INJECTION  RATE FOR FIRST  INJECTION  HALF-CYCLE                    1000.000000
   PRODUCTION RATE FOR FIRST  PRODUCTION HALF-CYCLE                    1000.000000
   INJECTION  RATE FOR SECOND INJECTION  HALF-CYCLE                    1000.000000
   PRODUCTION RATE FOR SECOND PRODUCTION HALF-CYCLE                    1000.000000

  VOLUME OF FLUID INJECTED OR PRODUCED (GALLONS)
   FLUID INJECTED IN FIRST  INJECTION  HALF-CYCLE       216000000.
   FLUID PRODUCED IN FIRST  PRODUCTION HALF-CYCLE       111335008.
   FLUID INJECTED IN SECOND INJECTION  HALF-CYCLE       216000000.

  TIME OF STATIC STORAGE (DAYS)
   AT THE END OF FIRST  INJECTION HALF-CYCLE                            180.000000
   AT THE END OF SECOND INJECTION HALF-CYCLE                            180.000000



                      CALCULATION OF RECOVERY EFFICIENCY
                      ----------------------------------


FLPRG4=   .143211E+09       CYLRDG=   .254546E+09       I=634
 RCEFF=   .663014E+00       CRCEFF=   .389227E+00       X=   .273672E+01
TILIFT=   .200000E+01       TILPFT=   .100000E+01
```

Table 6. POSITION OF FRONT AT THE END OF INJECTION

```
                                    DATA
POROUS MEDIUM

   THICKNESS OF THE MEDIUM (FT)                                               75.00000
   PERMEABILITY OF THE MEDIUM (MEINZERS)                                    5504.00000
   POROSITY OF THE MEDIUM (FRACTION)                                            .30000
   LONGITUDINAL DISPERSIVITY OF THE MEDIUM (CM)                                1.00000
   COEFFICIENT OF MOLECULAR DIFFUSION (SQ CM/SEC)                               .00000


FLUID PROPERTIES

  VISCOSITY OF THE FLUIDS (CP)
   VISCOSITY OF THE INJECTED FLUID                                             1.00000
   VISCOSITY OF THE NATIVE FLUID                                               1.00000
   MEAN VISCOSITY OF THE TWO FLUIDS                                            1.00000

  DENSITY OF THE FLUIDS (GM/CC)
   DENSITY OF THE INJECTED FLUID                                               1.00000
   DENSITY OF THE NATIVE FLUID                                                 1.00150
   DENSITY DIFF. BETWEEN THE FLUIDS                                             .00150


INJECTION RATE (GAL/MIN)                                                    1000.00000


VOLUME OF FLUID INJECTED (GALLONS)                                     216000000.00000



    POSITION OF FRONT AT THE END OF INJECTION
    -----------------------------------------



  RADII ON FLOOR OF AQUIFER (FEET)

    LAGGING EDGE OF MIXED ZONE                        553.76
    LEADING EDGE OF MIXED ZONE                        573.76


  RADII ON ROOF OF AQUIFER (FEET)

    LAGGING EDGE OF MIXED ZONE                        686.46
    LEADING EDGE OF MIXED ZONE                        706.46


  COMPUTATION INTERVAL LENGTH (FEET)                   10.00
```

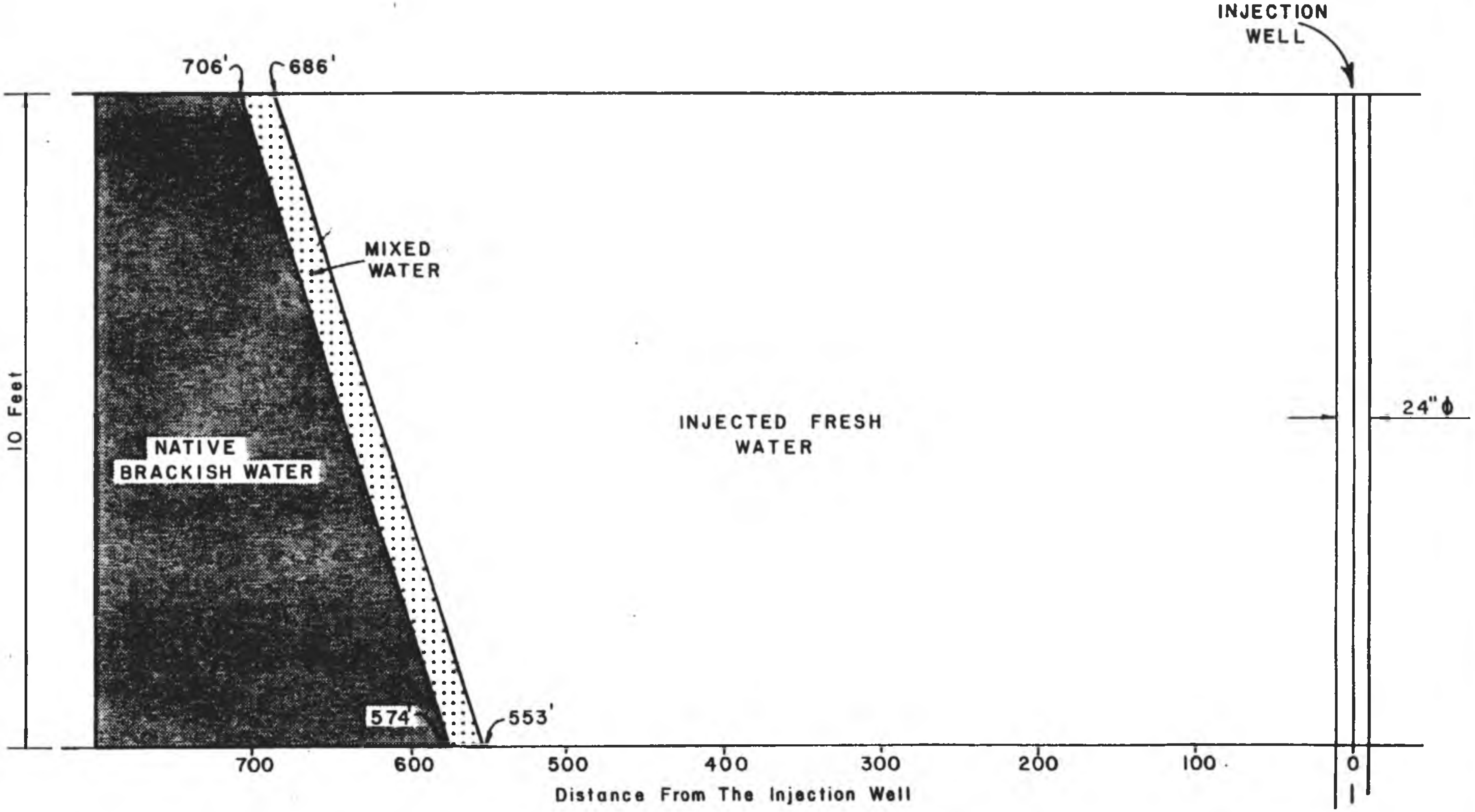


Figure 8 POSITION OF FRONT AT THE END OF INJECTION

SENSITIVITY ANALYSIS

In computer modeling, sensitivity analysis is performed to examine the impact of a certain variable on the overall performances of the model. Additionally, sensitivity analysis can also help to predict the recovery efficiency of the cyclic storage for other project areas where the parameters are different.

The important parameters that influence the cyclic storage of fresh water in brackish aquifers are 1) total dissolved solids of native water, 2) aquifer thickness, 3) permeability, 4) dispersivity, and 5) time of static storage.

Effect of Total Dissolved Solids of Native Water

The total dissolved solids of the native water is directly proportional to the density of the native fluid. It is well known that the TDS of the water obtained from brackish aquifers from different locations varies. In order to see how different densities (TDS) affect the overall recovery percentage, the densities of the native fluid will be varied in several runs with the other parameters being fixed. Presented in Tables 7a, 7b, and 7c are the different density values of the native fluids with the other parameters being fixed.

Table 7a. CALCULATION OF RECOVERY EFFICIENCY
DENSITY .0097
DATA

