Optimization Study of a Pump-and-Treat System At Massachusetts Military Reservation

by

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B.S.E., Civil Engineering
Princeton University, 1999

Submitted to the Department of Civil and Environmental Engineering
In Partial Fulfillment of the Requirement for the Degree of

MASTER OF ENGINEERING
In Civil and Environmental Engineering
at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2000

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ABSTRACT

The Massachusetts Military Reservation is located in the western portion of Cape Cod. World War II and the period immediately afterward saw the most intense military activity on the base. During this time, chemicals leached into the groundwater and contaminated the aquifer. One of the larger regions, or plumes, of groundwater contamination is the Chemical Spill 10 (CS-10) plume, a region in which maximum contaminant levels of trichloroethene and perchloroethene are exceeded. The treatment system that is in place at the CS-10 site consists of pump-and-treat technology. The newest component of the system is known as the Southern Southwest Remedial Design (SSRD). It includes three extraction wells, one in the in-plume section, and two along leading edges, and a lengthening of two existing infiltration trenches.

For the current analysis, a MODFLOW model of the system developed by the Jacobs Engineering Group Inc. was modified in order to facilitate display and manipulation within the preprocessor Visual MODFLOW. This simplified version of the model was calibrated to the pre-pumping steady state water table elevations at the site. It served as a more manageable representation of the CS-10 system.

With this model as a basis, the software MODOFC was implemented to perform an optimization of groundwater extraction rates. The results of the optimization procedure led to the recommendation to activate only the most centrally located of the three SSRD wells. The results were subjected to a drawdown analysis, which confirmed that their effects are within an acceptable threshold of impact to the aquifer. Consequently, it is recommended that contaminant transport analysis be performed with the wells performing at the rates optimized in this study for comparison with the Jacobs Engineering Group's final SSRD design.

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ACKNOWLEDGEMENTS

I would like to express my thanks to:

Dr. Peter Shanahan for his tireless support and guidance, regarding everything from grammar to FORTRAN syntax to obtaining the necessary reports. Without his constant accessibility and encouragement, (as well as the memorable suggestion to "declare victory and retreat"), this paper would not have been completed.

Spence Smith, Remedial Project Manager with the Air Force Center for Environmental Excellence, whose suggestions inspired this project and who served as the main MMR contact throughout its development.

Ken Black of the Jacobs Engineering Group, Inc., for going out of his way to provide the extensive data essential to the completion of this study. Thanks also to Ken for his continuing advice, which was critical in smoothing out the modeling process.

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1 Site Background and Description

1.1 Massachusetts Military Reservation

The Massachusetts Military Reservation is located in Barnstable County, Massachusetts, in the western portion of Cape Cod known as the "upper Cape." It is comprised of about 22,000 acres, within the towns of Bourne, Falmouth, Mashpee, and Sandwich. (Jacobs Engineering Group Inc., 1999g, B-10).

The MMR site has played host to several branches of the United States Military since its beginning as a training ground for the Massachusetts National Guard in 1911. In the 1920s and early 30s, the reservation had private owners, but was bought by the government and transformed into a National Guard training camp in 1935. World War II marked the peak in military activity at MMR. The war effort spawned tremendous growth within the facility as over 1,400 buildings were built, and over 50,000 people were assigned to the training camp at that time in preparation for war. (Rolbein, 1995)

Following World War II, the MMR lease was reorganized several times among its occupants, primarily the Air Force, the Army, and the Coast Guard. The current lease of the MMR property from the Commonwealth of Massachusetts is partitioned among these parties. The 5,000-acre cantonment in the southern portion of the base has seen the most activity over the past century. It has been used by all three military branches and contains aircraft runways, roads, housing, and maintenance facilities for both air and land vehicles. (Massachusetts Military Reservation (MMR) Installation Restoration Program (IRP), 1996).

During and after World War II extensive contamination occurred throughout the base, stemming from equipment maintenance, wastewater disposal, fire training, and fuel transport and storage. Volatile organic compounds (VOCs), fuels, and chlorinated solvents such as TCE and PCE are among the contaminants that were utilized and disposed of on the base. During the 1960's the base began to receive fuel via an underground pipeline. Throughout its operation, several ruptures and fuel spills occurred, including the largest of over 2,000 gallons in 1972. (Rolbein, 1995).

As a result of these activities, contaminants spread throughout much of the reservation's subsurface. In the late 1970's, the Town of Falmouth discovered detergents within the drinking water supply during a groundwater monitoring test. The spills were immediately considered a threat to neighboring communities because they had moved via the groundwater off of the reservation grounds. By 1982 Congress required that the Department of Defense create the Installation Restoration Program (IRP). The IRP's objectives were to identify, investigate, and clean up hazardous wastes from the areas under military control ("Base History," 1996; MMR IRP, 1996).

By 1986, 73 Study Areas, locations suspected to be contaminated, had been identified. Following Phase II site inspections, additional investigation was determined necessary at 43 such locations. MMR was placed on the National Priorities List in 1989. Extensive study was undertaken to delineate zones, or "plumes," of groundwater contamination. Propagation occurred relatively rapidly because of the high conductivity of the sandy soil, and resulted in plumes that were found to extend several miles in some cases. A map of these plumes and the MMR can be found in Figure 1.1.

Numerous studies continue to be conducted on the plumes and the effects that they are having on the community outside of the base. Remediation techniques such as pump and treat, and low temperature thermal desorption have been employed, but a great deal of work and study must be done on the reservation before the IRP's work is complete. (Rolbein, 1995)

1.2 Chemical Spill 10 Background and History

The Chemical Spill 10 (CS-10) plume is located in the southeastern portion of the Massachusetts Military Reservation. The northern end of the site was the location of the 38-acre Boeing Michigan Aerospace Research Center (BOMARC) Missile Site from 1960 to 1973. During this period, as many as 56 ground to air missiles were housed and maintained at the site. Since 1978 the Unit Training Equipment Site (UTES) has occupied this area. These operations contributed spills and releases of chemicals to the CS-10 plume. In addition, eleven other sites are suspected to have been sources of pollution. The primary contaminants are the solvents trichloroethene (TCE) and perchloroethene (PCE). Ethylene dibromide (EDB), which was used in gasoline to prevent lead from accumulating in engines, has also been detected ("CS-10 Groundwater Plume, Community Guide," 1998).

The CS-10 plume is located predominately within the Mashpee Pitted Plain (MPP), one of three geological formations which are prevalent over the western portion of Cape Cod; the other two are known as the Buzzards Bay Moraine (BBM) and the Sandwich Moraine (SM). All three types of sediments are of glacial origin. The MPP is comprised mostly of unsorted coarse and fine-grained sand and some gravel. Within the sand are clay and silt deposits, generally in the form of lenses rather than continuous layers. (Jacobs Engineering, Inc., 1999f, 4-2).

The aquifer is bounded on the north, south, and western sides by the ocean, and on the east by the Bass River in Yarmouth. It is the source of water for the western portion of Cape Cod. Groundwater flow in the aquifer is generally horizontal, driven by an average gradient of around 0.0011 ft/ft. Vertical flow does exist at the local level, mostly within discharge areas. The depth from ground surface to the low permeability underlying bedrock ranges from about 150 feet to 400 feet. Hydraulic conductivities in the region of the CS-10 plume vary from approximately 27 to 340 ft/day, and decrease with depth. Runoff in the vicinity is limited due to the high permeability of the ground, and recharge comprises a relatively large percentage of yearly precipitation. (Jacobs Engineering, Inc., 1999h, 2-3).

The plume's footprint (Figure 1.1) delineates the region in which the maximum contaminant level (MCL) of 5 parts per billion (ppb) for TCE and PCE are exceeded.

Although EDB has also been located in the region of the plume, it does not consistently exceed its MCL. The plume extends over a length of about 17, 000 ft, and is about 4,000 feet wide and 150 feet thick at its respective maxima. The plume consists of three sections: the central, or "in-plume" portion, the lobe that extends southward toward Sandwich Road and Ashumet Pond, and the southwestern lobe (Jacobs Engineering, Inc., 1999f, 2-1).