```
POROUS MEDIUM

    THICKNESS OF THE MEDIUM (FT)
    PERMEABILITY OF THE MEDIUM (MEINZERS)
    POROSITY OF THE MEDIUM (FRACTION)
    LONGITUDINAL DISPERSIVITY OF THE MEDIUM (CM)
    COEFFICIENT OF MOLECULAR DIFFUSION (SQ CM/SEC)


FLUID PROPERTIES

   VISCOSITY OF THE FLUIDS (CP)
    VISCOSITY OF THE INJECTED FLUID
    VISCOSITY OF THE NATIVE FLUID
    MEAN VISCOSITY OF THE TWO FLUIDS

   DENSITY OF THE FLUIDS (GM/CC)
    DENSITY OF THE INJECTED FLUID
    DENSITY OF THE NATIVE FLUID
    DENSITY DIFF. BETWEEN THE FLUIDS                                .002300


OPERATING CONDITIONS

   INJECTION AND PRODUCTION RATES
    INJECTION  RATE FOR FIRST  INJECTION HALF-CYCLE              1000.000000
    PRODUCTION RATE FOR FIRST  PRODUCTION HALF-CYCLE              1000.000000

   VOLUME OF FLUID INJECTED OR PRODUCED (GALLONS)
    FLUID INJECTED IN FIRST  INJECTION  HALF-CYCLE         216000000.

   TIME OF STATIC STORAGE (DAYS)
    AT THE END OF FIRST INJECTION HALF-CYCLE                     180.000000


                 CALCULATION OF RECOVERY EFFICIENCY
                 ----------------------------------


FLPRG2=  .986898E+08      CYLRDG=  .986898E+08      I= 69
 RCEFF=  .456897E+00      CRCEFF=  .456897E+00      X=   .750636E-
TILIFT=  .500000E+02      TILPFT=  .300000E+01
```

Table 7b. CALCULATION OF RECOVERY EFFICIENCY
DENSITY 1.0085 (8000 TDS)
DATA

```
POROUS MEDIUM

   THICKNESS OF THE MEDIUM (FT)                                           75.000000
   PERMEABILITY OF THE MEDIUM (MEINZERS)                                5504.000000
   POROSITY OF THE MEDIUM (FRACTION)                                        .300000
   LONGITUDINAL DISPERSIVITY OF THE MEDIUM (CM)                            1.000000
   COEFFICIENT OF MOLECULAR DIFFUSION (SQ CM/SEC)                           .000001


FLUID PROPERTIES

  VISCOSITY OF THE FLUIDS (CP)
   VISCOSITY OF THE INJECTED FLUID                                         1.000000
   VISCOSITY OF THE NATIVE FLUID                                           1.000000
   MEAN VISCOSITY OF THE TWO FLUIDS                                        1.000000

  DENSITY OF THE FLUIDS (GM/CC)
   DENSITY OF THE INJECTED FLUID                                           1.000000
   DENSITY OF THE NATIVE FLUID                                             1.008500
   DENSITY DIFF. BETWEEN THE FLUIDS                                         .008500


OPERATING CONDITIONS

  INJECTION AND PRODUCTION RATES (GAL/MIN)
   INJECTION  RATE FOR FIRST  INJECTION HALF-CYCLE                   1000.000000
   PRODUCTION RATE FOR FIRST  PRODUCTION HALF-CYCLE                   1000.000000

  VOLUME OF FLUID INJECTED OR PRODUCED (GALLONS)
   FLUID INJECTED IN FIRST  INJECTION  HALF-CYCLE       216000000.

  TIME OF STATIC STORAGE (DAYS)
   AT THE END OF FIRST INJECTION HALF-CYCLE                          180.000000


                        CALCULATION OF RECOVERY EFFICIENCY
                        ----------------------------------


 FLPRG2=  .785772E+08      CVLRDG=  .785772E+08      I= 57
  RCEFF=  .363783E+00      CRCEFF=  .363783E+00      X=   .174774E+01
 TILIFT=  .500000E+02      TILPFT=  .300000E+01
```

Table 7c.

CALCULATION OF RECOVERY EFFICIENCY
DENSITY 1.025 (TDS 35,000 SEA WATER)
DATA

```
POROUS MEDIUM

   THICKNESS OF THE MEDIUM (FT)                                        75.000000
   PERMEABILITY OF THE MEDIUM (MEINZERS)                             5504.000000
   POROSITY OF THE MEDIUM (FRACTION)                                    .300000
   LONGITUDINAL DISPERSIVITY OF THE MEDIUM (CM)                        1.000000
   COEFFICIENT OF MOLECULAR DIFFUSION (SQ CM/SEC)                       .000001


FLUID PROPERTIES

  VISCOSITY OF THE FLUIDS (CP)
   VISCOSITY OF THE INJECTED FLUID                                     1.000000
   VISCOSITY OF THE NATIVE FLUID                                       1.000000
   MEAN VISCOSITY OF THE TWO FLUIDS                                    1.000000

  DENSITY OF THE FLUIDS (GM/CC)
   DENSITY OF THE INJECTED FLUID                                       1.000000
   DENSITY OF THE NATIVE FLUID                                         1.025000
   DENSITY DIFF. BETWEEN THE FLUIDS                                     .025000


OPERATING CONDITIONS

  INJECTION AND PRODUCTION RATES (GAL/MIN)
   INJECTION  RATE FOR FIRST  INJECTION HALF-CYCLE                  1000.000000
   PRODUCTION RATE FOR FIRST  PRODUCTION HALF-CYCLE                 1000.000000

  VOLUME OF FLUID INJECTED OR PRODUCED (GALLONS)
   FLUID INJECTED IN FIRST  INJECTION  HALF-CYCLE              216000000.

  TIME OF STATIC STORAGE (DAYS)
   AT THE END OF FIRST INJECTION HALF-CYCLE                          180.000000



                        CALCULATION OF RECOVERY EFFICIENCY
                        ----------------------------------



 FLPRGZ=  .514440E+08       CVLRDG=  .514440E+08       I= 43
  RCEFF=  .238167E+00       CRCEFF=  .238167E+00       X=  .347461E+01
 TILIFT=  .500000E+02       TILPFT=  .300000E+01
```

Table 7d. EFFECT OF DENSITY OF THE NATIVE FLUID ON RECOVERY EFFICIENCY

	DENSITY OF THE NATIVE FLUID		
	.9997 1500 mg/l	1.0085 8000 mg/l	1.025 35,000 mg/l
Recovery efficiency	.45	.36	.23

It has been reported that temperature of the native water influences its density. Assuming that to be true, if the temperature of the native water is higher than that of the injected fluid, the density of the native water will be low. If that is the case, then recovery efficiency will decrease from 51% to 45%.

Additionally, if the density of the native fluid is higher, say 1.0085 which corresponds to a TDS of 8000 mg/l, then the % of recovery of the injected fluid will drop to 36%. If the density is 1.025, which corresponds to the TDS of seawater (35,000 mg/l), recovery efficiency is only 23%.

Effect of Aquifer Thickness on Recovery Efficiency

The aquifer thickness of the first producing zone of the Floridan aquifer was assumed to be 75 feet. However, if it is found to be thicker (100 feet) or thinner (50 feet) with every other parameter remaining the same, the following changes will take place in recovery efficiency (see Tables 8a, 8b, and 8C.

Table 8a. EFFECT OF AQUIFER THICKNESS ON RECOVERY EFFICIENCY

	Aquifer Thickness (ft.)	
	50 feet	100 feet
Recovery efficiency	67	35

The above result shows that the thinner the aquifer, the better the recovery efficiency, as dispersion takes place mostly on the horizontal direction.

Table 8b.

EFFECT OF AQUIFER THICKNESS ON RECOVERY EFFICIENCY AQUIFER THICKNESS - 50 FEET

DATA

```
POROUS MEDIUM

   THICKNESS OF THE MEDIUM (FT)                                        50.000000
   PERMEABILITY OF THE MEDIUM (MEINZERS)                             5504.000000
   POROSITY OF THE MEDIUM (FRACTION)                                     .300000
   LONGITUDINAL DISPERSIVITY OF THE MEDIUM (CM)                         1.000000
   COEFFICIENT OF MOLECULAR DIFFUSION (SQ CM/SEC)                        .000001


FLUID PROPERTIES

  VISCOSITY OF THE FLUIDS (CP)
   VISCOSITY OF THE INJECTED FLUID                                      1.000000
   VISCOSITY OF THE NATIVE FLUID                                        1.000000
   MEAN VISCOSITY OF THE TWO FLUIDS                                     1.000000

  DENSITY OF THE FLUIDS (GM/CC)
   DENSITY OF THE INJECTED FLUID                                        1.000000
   DENSITY OF THE NATIVE FLUID                                          1.001500
   DENSITY DIFF. BETWEEN THE FLUIDS                                      .001500


OPERATING CONDITIONS

  INJECTION AND PRODUCTION RATES (GAL/MIN)
   INJECTION  RATE FOR FIRST  INJECTION HALF-CYCLE                 1000.000000
   PRODUCTION RATE FOR FIRST  PRODUCTION HALF-CYCLE                 1000.000000

  VOLUME OF FLUID INJECTED OR PRODUCED (GALLONS)
   FLUID INJECTED IN FIRST  INJECTION  HALF-CYCLE        216000000.