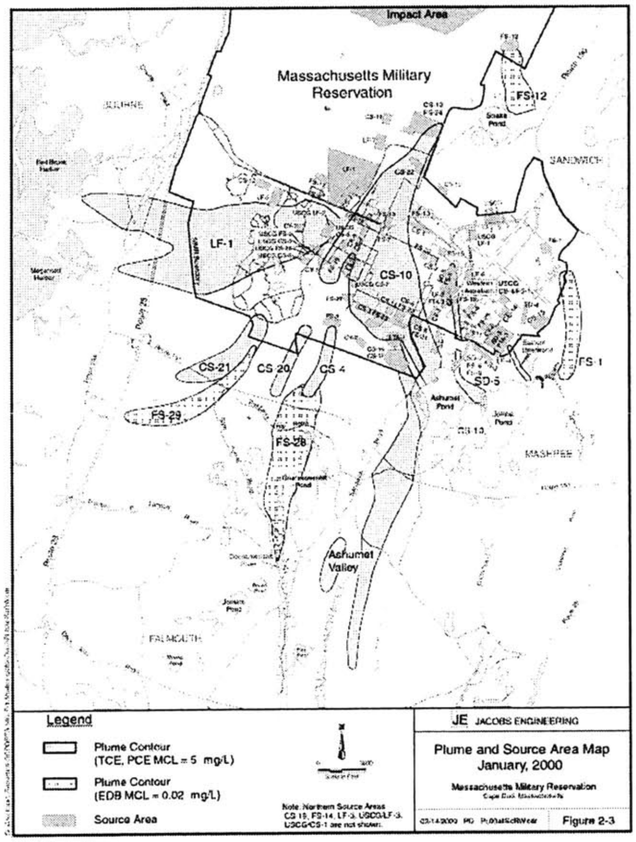

Figure 1.1 The CS-10 plume is located in the southeast corner of MMR, in an area of high contaminant density. (Source: "Plume and Source Area Map," January, 2000).

The total mass of contaminants in the aquifer has been estimated as the sum of mass in the aqueous phase and that which is sorbed onto the aquifer materials. The total mass of TCE in the aquifer has been estimated by Jacobs Engineering as 5,028 kg, 3,225 kg of which are present in the aqueous phase, while that of PCE is approximated at 466 kg, with 213 kg dissolved in the ground water (Jacobs Engineering, Inc., 1999g, 4-7).

In 1997, after a public comment period, the Air Force Center for Environmental Excellence (AFCEE), the U.S. Environmental Protection Agency (EPA), and the Massachusetts Department of Environmental Protection (DEP) engaged in considerable discussion regarding CS-10. The result was a mutual decision to employ extraction, treatment, and reinjection (ETR), or "pump-and-treat", technology, to remedy the contamination. This type of technology was selected for CS-10 with a number of goals in mind, the ultimate objective being to protect the drinking water supply of Upper Cape Cod. Others include "maximizing the capture and treatment of contaminants, minimizing hydrological and ecological impacts and risk, and minimizing the impacts of construction and operation on affected neighborhoods" ("Chemical Spill 10 Plume Response Decision," 1997).

2 Extraction, Treatment, and Reinjection Technology

2.1 Background

Extraction, treatment, and reinjection (ETR) technology, or "pump-and-treat", is one of the most commonly employed strategies for groundwater remediation. It is implemented at about 75% of Superfund sites at which groundwater is contaminated. In addition, this method is employed at a majority of the sites where the Resource Conservation and Recovery Act (RCRA) and/or state laws require cleanup (U.S. EPA, 1996).

Pump-and-treat involves using extraction wells to bring contaminated water to the surface, where it is treated and returned to the aquifer. Contaminated water must first be able to reach the extraction wells in order to be affected by treatment. There are systems in which the applicability of pump and treat is restricted by the local hydrogeology and/or the properties of the contaminant of concern. For example, low conductivity zones in a heterogeneous aquifer will restrict the flow of contaminants to extraction wells. Also, strong sorption of contaminants to soil particles reduce the contaminant concentration in solution and thus limit the amount of mass that can be removed with pumping. Often, additional remediation technologies, such as bioremediation or vacuum extraction, are applied to mitigate these difficulties.

There are additional complications associated with the removal of non-aqueous phase liquids (NAPLs) such as TCE and PCE. These substances can become stuck in pore spaces by capillary forces and remain in the subsurface when water is removed. As a result, the speed with which the NAPLs dissolve becomes crucial in determining the rate at which the system can perform (Cheremisinoff, 1997).

A pump-and-treat system is generally comprised of four components: pumping wells, a pipeline for transport, treatment plant(s), and a reinjection system (Gorelick *et al.*, 1993). The pumping wells must be screened at different depths in order to capture the vertical extent of the plume. Extraction wells are usually placed adjacent to one another, either in regions of high pollutant concentration, or such that they intercept the flow path of the affected groundwater. Reinjection tends to occur at or near the plume's leading edge ("Groundwater Treatment Technologies", 1997).

The implementation of pumping wells as part of a remedial strategy usually aims at one of two objectives: cleanup of the contaminant or retardation of its transport through the aquifer, or a combination of both. A cleanup strategy generally requires that contaminants are no longer being released into the aquifer from the source (Cohen *et al.*, 1997) For removal, extraction wells are generally placed within the zones of highest concentration. It is usually infeasible to try to completely remove pollutants from the groundwater. The pump-and-treat process is sustained until concentrations are found to fall below some target level. One drawback of this method is that once concentration goals are reached, and pumping wells are shut off, concentrations may again rise above the target level. At this point, those involved are faced with choosing between allowing concentrations to exceed standards, or pumping large amounts of water to remove relatively little contaminant (Gorelick *et al.*, 1993).

Containment often represents a more realistic goal, especially in cases where the source of contamination cannot be eliminated, as in the case of a landfill (Cohen *et al.*, 1997). Pumping and reinjection of groundwater facilitates the manipulation of hydraulic head gradients to prevent the plume from spreading to unaffected portions of the aquifer. The reinjection of water can serve as an important component in the control of the flow regime, in addition to mitigating the drawdown effects caused by extraction. Containment and cleanup strategies are combined in situations where it is appropriate to implement containment in the vicinity of an active or high concentration source, and remediation of more dilute concentrations further down gradient (Cohen *et al.*, 1997).

2.2 CS-10 Treatment System

The current treatment system in place for the CS-10 plume employs a combined strategy and consists of several components in various stages of development. A map of the treatment system is displayed in Figure 2.1. The Sandwich Road remedial system, near the southernmost, or down gradient portion of the plume, consists of a fence of eight extraction wells flanked on each side by three re-infiltration trenches. The Sandwich Road system extracts at a rate of 820 gallons per minutes (gpm), and was brought on line on May 18, 1999. The in-plume remediation system is comprised of five extraction wells within the central portion of the plume (wells 03EW2102-2106), a southern infiltration trench bordering the edge of the plume, and an infiltration trench at the tip of the southwestern lobe. The in-plume system start-up took place on June 24, 1999. The extraction rate for this system is currently 1,200 gpm. Both systems operate on-base water treatment plants. (Jacobs Engineering Group Inc., 1999g, 2-1).

Both the in-plume and the Sandwich Road treatment plants employ activated carbon systems. As the contaminated water passes through a carbon filter, the carbon adsorbs organic molecules, removing them from the water. Eventually, the carbon becomes saturated and must be replaced, and the used carbon is sent off-site to be recycled ("Groundwater Treatment Technologies," 1997).

The latest design innovation is known as the Southwest/Southern Remedial Design (SSRD). It includes three additional extraction wells within the CS-10 plume (wells 03EW2107, 03EW2109, 03EW2110). The extracted water will be pumped to two new treatment plants near the plant corresponding to the in-plume system. Granular activated carbon will once again be utilized to filter the contaminants from the water. Water will be returned to the aquifer via the existing infiltration trenches. To accommodate the additional load from the SSRD, the trenches corresponding to the in-plume system are being extended to a total length of 2,400 feet.