  TIME OF STATIC STORAGE (DAYS)
   AT THE END OF FIRST INJECTION HALF-CYCLE                         180.000000



                        CALCULATION OF RECOVERY EFFICIENCY
                        ----------------------------------


  FLPRG2=  .144741E+09      CVLRDG=  .144741E+09      I=127
   RCEFF=  .670095E+00      CRCEFF=  .670095E+00      X=  .858406E+00
  TILIFT=  .500000E+02      TILPFT=  .300000E+01
```

Table 8c. EFFECT OF AQUIFER THICKNESS ON RECOVERY EFFICIENCY AQUIFER THICKNESS - 100 FEET

DATA

```
POROUS MEDIUM

   THICKNESS OF THE MEDIUM (FT)                                          100.000000
   PERMEABILITY OF THE MEDIUM (MEINZERS)                                5504.000000
   POROSITY OF THE MEDIUM (FRACTION)                                        .300000
   LONGITUDINAL DISPERSIVITY OF THE MEDIUM (CM)                            1.000000
   COEFFICIENT OF MOLECULAR DIFFUSION (SQ CM/SEC)                           .000001


FLUID PROPERTIES

  VISCOSITY OF THE FLUIDS (CP)
   VISCOSITY OF THE INJECTED FLUID                                         1.000000
   VISCOSITY OF THE NATIVE FLUID                                           1.000000
   MEAN VISCOSITY OF THE TWO FLUIDS                                        1.000000

  DENSITY OF THE FLUIDS (GM/CC)
   DENSITY OF THE INJECTED FLUID                                           1.000000
   DENSITY OF THE NATIVE FLUID                                             1.001500
   DENSITY DIFF. BETWEEN THE FLUIDS                                         .001500


OPERATING CONDITIONS

  INJECTION AND PRODUCTION RATES (GAL/MIN)
   INJECTION  RATE FOR FIRST  INJECTION HALF-CYCLE                     1000.000000
   PRODUCTION RATE FOR FIRST  PRODUCTION HALF-CYCLE                     1000.000000

  VOLUME OF FLUID INJECTED OR PRODUCED (GALLONS)
   FLUID INJECTED IN FIRST  INJECTION  HALF-CYCLE                 216000000.

  TIME OF STATIC STORAGE (DAYS)
   AT THE END OF FIRST INJECTION HALF-CYCLE                             180.000000


                       CALCULATION OF RECOVERY EFFICIENCY
                       ----------------------------------


 FLPRG2=  .756663E+08      CVLRDG=  .756663E+08      I= 58
  RCEFF=  .350307E+00      CRCEFF=  .350307E+00      X=  .456200E+00
 TILIFT=  .500000E+02      TILPFT=  .300000E+01
```

Effect of Aquifer Transmissivity on Recovery Efficiency

One of the important parameters used in the model for cyclic storage of fresh water in brackish water is permeability. Permeability value was obtained by dividing the transmissivity value by the aquifer thickness. Even though aquifer thickness might remain unchanged, the transmissivity value changes. Additionally, the transmissivity value used in the model seems to be rather high. In order to evaluate the effect of this important parameter on recovery efficiency, several computer runs were made using lower values. The runs were made for the following values.

Thickness (ft.)	Transmissivity (G/D/F)	Permeability (G/D/Ft.^{2})
75	412,800	5504
75	200,000	2666
75	100,000	1333
75	50,000	666

In tables 9a, b, c, and d, the recovery efficiency of the cyclic storage system, using different permeability values but keeping all other parameters constant, is presented. It can be seen that the lower the transmissivity value, the higher the recovery efficiency.

Table 9a. EFFECT OF PERMEABILITY ON RECOVERY EFFICIENCY

	Aquifer Permeability			
	5504	2666	1333	666
Recovery efficiency	51.5	68.6	78.6	87.1

Table 9b.

CALCULATION OF RECOVERY EFFICIENCY
T = 200,000

DATA

```
POROUS MEDIUM

   THICKNESS OF THE MEDIUM (FT)                                      75.000000
   PERMEABILITY OF THE MEDIUM (MEINZERS)                           2666.000000
   POROSITY OF THE MEDIUM (FRACTION)                                  .300000
   LONGITUDINAL DISPERSIVITY OF THE MEDIUM (CM)                      1.000000
   COEFFICIENT OF MOLECULAR DIFFUSION (SQ CM/SEC)                     .000001


FLUID PROPERTIES

  VISCOSITY OF THE FLUIDS (CP)
   VISCOSITY OF THE INJECTED FLUID                                   1.000000
   VISCOSITY OF THE NATIVE FLUID                                     1.000000
   MEAN VISCOSITY OF THE TWO FLUIDS                                  1.000000

  DENSITY OF THE FLUIDS (GM/CC)
   DENSITY OF THE INJECTED FLUID                                     1.000000
   DENSITY OF THE NATIVE FLUID                                       1.001500
   DENSITY DIFF. BETWEEN THE FLUIDS                                   .001500


OPERATING CONDITIONS

  INJECTION AND PRODUCTION RATES (GAL/MIN)
   INJECTION  RATE FOR FIRST  INJECTION HALF-CYCLE              1000.000000
   PRODUCTION RATE FOR FIRST  PRODUCTION HALF-CYCLE              1000.000000

  VOLUME OF FLUID INJECTED OR PRODUCED (GALLONS)
   FLUID INJECTED IN FIRST  INJECTION  HALF-CYCLE         216000000.

  TIME OF STATIC STORAGE (DAYS)
   AT THE END OF FIRST INJECTION HALF-CYCLE                      180.000000



                         CALCULATION OF RECOVERY EFFICIENCY
                         ----------------------------------


  FLPRG2=   .148318E+09       CVLRDG=   .148318E+09       I=102
   RCEFF=   .686658E+00       CRCEFF=   .686658E+00       X=   .289107E+00
  TILIFT=   .500000E+02       TILPFT=   .300000E+01
```

Table 9c.

CALCULATION OF RECOVERY EFFICIENCY
T = 100,000
DATA

```
POROUS MEDIUM

   THICKNESS OF THE MEDIUM (FT)                                       75.000000
   PERMEABILITY OF THE MEDIUM (MEINZERS)                            1333.000000
   POROSITY OF THE MEDIUM (FRACTION)                                    .300000
   LONGITUDINAL DISPERSIVITY OF THE MEDIUM (CM)                        1.000000
   COEFFICIENT OF MOLECULAR DIFFUSION (SQ CM/SEC)                       .000001


FLUID PROPERTIES

  VISCOSITY OF THE FLUIDS (CP)
   VISCOSITY OF THE INJECTED FLUID                                     1.000000
   VISCOSITY OF THE NATIVE FLUID                                       1.000000
   MEAN VISCOSITY OF THE TWO FLUIDS                                    1.000000

  DENSITY OF THE FLUIDS (GM/CC)
   DENSITY OF THE INJECTED FLUID                                       1.000000
   DENSITY OF THE NATIVE FLUID                                         1.001500
   DENSITY DIFF. BETWEEN THE FLUIDS                                     .001500


OPERATING CONDITIONS

  INJECTION AND PRODUCTION RATES (GAL/MIN)
   INJECTION  RATE FOR FIRST  INJECTION HALF-CYCLE                  1000.000000
   PRODUCTION RATE FOR FIRST  PRODUCTION HALF-CYCLE                 1000.000000

  VOLUME OF FLUID INJECTED OR PRODUCED (GALLONS)
   FLUID INJECTED IN FIRST  INJECTION  HALF-CYCLE           216000000.

  TIME OF STATIC STORAGE (DAYS)
   AT THE END OF FIRST INJECTION HALF-CYCLE                         180.000000


                     CALCULATION OF RECOVERY EFFICIENCY
                     ----------------------------------


FLPRG2=  .169905E+09       CVLRDG=  .169905E+09      I=120
 RCEFF=  .786596E+00       CRCEFF=  .786596E+00      X=  .149663E+00
TILIFT=  .500000E+02       TILPFT=  .300000E+01
```

Table 9d. CALCULATION OF RECOVERY EFFICIENCY
T = 50,000

DATA

```
POROUS MEDIUM

   THICKNESS OF THE MEDIUM (FT)                                      75.000000
   PERMEABILITY OF THE MEDIUM (MEINZERS)                            666.000000
   POROSITY OF THE MEDIUM (FRACTION)                                   .300000
   LONGITUDINAL DISPERSIVITY OF THE MEDIUM (CM)                       1.000000
   COEFFICIENT OF MOLECULAR DIFFUSION (SQ CM/SEC)                      .000001


FLUID PROPERTIES

  VISCOSITY OF THE FLUIDS (CP)
   VISCOSITY OF THE INJECTED FLUID                                    1.000000
   VISCOSITY OF THE NATIVE FLUID                                      1.000000
   MEAN VISCOSITY OF THE TWO FLUIDS                                   1.000000

  DENSITY OF THE FLUIDS (GM/CC)
   DENSITY OF THE INJECTED FLUID                                      1.000000
   DENSITY OF THE NATIVE FLUID                                        1.001500
   DENSITY DIFF. BETWEEN THE FLUIDS                                    .001500


OPERATING CONDITIONS

  INJECTION AND PRODUCTION RATES (GAL/MIN)
   INJECTION  RATE FOR FIRST  INJECTION HALF-CYCLE              1000.000000
   PRODUCTION RATE FOR FIRST  PRODUCTION HALF-CYCLE              1000.000000

  VOLUME OF FLUID INJECTED OR PRODUCED (GALLONS)
   FLUID INJECTED IN FIRST  INJECTION  HALF-CYCLE      216000000.

  TIME OF STATIC STORAGE (DAYS)
   AT THE END OF FIRST INJECTION HALF-CYCLE                      180.000000


                    CALCULATION OF RECOVERY EFFICIENCY
                    ----------------------------------


  FLPRG2=  .188336E+09      CVLRDG=  .188336E+09      I=140
   RCEFF=  .871925E+00      CRCEFF=  .871925E+00      X=   .733900E-01
  TILIFT=  .500000E+02      TILPFT=  .300000E+01
```

Effect of Dispersivity on Recovery Efficiency

As stated earlier, dispersivity is a relatively new parameter in groundwater hydrology and differs from one location to another, as do the transmissivity values. In all the above runs, the average value of 1.0 was used. Dispersivity values are changed for the sensitivity analysis to show the effect of this parameter on the overall recovery efficiency and are presented in Tables 10a, b, c, and d.

Table 10a. EFFECT OF DISPERSIVITY VARIATION ON RECOVERY EFFICIENCY

	Dispersivity Coefficient		
	.10	1.0	10.0
Recovery Efficiency	40.7	51.5	63.8

It can be seen from the above table that the higher the dispersivity coefficient, the higher the recovery efficiency. This is expected as the dispersivity coefficient is the parameter which influences the dispersion of the injected fluid pushing the native fluid further. This statement is true only for thin aquifer depths. High dispersivity values will lower recovery efficiency for thick aquifers.

Table 10b. CALCULATION OF RECOVERY EFFICIENCY
.10 DISPERSIVITY COEFFICIENT
DATA

```
POROUS MEDIUM

   THICKNESS OF THE MEDIUM (FT)                                          75.000000
   PERMEABILITY OF THE MEDIUM (MEINZERS)                               5504.000000
   POROSITY OF THE MEDIUM (FRACTION)                                       .300000
   LONGITUDINAL DISPERSIVITY OF THE MEDIUM (CM)                            .100000
   COEFFICIENT OF MOLECULAR DIFFUSION (SQ CM/SEC)                          .000001


FLUID PROPERTIES

  VISCOSITY OF THE FLUIDS (CP)
   VISCOSITY OF THE INJECTED FLUID                                        1.000000
   VISCOSITY OF THE NATIVE FLUID                                          1.000000
   MEAN VISCOSITY OF THE TWO FLUIDS                                       1.000000

  DENSITY OF THE FLUIDS (GM/CC)
   DENSITY OF THE INJECTED FLUID                                          1.000000
   DENSITY OF THE NATIVE FLUID                                            1.001500
   DENSITY DIFF. BETWEEN THE FLUIDS                                        .001500


OPERATING CONDITIONS

  INJECTION AND PRODUCTION RATES (GAL/MIN)
   INJECTION  RATE FOR FIRST  INJECTION HALF-CYCLE                    1000.000000
   PRODUCTION RATE FOR FIRST  PRODUCTION HALF-CYCLE                   1000.000000

  VOLUME OF FLUID INJECTED OR PRODUCED (GALLONS)
   FLUID INJECTED IN FIRST  INJECTION  HALF-CYCLE               216000000.