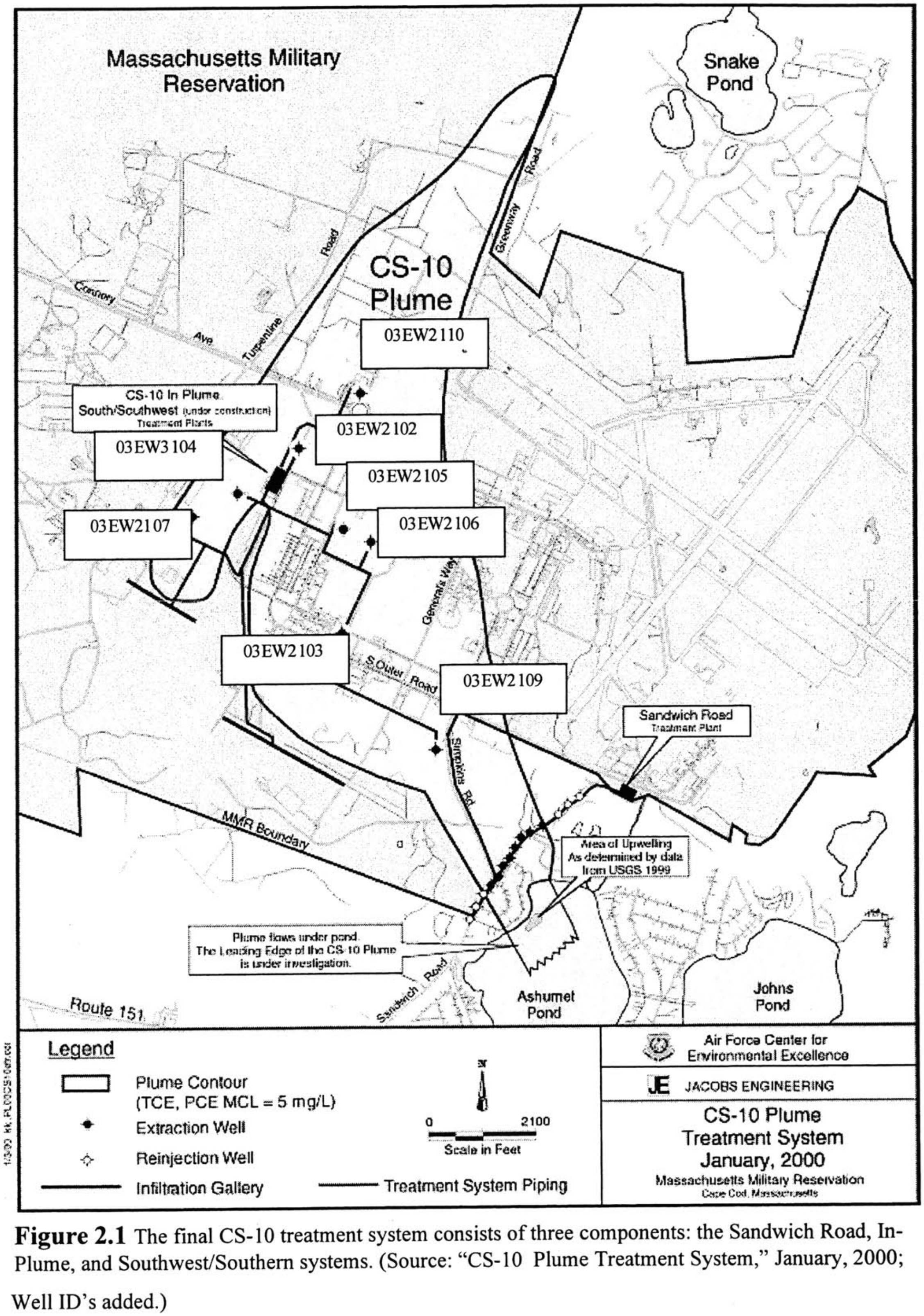

Figure 2.1 The final CS-10 treatment system consists of three components: the Sandwich Road, In-Plume, and Southwest/Southern systems. (Source: "CS-10 Plume Treatment System," January, 2000; Well ID's added.)

There is considerable motivation for the development of adaptive pumping schedules for the implementation of the SSRD. Adaptive pumping is a strategy by which the extraction wells within a remediation system are strategically shut off when contaminant levels fall below maximum contaminant levels (MCLs). Achievement of these threshold concentrations can be verified either by evaluation of water pumped from the extraction wells, or by the use of local monitoring wells (Jacobs Engineering Group Inc., 1999g, B-33). Jacobs Engineering Group Inc., which is heavily involved in remediation activities over the entire base, conducted simulation studies in which both adaptive and continuous pumping strategies were assessed as treatment strategies for the CS-10 plume.

The *Draft CS-10 Southwest/Southern Wellfield Design Report* prepared by Jacobs Engineering, approximates the total volume of water extracted by the CS-10 system over a 50-year period to be 92.5 billion gallons without adaptive pumping. The report estimates that an adaptive pumping scheme may facilitate the reduction of this volume to around 45 billion gallons (Jacobs Engineering Group Inc., 1999g, B-3). Clearly, this represents considerable savings; specifically in terms of electricity, water treatment sampling, and long-term operations and maintenance.

The flow and transport modeling performed by Jacobs Engineering led to further conclusions as to the benefits of adaptive pumping. To summarize, continuous pumping requires a much higher volume-to-mass removal of contaminant. Also, the model results revealed that the spread of the plume is actually increased when pumping is continued at very low contaminant concentrations. Furthermore, to reach the target MCLs, the overall system will be required to remain in operation longer if the wells are pumped continuously. It is therefore anticipated that an adaptive pumping strategy will eventually be integrated into the latest CS-10 remedial design (Jacobs Engineering Group Inc., 1999g, B-3).

3 Modeling the CS-10 System

3.1 Structure and Methodology

The groundwater modeling program MODFLOW was used in representing the CS-10 system. MODFLOW is a three-dimensional finite-difference model written in Fortran 77. Developed by the U.S. Geological Survey in the early 1980s, it is the software most commonly employed for groundwater modeling (Leake, 1997). The program is designed to simulate saturated groundwater flow governed by Darcy's Law. The MODFLOW program is composed of a number of modules, or packages, each of which deals with an individual aspect of a groundwater flow system. For example, individual components handle factors such as river flow, recharge, well effects, and evapotranspiration (Rumbaugh and Rumbaugh, 1996).

The MODFLOW representation of the CS-10 site employed in the present analysis was adapted from the Jacobs Engineering Run 95 model, which was the final of 57 model runs in the southwest/southern wellfield design (Jacobs Engineering Group Inc., 1999g). Jacobs' representation of the CS-10 system consists of a grid composed of 161 rows, 159 columns, and 21 layers. Grid spacing ranges between 110 and 660 feet. The Run 95 representation was developed from the CS-10 Zoom Model (CSZM) built for the five well in-plume system design in the spring of 1999.

The CSZM covers the area overlying and immediately surrounding the CS-10 plume, a total of 22.3 square miles (Jacobs Engineering Group Inc., 1999j, A-13). A detailed account of the development of this model can be found in the *Draft CS-10 In-Plume Remedial System Design Groundwater Modeling Report* (Jacobs Engineering Group Inc., 1999i). The CSZM is actually a more finely discretized portion of a broader regional model, which was developed to cover the entire western portion of Cape Cod (Jacobs Engineering Group Inc., 1999g, B-22). A thorough account of the construction of this model can be found in the *Final Plume Response Groundwater Modeling Report* (Jacobs ngineering Group Inc., 1999j). A snapshot of the CSZM model as displayed by Visual MODFLOW (see section 3.3) is displayed in Figure 3.1. The MMR boundary is shown, as well as the local airfield, ponds and roads. The Sandwich Road well fence can easily be seen along the roadway near the southeastern border of the base. The construction of this model required the interpolation of conductivity, concentration, and transport measurements over a numerical grid.

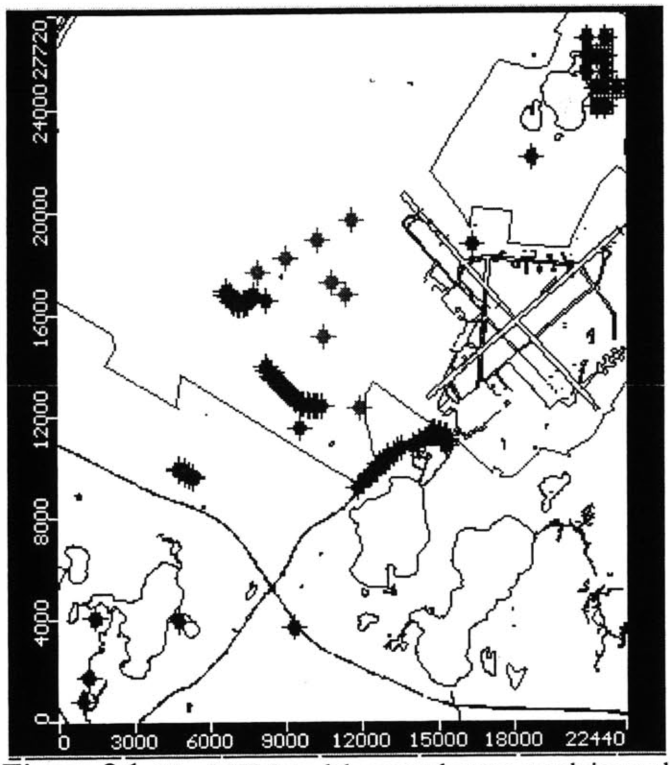

Figure 3.1. The CSZM model covers the area overlying and immediately surrounding the CS-10 plume.