  TIME OF STATIC STORAGE (DAYS)
   AT THE END OF FIRST INJECTION HALF-CYCLE                            180.000000



                      CALCULATION OF RECOVERY EFFICIENCY
                      ----------------------------------


    FLPRG2=   .880487E+08       CVLRDG=   .880487E+08       I= 63
     RCEFF=   .407633E+00       CRCEFF=   .407633E+00       X=   .984748E+00
    TILIFT=   .500000E+02       TILPFT=   .300000E+01
```

Table 10c.

CALCULATION OF RECOVERY EFFICIENCY
1.0 DISPERSIVITY COEFFICIENT
DATA

```
POROUS MEDIUM

   THICKNESS OF THE MEDIUM (FT)                                        75.000000
   PERMEABILITY OF THE MEDIUM (MEINZERS)                             5504.000000
   POROSITY OF THE MEDIUM (FRACTION)                                     .300000
   LONGITUDINAL DISPERSIVITY OF THE MEDIUM (CM)                         1.000000
   COEFFICIENT OF MOLECULAR DIFFUSION (SQ CM/SEC)                        .000001


FLUID PROPERTIES

  VISCOSITY OF THE FLUIDS (CP)
   VISCOSITY OF THE INJECTED FLUID                                      1.000000
   VISCOSITY OF THE NATIVE FLUID                                        1.000000
   MEAN VISCOSITY OF THE TWO FLUIDS                                     1.000000

  DENSITY OF THE FLUIDS (GM/CC)
   DENSITY OF THE INJECTED FLUID                                        1.000000
   DENSITY OF THE NATIVE FLUID                                          1.001500
   DENSITY DIFF. BETWEEN THE FLUIDS                                      .001500


OPERATING CONDITIONS

  INJECTION AND PRODUCTION RATES (GAL/MIN)
   INJECTION  RATE FOR FIRST  INJECTION HALF-CYCLE                   1000.000000
   PRODUCTION RATE FOR FIRST  PRODUCTION HALF-CYCLE                   1000.000000

  VOLUME OF FLUID INJECTED OR PRODUCED (GALLONS)
   FLUID INJECTED IN FIRST  INJECTION  HALF-CYCLE         216000000.

  TIME OF STATIC STORAGE (DAYS)
   AT THE END OF FIRST INJECTION HALF-CYCLE                           180.000000



                    CALCULATION OF RECOVERY EFFICIENCY
                    ----------------------------------


FLPRG2=  .113613E+09      CVLRDG=  .113613E+09      I= 78
 RCEFF=  .525987E+00      CRCEFF=  .525987E+00      X=  .573360E+00
TILIFT=  .500000E+02      TILPFT=  .300000E+01
```

Table 10d.

CALCULATION OF RECOVERY EFFICIENCY
10.0 DISPERSIVITY COEFFICIENT
DATA

```
POROUS MEDIUM

   THICKNESS OF THE MEDIUM (FT)                                          75.000000
   PERMEABILITY OF THE MEDIUM (MEINZERS)                               5504.000000
   POROSITY OF THE MEDIUM (FRACTION)                                      .300000
   LONGITUDINAL DISPERSIVITY OF THE MEDIUM (CM)                         10.000000
   COEFFICIENT OF MOLECULAR DIFFUSION (SQ CM/SEC)                         .000001


FLUID PROPERTIES

  VISCOSITY OF THE FLUIDS (CP)
   VISCOSITY OF THE INJECTED FLUID                                       1.000000
   VISCOSITY OF THE NATIVE FLUID                                         1.000000
   MEAN VISCOSITY OF THE TWO FLUIDS                                      1.000000

  DENSITY OF THE FLUIDS (GM/CC)
   DENSITY OF THE INJECTED FLUID                                         1.000000
   DENSITY OF THE NATIVE FLUID                                           1.001500
   DENSITY DIFF. BETWEEN THE FLUIDS                                       .001500


OPERATING CONDITIONS

  INJECTION AND PRODUCTION RATES (GAL/MIN)
   INJECTION  RATE FOR FIRST  INJECTION HALF-CYCLE                    1000.000000
   PRODUCTION RATE FOR FIRST  PRODUCTION HALF-CYCLE                   1000.000000

  VOLUME OF FLUID INJECTED OR PRODUCED (GALLONS)
   FLUID INJECTED IN FIRST  INJECTION  HALF-CYCLE              216000000.

  TIME OF STATIC STORAGE (DAYS)
   AT THE END OF FIRST INJECTION HALF-CYCLE                            180.000000



                       CALCULATION OF RECOVERY EFFICIENCY
                       ----------------------------------



    FLPRG2=  .138021E+09      CVLRDG=  .138021E+09      I= 92
     RCEFF=  .638988E+00      CRCEFF=  .638988E+00      X=  .331092E+00
    TILIFT=  .500000E+02      TILPFT=  .300000E+01
```

Effect of Long-term Storage on Recovery Efficiency

The final sensitivity analysis is performed to determine the effect of long-term storage on the recovery efficiency. In lieu of leaving the injected fluid in storage for 180 days, the static storage time will be increased to 365 and 730 days. Presented in Tables 11a, b and c is the recovery efficiency after the injected fluid is left in static storage for 365 and 730 days, respectively.

Table 11a. EFFECT OF STATIC STORAGE ON RECOVERY EFFICIENCY

	Static Storage (Days)		
	180	365	730
Recovery Efficiency	51.5	39.2	27.9

As expected, the longer the static storage, the lower the recovery efficiency. However, this is true only of one injection cycle. The recovery efficiency will go up after several injection/storage and production cycles.

Table 11b. CALCULATION OF RECOVERY EFFICIENCY
365 DAYS STORAGE

DATA

```
POROUS MEDIUM

   THICKNESS OF THE MEDIUM (FT)                                             75.000000
   PERMEABILITY OF THE MEDIUM (MEINZERS)                                  5504.000000
   POROSITY OF THE MEDIUM (FRACTION)                                          .300000
   LONGITUDINAL DISPERSIVITY OF THE MEDIUM (CM)                              1.000000
   COEFFICIENT OF MOLECULAR DIFFUSION (SQ CM/SEC)                             .000001