3.2 Data Collection

Extensive data collection activities were performed to characterize the CS-10 site for the update of CS-10 Zoom Model. The field tests and sampling procedures are fully logged in the *Draft CS-10 Comprehensive Technical Memorandum* (Jacobs Engineering Group Inc., 1999f). This publication consists of eight volumes. Included are water sampling logs, soil boring logs, and concentration data. The data most pertinent to the present analysis is documented in Volume V of the *Technical Memorandum.* This consists of slug tests that were performed at 41 monitoring wells in the vicinity of the CS-10 plume.

Slug tests were carried out by inserting a pressure transducer into each well at approximately 10 feet below the static water level. The pressure transducer was connected to a data logger. To perform the test, a cylindrical slug with a length of 5 feet and a diameter of 1.5 inches was lowered to about six feet below the water level. The data logger recorded the water level in the well with time elapsed, or the rate of decline of the water surface. This test was also performed in the reverse direction, with the slug removed from the well, and the water level recovery measured with time. The time/water level data was converted to time/displacement data and input into software which, using some additional well and hydrogeologic data, calculated values of hydraulic conductivity (K, ft/day). The mean of these 41 conductivity measurements was 87 ft/day, with 55 and 45% above and below the mean, respectively (Jacobs Engineering Group Inc., 1999f, F-2, F-5).

The hydrogeology of the system was further characterized through several tests. Pumping tests were performed at extraction well 03EW2102, in the northern in-plume area, and 03EW2103 in the southern in-plume area. This procedure consisted of pumping at a constant rate for a given amount of time, and using drawdown to estimate transmissivity and hydraulic conductivity. Additional slug tests were also performed at the 41 aforementioned monitoring wells. These tests provided information on deeper conductivity values amid silt and clay lenses. The data gleaned from these analyses were generally consistent with those implemented in the CS-10 Zoom model. Therefore, reevaluation of the conductivity field within this model was deemed unnecessary. (Jacobs Engineering Group Inc., 1999g, 3-5-6).

3.3 Modeling Activities

The model was thoroughly tested and analyzed as it evolved throughout the SSRD design process. The CSZM accounted for both flow and solute transport through the aquifer. Flow and transport parameters were varied to evaluate the sensitivity of the model. Different well locations, screening depths and infiltration trench settings were assessed. Behaviors particular to the contaminants TCE and PCE were represented in terms of dispersion, retardation and degradation and the effects of these mechanisms on concentrations. (Jacobs Engineering Group Inc., 1999g).

The final SSRD design developed by Jacobs Engineering integrated the modeling project performed by their own group with two independent projects, completed by Dr. Richard Peralta of HydroGeoSystems Group and Utah State University, and Dr. Chunmiao Zheng of Groundwater Systems Research Limited and the University of Alabama. While the Jacobs group used a more traditional modeling approach, both Peralta and Zheng experimented with numerical optimization techniques. (Jacobs Engineering Group Inc., 1999g, 4-10). The SSRD design process implemented both hydraulic and solute transport analyses to simulate the combined effects of advection, dispersion, degradation, and retardation on the flow volume and contaminant mass recovery at the extraction wells (Jacobs Engineering Group Inc., 1999g, B-1). Some of the hydrogeological and contaminant transport parameters used to represent the CS-10 system are shown in Table 3.1. These values were varied to test the sensitivity of the model to their uncertainty (Jacobs Engineering Group Inc., 1999g, B-26).

Table 3.1. Hydrogeological and contaminant transport parameters were varied to test the sensitivity of the model to their uncertainty (Source: Jacobs Engineering Group Inc., 1999g, B26-7).

Parameter	Symbol	Value	Units
Total Porosity	N	0.36	Unitless
Effective Porosity	n_{eff}	0.30	Unitless
Soil Bulk Density	ρ_b	1.68	g/cm^3
Longitudinal Dispersivity	α_L	35	Ft
Transverse Dispersivity	α_T	3.5	Ft
Vertical Dispersivity	α_V	0.35	Ft
Fraction of soil organic carbon	f_{oc}	0.08	Unitless
TCE Partition Coefficient	K_d	0.075	mL/g
PCE Partition Coefficient	K_d	0.21	mL/g

For each of the model runs that comprised the SSRD design process, a number of factors were assessed. Key components included the total recovery of contaminant mass, mass recovery at each well, and the time at which contaminant concentration falls below 5µg/L at each well. Also considered were hydrologic effects such as drawdown and mounding at local ponds.

The final SSRD design, represented by Jacobs Engineering's Run 95, was developed to maintain all these variables within acceptable thresholds. The total extraction rate for the five pre-existing in-plume wells is increased to about 1,922 gpm. The three new southern/southwest wells pump a combined 778 gpm, for a total of 2,700 gpm among the eight wells. One of the SSRD wells, 03EW2110, is located in the internal portion of the plume in a region of high contaminant concentration. The other two are situated at leading-edge locations; well 03EW2109 is in the southern lobe just north of the Sandwich Road system, and well 03EW2107 is in the southwestern lobe. (Refer to Figure 2.1.)

The well locations for the SSRD and in-plume extraction wells in Massachusetts State Plane (MSP) coordinates and the corresponding MODFLOW grid coordinates are displayed in Table 3.2. The conversion was performed by rotating the MSP points -11°

about a base point at (852413 ft, 222347 ft) and then translating them from this base point to (0 ft, 0 ft) (Black, 2000). The infiltration trenches corresponding to the in-plume system will be extended to accommodate the additional load. This system is scheduled to begin running on April 30, 2000, with an anticipated lifetime of 30 years (Jacobs Engineering Group Inc., 1999g, 2-1).

Table 3.2. The SSRD and in-plume well locations were converted from Massachusetts State Plane coordinates to MODFLOW coordinates.

Well ID	System	Easting (ft)	Northing (ft)	MODFLOWx (ft)	MODFLOWy (ft)
03EW2102	In-Plume	858951.93	242822.77	10325.75	18851.89
03EW2103	In-Plume	859806.32	239178.86	10469.15	15111.90
03EW2104	In-Plume	857771.00	241881.00	8986.82	18152.75
03EW2105	In-Plume	859752.00	241291.00	10818.85	17195.60
03EW2106	In-Plume	860383.00	240985.00	11379.87	16774.82
03EW2107	SSRD	856765.00	241178.00	7865.17	17654.62
03EW2109	SSRD	861789.00	236664.00	11935.55	12264.93
03EW2110	SSRD	860059.00	243836.00	11605.82	19635.26

The SSRD design was found to comply with ecological standards, as well as thresholds for impact upon neighboring contaminant plumes. The model indicated that the 2,700 gpm required by the combined in-plume and SSRD systems would not create excessive drawdown in the aquifer due to its relatively high transmissivity. Furthermore, pond surface mounding due to reinfiltration was within the design criterion of 0.5 feet. (Jacobs Engineering Group Inc., 1999g, 5-3,5-6). Furthermore, model performance in terms of product mass recovery was found to be sufficient. Long-term monitoring will ensure that standards continue to be met throughout the life of the system.

While the SSRD design determined the wellfield layout, it did not conclusively address the distribution of pumping rates among the eight wells of the in-plume and SSRD systems, which are located at relatively close proximity to one another. The addition of the SSRD wells, as well as the augmented pumping of the in-plume wells, represent an increased level of stress to the aquifer. Therefore, it is necessary to determine the pumping scheme for this updated well configuration. The third component of the CS-10 system, Sandwich Road, will continue according to its original design. None of the SSRD designs simulated in the 57 model runs was found to have more than a 1% effect on the performance of the Sandwich Road system (Jacobs Engineering Group Inc., 1999g, B36-7). As a result, the Sandwich Road configuration is not considered in the present analysis.

3.3 Adaptation of MODFLOW Model

For the purposes of this analysis, the numerical model of the CS-10 site was displayed and manipulated using Visual MODFLOW, a three-dimensional graphical user interface developed by Nilson Guiguer and Thomas Franz of Waterloo Hydrogeologic, Inc (Delaney, 2000). Visual MODFLOW allows the user to build a subsurface model without a detailed knowledge of the actual Fortran MODFLOW program. The program displays the system graphically as a three-dimensional grid. Within this grid, the user can view any layer in plan, and any row or column in cross section. Features such as layers, rows, and columns, in addition to constant head zones, recharge areas, and wells can be input graphically. Ground surface and aquifer bottom elevations can be simulated either by hand or via input files. Visual MODFLOW also allows the user to import an externally generated base map of the site in the form of a '.dxf' or '.bmp' file. The base map underlies the grid and displays site characteristics, providing a visual frame of reference.

Crucial aquifer characteristics, such as whether the unit is confined or unconfined, are generally assigned by pointing and clicking. The user can select between several numerical solvers and determine the parameters within which the chosen solver will operate. Visual MODFLOW displays the results of steady state groundwater flow systems in the form of three-dimensional hydraulic head contours. It also has the capacity to display velocity vectors, as well as particle-tracking paths for contaminant transport simulations.

The set of files that comprised the original Run 95 model from Jacobs Engineering is too large to be run in Visual MODFLOW on a personal computer. As a result, it was necessary to condense the Jacobs model so that it would be able to be both displayed and run through Visual MODFLOW, as well as implemented within optimization software. The goal of the modification was to reduce the size of the model while retaining sufficient detail to adequately represent the system. To maintain the validity of the representation, steady state output from the pared down model was compared with Figure B5-3 in the Draft CS-10 Southwest/Southern Wellfield Design Report, which is a map of water table elevations within the CS-10 system (Jacobs Engineering Group Inc., 1999g). A match between this output and that of the refined model would indicate that the newer model is sufficient to represent the behavior of the system when subjected to the additional stresses of the SSRD. The final pared down model consists of 85 rows, 96 columns, and 8 layers. The original and modified MODFLOW grids are displayed in plan view in Figures 3.2a and b.

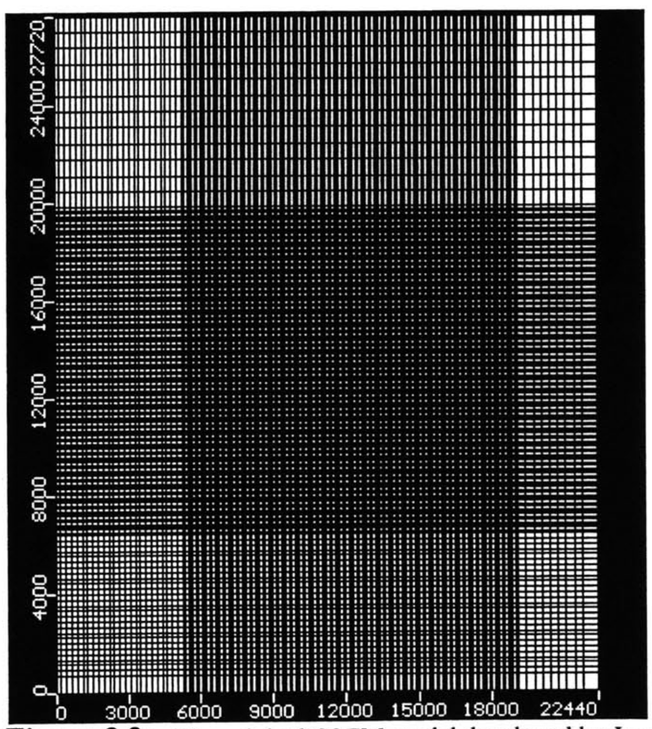

Figure 3.2a. The original CSZM model developed by Jacobs Engineering Group Inc. consists of 161 rows, 159 columns, and 21 layers.

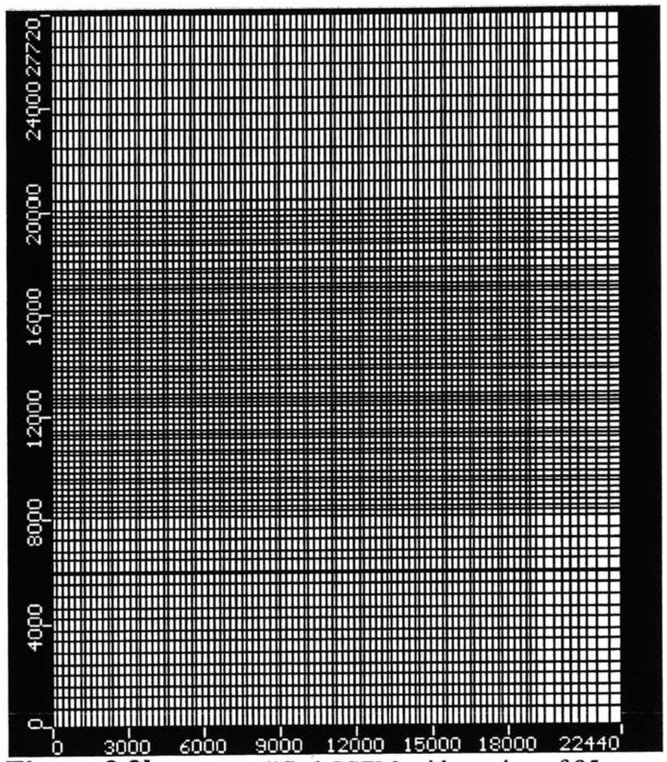

Figure 3.2b. The modified CSZM grid consists of 85 rows, 96 columns, and 8 layers.

The result of this calibration is the field of water table elevations shown in Figure 3.3 that closely matches the pre-pumping elevations in the CS-10 Zoom Model. This match confirms that accuracy is not sacrificed in condensing the model into a more manageable form. This exercise calls into question the merit of the more complex model. The greater detail in the original CSZM model does not seem to affect the steady state output of the system, at least in terms of groundwater flow. However, the bulkier input files corresponding to this model increase computational time, and make it difficult to implement a visual pre-processor. Whether or not such a graphical user interface can be employed has a great impact on the ease with which the model can be manipulated, and therefore affects its fundamental efficacy as a modeling tool.

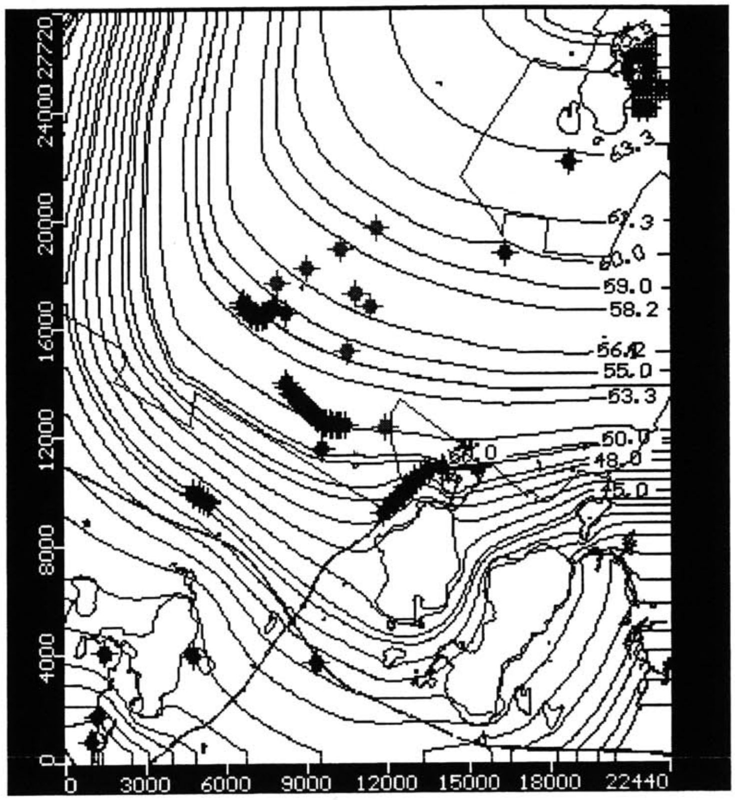

Figure 3.3. The modified version of the CSZM produces steady-state water table elevations that closely match the output of the original CSZM model (Jacobs Engineering Group Inc., 1999g, Figure B5-3).

4 Optimization Background

4.1 Applicability to Current System

The practical implementation of optimization procedures in groundwater remediation design is fairly new and still in a developmental stage. The methods that are used by practicing hydrologists are quite simple, dealing with linear optimization, an advection-based contaminant transfer model, and uniform density miscible contaminants (Gorelick *et al.*, 1993). Molecular diffusion and mechanical dispersion, two additional contaminant transport mechanisms, are generally ignored in practical applications, as they introduce nonlinearities to the transport equation, which in turn cause the optimization problem to become nonlinear. Nonlinear optimization methods have not yet been integrated into practical software applications (Gorelick *et al.*, 1993).