FLUID PROPERTIES

  VISCOSITY OF THE FLUIDS (CP)
   VISCOSITY OF THE INJECTED FLUID                                           1.000000
   VISCOSITY OF THE NATIVE FLUID                                             1.000000
   MEAN VISCOSITY OF THE TWO FLUIDS                                          1.000000

  DENSITY OF THE FLUIDS (GM/CC)
   DENSITY OF THE INJECTED FLUID                                             1.000000
   DENSITY OF THE NATIVE FLUID                                               1.001500
   DENSITY DIFF. BETWEEN THE FLUIDS                                           .001500


OPERATING CONDITIONS

  INJECTION AND PRODUCTION RATES (GAL/MIN)
   INJECTION  RATE FOR FIRST  INJECTION HALF-CYCLE                        1000.000000
   PRODUCTION RATE FOR FIRST  PRODUCTION HALF-CYCLE                        1000.000000

  VOLUME OF FLUID INJECTED OR PRODUCED (GALLONS)
   FLUID INJECTED IN FIRST  INJECTION  HALF-CYCLE      216000000.

  TIME OF STATIC STORAGE (DAYS)
   AT THE END OF FIRST INJECTION HALF-CYCLE                                365.000000


                        CALCULATION OF RECOVERY EFFICIENCY
                        ----------------------------------


   FLPRG2=   .847924E+08       CYLRDG=   .847924E+08       I= 61
    RCEFF=   .392558E+00       CRCEFF=   .392558E+00       X=   .826626E+00
   TILIFT=   .500000E+02       TILPFT=   .300000E+01
```

Table 11c. CALCULATION OF RECOVERY EFFICIENCY
730 DAYS STORAGE

DATA

```
POROUS MEDIUM

   THICKNESS OF THE MEDIUM (FT)                                        75.000000
   PERMEABILITY OF THE MEDIUM (MEINZERS)                             5504.000000
   POROSITY OF THE MEDIUM (FRACTION)                                     .300000
   LONGITUDINAL DISPERSIVITY OF THE MEDIUM (CM)                         1.000000
   COEFFICIENT OF MOLECULAR DIFFUSION (SQ CM/SEC)                        .000001


FLUID PROPERTIES

  VISCOSITY OF THE FLUIDS (CP)
   VISCOSITY OF THE INJECTED FLUID                                      1.000000
   VISCOSITY OF THE NATIVE FLUID                                        1.000000
   MEAN VISCOSITY OF THE TWO FLUIDS                                     1.000000

  DENSITY OF THE FLUIDS (GM/CC)
   DENSITY OF THE INJECTED FLUID                                        1.000000
   DENSITY OF THE NATIVE FLUID                                          1.001500
   DENSITY DIFF. BETWEEN THE FLUIDS                                      .001500


OPERATING CONDITIONS

  INJECTION AND PRODUCTION RATES (GAL/MIN)
   INJECTION  RATE FOR FIRST  INJECTION HALF-CYCLE                  1000.000000
   PRODUCTION RATE FOR FIRST  PRODUCTION HALF-CYCLE                 1000.000000

  VOLUME OF FLUID INJECTED OR PRODUCED (GALLONS)
   FLUID INJECTED IN FIRST  INJECTION  HALF-CYCLE               216000000.