However, such limited conditions are compatible with a considerable percentage of contamination problems. The alternative approach generally consists of trial and error and subsequent model analysis. Optimization methodology introduces "a rigorous and objective measure of *efficiency* to the design process," (Gorelick *et al.*, 1993). It allows for the coordination of both financial and technical analysis in the selection and design of a remedial alternative (Freeze and Gorelick, 1999).

In 1999 the Technology Innovation Office and the Office of Research and Development of the U.S. EPA joined with HSI GeoTrans to conduct an analysis of pump-and-treat optimization and its effect on the costs of operation and maintenance. Hydraulic optimization was performed at three distinct locations. The result was a cost saving of as much as $550,000 per year. In response, EPA wrote guidelines for the implementation of hydraulic optimization and has planned workshops dedicated to this strategy (Yager and Greenwald, 1999).

The MMR site, particularly the CS-10 plume, is especially conducive to analysis within the limitations of practical remedial optimization. Flow is predominantly horizontal through a relatively conductive, sandy medium. The contaminants of concern are dissolved organic solvents. The distribution and dispersion terms do not significantly affect the modeled contaminant recovery, so an advection-dominated flow model is appropriate. Furthermore, while optimization techniques can theoretically be applied to a number of remediation technologies, they are generally implemented within a pump-and-treat framework. The reason for this is twofold. First, the mathematical representation of a pump-and-treat system is far simpler than what would be necessary for vapor extraction, or permeable treatment wall technology, for example. Second, the widespread use of pump-and-treat technology in remedial practice makes this type of analysis immediately relevant. (Freeze and Gorelick, 1999).

4.2 Theory and Methodology

The optimization procedure consists of defining an objective function, which is a mathematical representation of costs or benefits. The goal is to set the arguments of this function such that benefits are maximized and costs are minimized. A typical objective function for groundwater capture optimization is the net present value of the combined costs of the remediation, discounted at the market interest rate, over a specified time period. There may be several components contributing to the total cost, such as data collection, well installation, pumping costs, and treatment plant construction and operational costs (Gorelick *et al.*, 1993).

The factors that are adjusted are known as the "decision variables," which are "engineered features that we would like to manage optimally" (Freeze and Gorelick, 1999). In the design of a pump-and-treat system the decision variables may consist of the number and location of wells, in addition to pumping rates. The assignment of values to the decision variables impacts the "state variables," which define the physical environment of the system. In a groundwater system these include hydraulic head contours and gradients. Contaminant concentration may also be considered as a state variable. Finally, auxiliary variables are additional calculated parameters that may be useful, such as groundwater velocity, travel time, or well capture zone area (Gorelick *et al.*, 1993)

The restrictions imposed upon the state variables, by either regulations or design goals, are "constraints". Constraints can be set to limit any of the three types of variable: decision, state or auxiliary. For example, a constraint on a pump-and-treat system may be to limit drawdown over a given area to a maximum of one foot.

The objective function encapsulates the relationship between the costs and/or benefits and the decision variables. The constraints place restrictions on certain aspects of the system that are also influenced by the decision variables. Thus in terms of environmental reclamation projects, optimization attempts to balance the aims of the project with environmental, regulatory, and technical limitations. It operates within the framework of a model that represents the system. In this case, the system is the subsurface flow regime. The optimization method that is usually applied to groundwater systems is known as linear programming. For this technique, a linear objective function, as well as linear constraint and groundwater flow equations are necessary (Gorelick *et al.*, 1993).

The strategy employed in the current study is, in reality, a hybrid of optimization and a technique known as decision analysis. While both methods have the same general aims, there are a few fundamental differences in procedure. In optimization, one remediation technology is considered at a time. The analysis seeks the best possible design considering within this framework alone. Decision analysis determines the best among a detailed set of specific remediation designs, which may include multiple technological alternatives (Freeze and Gorelick, 1999).

For example, an optimization problem might consist of determining the number, locations, and pumping rates of wells within a wellfield, which will meet flow recovery requirements at the lowest possible cost. Decision analysis, on the other hand, might determine whether a given wellfield alignment would meet requirements at a cost lower than either a certain permeable treatment wall design or specific vapor-extraction system.

The current analysis is actually a combination of the two methods. As in optimization, the remediation strategy, pump-and-treat, has been previously established. However, the wellfield layout is also specified beforehand, as in a decision analysis, and is therefore not a variable, as would usually be the case in an optimization. There is, however, more resemblance to a traditional optimization procedure, in that pumping rates are not selected from among several fixed alternatives, but from a continuous range within upper and lower limits.

A prerequisite of any optimization or decision analysis procedure is the development of a model that simulates the groundwater flow regime. This serves as the link between the optimization algorithm and the physical behavior of the system. Gorelick *et al.* (1993) describe the synthesis of modeling and optimization as an "organized and methodical trial-and-error" technique. Ideally, it results in a number of solutions, each corresponding to a particular set of design parameters and constraints. Yet it is more formal than the typical trial-and-error approach in that the steps are well defined and the "best" solution for a given set of conditions can be identified quantitatively.

4.3 Prior Applications

As previously mentioned, optimization was employed in the design for the SSRD. Under the auspices of the Air Force Center for Environmental Excellence (AFCEE), the Environmental Technology Center used groundwater modeling in optimization of the CS-10 wellfield layout. Dr. Richard Peralta of HydroGeo Systems Group and Utah State University and Dr. Chunmiao Zheng of Groundwater Systems Research Limited and the University of Alabama each performed independent numerical optimization studies (Smith, 1999). The objectives of both of these efforts were to maximize mass removal and to minimize costs.

These studies sought the optimal number and placement of SSRD extraction wells. The five in-plume wells were included, but the Sandwich Road fence was neglected in the model. A fixed pumping rate was used and only TCE contamination was addressed. Both studies sought to maximize the mass of TCE removed. While the same magnitude of total flow was implemented, the two studies yielded somewhat different results. Peralta's work resulted in an addition of four SSRD wells, for a total of nine extraction wells. Zheng's recommendation consisted of the addition of one SSRD well, and the removal of one of the in-plume wells, for a total of five wells (Jacobs Engineering Group Inc., 1999g, B-38-9).

The optimization studies made several valuable contributions to the final design of the system. For example, Peralta's analysis found the planned placement of an extraction well in the southwest lobe to be inefficient. Conclusions drawn from these investigations were implemented into the final design produced by Jacobs Engineering Group Inc. (1999g). In particular, the optimization procedures helped to pinpoint low-efficiency wells that tended to inflate costs (Jacobs Engineering Group Inc., 1999g, B-39).

4.4 Optimization Software

For the purposes of the current analysis, the optimization software MODOFC was selected. David Ahlfeld, who was previously at the University of Connecticut and is currently at the University of Massachusetts, wrote the original version of this software. R. Guy Riefler of the University of Connecticut expanded the capabilities of MODOFC (Ahlfeld, 1998). Riefler's work enabled the program to determine solutions for unconfined aquifers and transient systems. It also provided for the inclusion of constraints on extraction and injection, wells screened over several intervals, and well construction expenses ("Contact the Creators of MODOFC," 2000).

MODOFC utilizes the groundwater modeling application MODFLOW in combination with optimization algorithms ("How Does MODOFC Work?" 2000). Given a set of candidate well locations and constraints, MODOFC searches for the least costly remediation scheme. The user specifies potential well locations, as well as pumping and injection costs. Other variables that can be constrained include total extraction or injection and head values at given locations, which may be utilized to simulate physical pumping capacity or limits on allowable drawdown, respectively. Head difference constraints make it possible to restrict the direction of groundwater flow. Also, the user can define capture zones in terms of a set of line segments ("How Does MODOFC Work?" 2000).

MODOFC has the capability to solve either a linear program using the simplex algorithm, or a mixed binary program using the branch and bound algorithm. To analyze confined aquifers or unconfined aquifers within systems where anticipated drawdown is minimal, the program assumes a linear relationship between pumping and hydraulic head. For unconfined aquifers in which drawdown is a factor, this relationship is nonlinear ("How Does MODOFC Work?" 2000).

The program allows for two possible objective function formulations. The simpler of the two is a minimization of total well operating cost, which is a linear function of the pumping rates. The other option involves minimization of total costs, including well construction costs. This is a linear function of the number of candidate wells that are actually utilized, and thus involves binary variables. (Ahlfeld, 1998).

MODOFC accepts its input via a file entitled *opt.in*. This file is the key to all MODOFC input and establishes the link between MODOFC and MODFLOW. It is composed of seven sections. The main section establishes the basic parameters of the optimization problem. Included in this segment are the number of wells that is allowable in the final solution, the number of each type of constraint that is imposed upon the system, and the program's pointer to the corresponding MODFLOW model. As a consequence of this link with MODFLOW, all values read into MODOFC, such as extraction rates, must be given in the same units with which they are represented in MODFLOW.

The *opt.in* file directs MODOFC to the MODFLOW model by pointing to a names file, in which all of the relevant MODFLOW files are referenced. These files must be present within the same directory. The subsequent six sections in the *opt.in* file deal with candidate wells, recharge balance constraints, total pumping constraints, head bound constraints, head difference constraints, and capture zone constraints, respectively. They fill in the relevant details, such as the specific locations of candidate wells, minimum or maximum pumping rates at each of those wells, total extraction and injection rates and/or upper and lower limits on head at particular locations ("How Does MODOFC Work?" 2000).

The main output generated by MODOFC is a selection of wells from among the candidates and corresponding pumping rates that satisfy the constraints imposed by the user, if such a solution is feasible. Output generated by MODOFC also includes as many as five files. The three primary output files are *solution*, *setup*, and *iterate*. A listing file and a *response* file are also generated (Ahlfeld, 1998).

Upon a successful run of MODOFC, the main output file of concern is the *solution* file. This file lists which wells will be activated, and at what rates they will extract or inject. (The minimum and maximum extraction rates set for each well in the *opt.in* file only constrain pumping when the well is active. MODOFC always retains the option of shutting the well off.) The file displays the total pumping rate, as well as the value of the objective function. Also displayed are the pumping costs associated with each individual well. The file indicates which of the imposed constraints was binding in the optimization procedure. Another feature of the solution file is the display of shadow prices. This variable is indicative of "the local sensitivity of the objective function value to changes in the right-hand side of a particular constraint" (Ahlfeld, 1998).

The *setup* and *iterate* files provide information related to the response of MODOFC to the input files. The *setup* file is basically a log of MODOFC's interpretation of the *opt.in* file. The iterate file contains details on the progress of MODOFC, such as the optimal pumping rates at the conclusion of each iteration, and whether each constraint is violated or satisfied at that point. The listing file records the output generated by MODFLOW and the response file keeps track of the MODFLOW response matrix. This can be reused in subsequent MODOFC runs to save computational time if the MODFLOW configuration is to remain the same (Ahlfeld, 1998).

5 Optimization Analysis

5.1 Problem Basis and Setup

The current optimization analysis seeks to build upon the foundation laid during the SSRD design process. The physical design of the wellfield is assumed to be identical to that described briefly in the preceding chapters and more extensively in Jacobs Engineering's *Draft CS-10 Southwest/Southern Wellfield Design Report.* (Jacobs Engineering Group Inc., 1999g). The decision variables consist of the pumping rates at each of the three SSRD wells, in addition to the five in-plume wells. In contrast to the original design, this analysis does not consider contaminant mass capture, but deals with flow only. It is assumed that the total pumping rates determined in the Jacobs Engineering Group's analysis adequately account for mass recovery.

The program was run as a steady-state problem, meaning that MODOFC results were determined for a single stress period. A single total pumping constraint was imposed. The entire eight-well system was restricted to operate at an extraction rate of between 2,700 gal/min and 2,800 gal/min. The lower limit is the target rate for the system, based on mass recovery goals over a 15-20 year time horizon. The maximum is based on the projected water treatment capacity of the SSRD plant. (Jacobs Engineering Group Inc., 1999g, 4-11, 7-5). No head difference or capture zone constraints were imposed. Although Jacobs Engineering Group performed previous work to determine allowable levels of drawdown and mounding, these results were not implemented into head bound constraints within the current analysis. Such constraints were not set because the drawdown found to occur within the allowable range of pumping was well enough within the threshold values to be deemed insignificant.

In the candidate wells section, the minimum and maximum number of pumping wells were 0 and 8, respectively. This would allow MODOFC to select the most favorable from all possible combinations of in-plume and SSRD wells. Specifications for the candidate wells consist of several components. As mentioned in the previous chapter, MODOFC allows for the possibility of well installation costs to be accounted for in the optimization, using binary variables. This method was not employed here, however, because the in-plume wells are already in place. The SSRD wellfield design had been confirmed and construction was well under way at the time of this study.

Well locations are given in terms of the corresponding row, column, and layer(s) in the MODFLOW grid. When wells are screened in several layers, as were all of the candidates in this instance, the input file must provide the ratio of flow in each screened layer to total flow entering the well. As suggested within the MODOFC documentation, this was set to equal the product of screen length within a given layer and the hydraulic conductivity of the corresponding layer. The candidate wells, along with the number of model layers over which each well is screened and corresponding screen lengths are displayed in Table 5.1.

Table 5.1. The in-plume and SSRD wells are each screened over multiple layers within the model.

Well ID	System	Layers Screened	Total Screen Length (ft)
03EW2102	In-Plume	5 – 8	108.78
03EW2103	In-Plume	5 – 6	54.14
03EW2104	In-Plume	3 – 8	178.87
03EW2105	In-Plume	4 – 6	62.47
03EW2106	In-Plume	3 – 6	76.56
03EW2107	SSRD	4 – 6	62.99
03EW2109	SSRD	4 – 8	138.23
03EW2110	SSRD	4 – 6	67.94

Each of the candidate wells was restricted to perform extraction only. It was assumed that the cost per unit volume of water pumped is the same over the eight candidate wells.

Therefore, the magnitude of the corresponding input parameter, PCST, was irrelevant as long as it was identical for all the wells. The sign of this variable, however, is important in that it determines the objective function. Positive values of PCST direct MODOFC to minimize the total pumping cost, while a negative sign tells the program to maximize the weighted value of total extraction (Ahlfeld, 1998). The PCST parameter was assigned a positive value, as one of the goals established by Jacobs Engineering is to minimize the total volume of water extracted (Jacobs Engineering Group Inc., 1999g).

5.2 Approximation of Aquifer Characteristics

A key issue that arose was the question of whether to model the CS-10 system as a confined or an unconfined aquifer. In reality, a water table aquifer exists at the site. While the representation of unconfined conditions does not cause any difficulties in MODFLOW, it greatly complicates the performance of MODOFC.

In MODOFC, when an aquifer is confined, the relationship between pumping and head is linear. The relationship between pumping and head is described via a first-order Taylor series with higher order terms disregarded. MODOFC uses perturbation to determine the response of the system to pumping. Through MODOFC, a "base value", is passed to MODFLOW (Ahlfeld, 1998). This value represents the magnitude of pumping that is simulated. The response of the aquifer is determined once, and then a linear relationship is used to predict further results as a function of extraction rates (Ahlfeld, 1998). However, when the aquifer is unconfined, the higher order terms in the Taylor series are no longer insignificant. Thus the problem becomes nonlinear (Ahlfeld, 1998).

The nonlinearity of the function complicates the solution procedure in MODOFC. The response of the aquifer to an initial pumping rate can no longer be used to completely characterize its reaction to pumping. Therefore, iterations must be implemented. MODFLOW simulates each pumping perturbation, determines the response of the aquifer, and then use that response as the basis for the next perturbation. This process is repeated until the change in heads from one perturbation to another is within a specified limit. The difference between successive pumping perturbations decreases as the resulting heads fall closer together (Ahlfeld, 1998).

The performance of a nonlinear optimization is quite sensitive to the perturbation increment, which is entered by the user via the *opt.in* file. The perturbation value must be large enough such that the response of the aquifer is precise to several significant digits, but small enough so that a given pumping perturbation will not dewater the aquifer. An inadequate choice of perturbation increment can lead MODOFC to conclude that a problem is infeasible when, in fact, it does have an optimal solution. The probability of such a result increases with the complexity of the model. MODOFC documentation explicitly warns, "If MODOFC cannot find a solution to an unconfined problem, it may still be possible that the problem is feasible." (Ahlfeld, 1998).

The outcome of the initial round of optimization attempts was consistent with this caveat. Attempts to optimize the unconfined system caused MODOFC to either exceed the maximum number of iterations or to deem the problem infeasible. A wide range of perturbation increments was tested, from 100 ft^3/day to 1,000,000 ft^3/day (MODOFC documentation recommends that the perturbation be set at approximately the magnitude of the expected solution), to no avail (Ahlfeld, 1998).