  TIME OF STATIC STORAGE (DAYS)
   AT THE END OF FIRST INJECTION HALF-CYCLE                          730.000000



                        CALCULATION OF RECOVERY EFFICIENCY
                        ----------------------------------



  FLPRG2=  .603486E+08      CVLROG=  .603486E+08      I= 48
   RCEFF=  .279392E+00      CRCEFF=  .279392E+00      X=  .134219E+01
  TILIFT=  .500000E+02      TILPFT=  .300000E+01
```

ECONOMICS

The key to any water supply alternative is economics. An alternative becomes feasible, from an engineering point of view, if it is economical.

In order to make an economic evaluation, a general design of the wellfield to meet the year 2000 demand of St. Lucie County (the individual wells connecting piping, pumps, motor and control) is needed.

Additional water required to meet the year 2000 demand is 960 million gallons (8 mg/day). As shown earlier, the efficiency of the cyclic storage system (the most conservative estimate) is 51.5%. Therefore, one would require 1,900 million gallons of water to be injected. As calculated earlier, 9 injection wells will be needed.

Capital Cost (1980 Prices)

a)	Hydrological survey	$ 300,000
b)	Land costs ($10,000/acre)	100,000
c)	Wells (9 wells, 700 feet deep)	900,000
d)	Motor & pump for wells ($30,000/well)	150,000
e)	Accessories, flow regulators, valves, instruments etc. ($15,000/well)	75,000
f)	Booster pump	50,000
g)	Elect. power to inject water (65,000 KWH @ 4.5¢)	3,000
h)	Eng. & legal fees (25% of c thru g)	195,000
Contingency (20% of c,d,e,f,g & h)		195,000
	TOTAL	$ 1,968,000

OMR Costs

Presently the Federal Government charges 8% for projects. Using 10% interest rate, the OMR costs of the cyclic storage would be as follows:

Facility Cost -	10 x 900,000 = $	90,000
Power -		3,000
Other -		37,500
		$ 130.000

Volume of water needed = 960,000,000

$$\text{Raw Water Cost/1000 gallons} = \frac{130,000 \times 100}{960,000} = 13.54 \text{ cents}$$

However, in order to supply potable water, the produced water must be treated and delivered. The transmission and the treatment costs have not been included in this analysis.

SUMMARY

1. Using hydrogeologic data gathered from a previous aquifer study of the Upper East Coast Planning Area, a feasibility study on the cyclic storage of fresh water in the brackish aquifer was made.
2. Use was made of computer programs developed by Louisiana State University.
3. The water for cyclic storage will come from one of the primary canals of the area. Presently, during the months of May-October, an average of almost 85 billion gallons of water is being discharged to the ocean due to lack of surface or subsurface storage.
4. Using the present per capita consumption and the median population projection by the University of Florida, it was estimated that an additional 8.0 million gallons of water will be needed to meet the year 2000 demand of St. Lucie County.
5. Using the above hydrogeologic, water supply, and demand data, the computer model calculated that at least 50% of the injected water can be recovered at the end of the storage/retrieval cycle after the water is left in storage for at least 180 days.

6. If a two cycle operation is made, the overall efficiency of recovery increases from 51.5% to 58.9% which proves the well known fact that recovery efficiency increases after several cycles of operation.

7. Sensitivity analyses on key important parameters were made to check their effect on the overall recovery efficiency.
   a) If the total dissolved solids of the native fluid is different than that found from the previous study, the recovery efficiency will change. For example, if the TDS of the native fluid is 8000 mg/l instead of 2000 mg/l, the recovery efficiency will go down to 36%. If the native fluid is seawater (35,000 mg/l of TDS), the efficiency of recovery will be only 23%.
   b) The thickness of the aquifer (first producing zone) was found, from the previous study, to be 75 feet. If the thickness is only 50 feet, the efficiency will go up to 67% on the first injection, storage, and recovery cycle; however, if the depth of the aquifer is 100 feet, the recovery efficiency will go down to 35%.
   c) The field value of transmissivity was determined to be 412,800 g/ft. This transmissivity value is for the whole thickness of the aquifer (3 producing zones). A realistic transmissivity value will be much lower than reported by Brown (1980). The model is very sensitive to transmissivity values. If the transmissivity of the formation is only 20,000 instead of 412,800 the recovery efficiency will go up to 68.6%. This writer feels that the T value of the first producing zone is around 100,000 g/ft. If it is so, the recovery efficiency will go up to 78% after the first injection recovery cycle.

d) Dispersivity coefficient is another key parameter of the model. A conservative value of 1.0 gave the recovery efficiency of 50%; however, if the coefficient is only .10 the efficiency will drop to 40%, and if it is 10, the efficiency will go up to 63.8%.

e) A question often asked is how long can the injected water be stored in the formation and what kind of efficiency will be achieved after long storage? For a one-cycle operation, if the injected water is left in the formation for 365 days, the recovery efficiency will drop to 39%, and after 730 days in storage, it will further drop to 28%. However, as stated earlier, the results shown above are for one single operation only. After several I/R cycles, the efficiency goes up.

8. The final analysis performed was on the economics of cyclic storage. Economic analysis shows that raw water for potable uses can be produced at 13.54 cents/1000 gallons; however, this water must be treated and delivered which will involve further costs. The treatment and delivery costs have not been calculated in this report.

CONCLUSIONS

One of the prime objectives of the River Basin Committee of St. Lucie and Martin counties is to salvage the runoff water being discharged to the ocean during the rainy season (almost 85 billion gallons/yr.).

An alternative for the above is being studied by the U. S. Army Corps of Engineers. The Corps of Engineers' project involves connecting C-23 with Lake Okeechobee (Martin County Plan). This plan would enable excess water to be pumped to the Lake during rainy periods. Water could also be released to the primary canals (C-23, C-24, and C-25 from the Lake when needed.

The second alternative to salvage this runoff water would be to construct local reservoirs; however, based on a study by Tai (1975), storage reservoirs in the area cannot provide enough carry-over storage to satisfy even agricultural water demand due to the fact that the rate of evaporation is so high in this flat area. Additionally, with the recent experience the District has had with the FPL dike failure, this alternative could be very costly.

A third alternative to salvage the excess runoff is to store it in the Floridan aquifer formation. If feasible, this alternative has many advantages; namely,

1) That it will replenish the potentiometric heads which are declining rapidly in the project area.
2) Water will be available close to the point of need.
3) As the potentiometric heads are above the ground surface, no pumping would be required during production cycles.

This study shows that the cyclic storage of fresh water in the Upper East Coast Planning Area is technically feasible; however, as stated, data used in the model came from another hydrogeologic study of the area.

If this alternative is to be pursued, a test program is recommended to determine the exact parameters from the field test.

REFERENCES

Bianchi, W.C. and Haskell, Jr., E.E. 1975. Field Observations of Transient Groundwater Mounds Produced by Artificial Recharge into an Unconfined Aquifer. Agr. Research Serv. U.S. Dept. of Agr. ARS W-27.

Brown, M.P. 1980. Aquifer Recovery Test Data and Analysis for the Floridan Aquifer System in the Upper East Coast Planning Area, South Florida Water Management District. Technical Publication #80-1.

Brown, M.P. and Reece, Dennis E. 1979. Hydrogeologic Reconnaissance of the Floridan Aquifer System, Upper East Coast Planning Area. Technical Map Series 79-1, Plates 1-10B. South Florida Water Management District.

Gelhar, L.W., et al. 1972. Density Induced Mixing in Confined Aquifer. U.S. EPA Project #16060 ELJ.

Heidari, M., et al. 1974. Analysis of Liquid Injection Wells in Illinois by Mathematical Models. Univ. of Illinois at Urbana Water Resource Center.

Kimbler, O.K., et al. 1975. Cyclic Storage of Fresh Water in Saline Aquifers. Louisiana State University, Baton Rouge, LA. Bulletin #10.

Smith, S.K. 1978. Projection of Florida Population by County. Bureau of Economics and Business Research, Division of Population Studies, University of Florida.

Smith, S.K. July 1977. 1980-20% Projection of Florida Population by County. Bureau of Economics and Business Research, University of Florida.

SFWMD Resource Planning Department. 1974. Memorandum Report on Surface Water Availability in the St. Lucie County Area.

Tai, C. Chia-Lsiung. 1975. Agricultural Reservoir Study. Technical Publication #75-3. Resource Planning Department, Central and Southern Florida Flood Control District (South Florida Water Management District).

Underground Waste Management and Artificial Recharge Vol. I and II. 1973. Sponsored by the American Association of Petroleum Geologists, U.S. Geological Survey and International Association of Hydrologic Sciences.

United Nations. 1975. Groundwater Storage and Artificial Recharge. National Research Water Series #2, ST/ESA/13.

Woehlcke, C. and Loving, Donald R. 1979. Non-Agricultural Water Use in the Upper East Coast Planning Area. Memorandum Report. South Florida Water Management District.