As described in the preceding sections, the subsurface system on Cape Cod is highly transmissive and areally extensive. As a result of this, it was reasonable to presume that the water table would not respond to pumping with excessive drawdown. Limited drawdown would allow the system to be modeled as confined without significant damage to the accuracy of the representation. To test the viability of this assumption, two distinct MODFLOW runs were executed. In one, all eight layers of the model were set to be Type 0 in MODFLOW. This parameter indicates that within the layer, both the transmissivity and the storage coefficient are constant for the entire simulation. In other words, the aquifer behaves as a confined unit. In the second run, all eight layers were set to be Type 3. Type 3 is used to simulate unconfined conditions. The transmissivity of the layer varies with the saturated thickness of the layer. The storage coefficient may also vary (Rumbaugh and Rumbaugh, 1996).

Both runs were executed using the same solver package (Strongly Implicit Procedure), with the solver parameters set to identical values. In both runs, the steady-state system was modeled prior to the activation of any of the eight in-plume or SSRD wells. Following each run, head elevations at thirteen grid points in Layer 1 were recorded. Some of these were selected at random, and others were chosen on the basis of their close proximity to operating extraction or injection wells. The results of this comparison are shown in Table 5.2.

Table 5.2. MODFLOW results vary little between the unconfined and confined simulations.

Model Row	Model Column	Unconfined Head (ft)	Confined Head (ft)	Difference (ft)
5	90	64.56	64.54	0.02
7	12	48.00	47.89	0.11
10	80	62.46	62.43	0.03
17	11	48.30	48.26	0.04
19	75	59.42	59.45	-0.03
24	34	54.78	54.75	0.03
42	43	52.17	52.15	0.02
51	44	51.05	50.77	0.28
52	48	50.11	50.09	0.02
54	26	46.43	46.40	0.03
57	66	48.78	48.65	0.13
73	68	43.25	43.24	0.01
74	6	33.43	33.48	-0.05

From the table it can be seen that even the largest of the thirteen observed differences, 0.28 ft is less than 0.002% of 150 ft, the approximate minimum aquifer thickness. This comparison confirms that a confined model is capable of producing an adequate representation of the system's response to pumping.

5.3 Optimization Activities

The target rates given by Jacobs Engineering Group Inc. for the total extraction rates of the in-plume and SSRD systems are 1,922 gpm and 778 gpm, respectively (Jacobs Engineering Group Inc., 1999g, 2-1). An obstacle was created by the fact that MODOFC offers no mechanism to place extraction bounds upon groups of wells. As mentioned previously, both total pumping and extraction at each individual well can be constrained.

Initially, when the optimization was run, the maximum extraction rate at each of the in-plume wells was set to the total target rate for the in-plume system, and the maximum rate at each SSRD well was set to the total target rate for the SSRD. The optimal solution that corresponds to this scenario consists of only two of the eight wells being utilized, both of which are in-plume wells. This scenario arises for two different objective functions: minimization of total cost and maximization of weighted total pumping. Since the SSRD wells have already been constructed, and are expected to extract around 778 gpm upon their activation, this result is not likely to be implemented.

The final Jacobs Engineering SSRD wellfield simulation was the result of the aforementioned model Run 95. As part of the model run, extraction rates were estimated at all of the wells within the CS-10 system, including the eight wells of concern in the current analysis. Since these pumping rates were derived from a simulation that considered TCE removal from the aquifer as well as hydraulic yield, they were implemented as a guideline in imposing restrictions on the eight wells of concern in the current study. New upper and lower bounds were set for all eight wells, requiring the extraction rate at each of the wells to be within 15% of its Run 95 value, given in Table B6-1 of the *Draft CS-10 Southwest/Southern Wellfield Design Report* (Jacobs Engineering Group Inc., 1999g). These values, along with the minima and maxima corresponding to the 15% criterion, are displayed in Table 5.3. A printout of the corresponding input file, *opt.in*, is shown on page 50 in the Appendix.

Table 5.3. The extraction rates were constrained to within 15% of the values determined in the Run 95 simulation.

Well ID	**Run95 Flow Rate (gpm)**	**MODOFC Minimum (gpm)**	**MODOFC Maximum (gpm)**
03EW2102	690.00	586.50	793.50
03EW2103	439.97	373.97	505.96
03EW2104	232.39	197.54	267.25
03EW2105	450.00	382.50	517.50
03EW2106	110.00	93.50	126.50
03EW2107	169.16	143.79	194.53
03EW2109	137.35	116.75	157.95
03EW2110	471.02	400.37	541.68
Total	2700		

Predictably, the more stringent constraints lead to model results that resemble the Run 95 output much more closely. The results of this optimization recommend the activation of six of the eight wells: all of the in-plume locations and one of the SSRD wells, 03EW2110. The MODOFC results are shown in Table 5.4, juxtaposed with the Run 95 flow rates. A printout of the *solution* file can be found on page 52 in the Appendix.

Table 5.4. Restricting extraction rates to within 15% lead to activation of six of the eight wells.

Well ID	MODOFC Flow Rate (ft^3/day)	MODOFC Flow Rate (gpm)	Run95 Flow Rate (gpm)	Difference (%)
03EW2102	1.43E+05	740.00	690.00	7.25
03EW2103	9.74E+04	505.96	439.97	15.00
03EW2104	5.15E+04	267.25	232.39	15.00
03EW2105	9.96E+04	517.50	450.00	15.00
03EW2106	2.44E+04	126.50	110.00	15.00
03EW2107	0.00E+00	0.00	169.16	100.00
03EW2109	0.00E+00	0.00	137.35	100.00
03EW2110	1.04E+05	541.68	471.02	15.00
Total	**5.19E+05**	**2700.02**	**2700.0**	**0**

Since in this case the objective function is set to minimize cost rather than to maximize pumping, the total extraction rate matches the Jacobs Engineering target rate of 2,700 gpm. The total pumping of the SSRD system, the entire burden of which is borne by well 03EW2110, is 541.68 gpm, 236.32 gpm less than the target rate of 778 gpm. Conversely, the total pumping of the in-plume system is 2158.32 gpm, 236.32 gpm above its target rate. Four of the five in-plume wells are operating at their maximum extraction rates.

Of the three SSRD wells, the well that is pumping, 03EW2110, is the most centrally located within the plume. The location at which it was installed was selected "to address an area of high contaminant concentrations and contaminant mass," (Jacobs Engineering Group Inc., 1999g, 2-1). According to this analysis, this well is also the most hydraulically efficient. Also for contaminant transport considerations, the Run 95 SSRD design specifically set the extraction rate of 03EW2107 to be relatively low. Due to the proximity of this to the Southwest infiltration trench, there is potential for some recirculation of treated water (Jacobs Engineering Group Inc., 1999g, 4-13). This analysis eliminates this possibility by allowing this well to remain inactive.

5.4 Water Table Response

MODFLOW analyses were employed to test the drawdown effects of these optimized pumping rates upon the water table elevation. Prior to the SSRD design, several standards were established to ensure that extraction from the aquifer would not result in damage to the local ecology. One such guideline limits the change in water level of three of the local ponds, Ashumet, Edmunds, and Osborne ponds, to 0.5 feet. As in the confined vs. unconfined comparison, MODFLOW was run twice: once without the activity of the eight in-plume and SSRD wells, and again with these wells pumping at the optimal rates determined by MODOFC. Subsequent steady state water table elevations were then compared at a number of given locations. A map of drawdown and mounding of the water table derived from the Run 95 model was used as a guide in selecting regions that had the most potential to exhibit significant drawdown effects (Jacobs Engineering Group Inc., 1999g, Figure B7-3). In addition, particular attention was given to locations in the vicinity of the aforementioned ponds.

A comparison of pre- and post-pumping water table elevations at 36 model locations is displayed in Table 5.5.

Table 5.5 Water table elevations were compared at pre- and post-pumping conditions at 36 locations within the model grid. (Boldfaced entries indicate pond locations.)

Model Row	Model Column	Pre-Pumping Head (ft)	Post-Pumping Head (ft)	Drawdown (ft)
18	47	57.78	55.96	1.82
19	46	57.46	55.81	1.65
15	52	58.80	57.25	1.56
16	50	58.43	56.92	1.51
16	46	58.00	56.49	1.51
16	51	58.53	57.04	1.49
19	44	57.23	55.81	1.42
23	52	57.18	55.86	1.32
23	46	56.58	55.32	1.26
15	55	59.12	57.92	1.20
21	53	57.68	56.51	1.17
29	48	55.67	54.63	1.04
32	53	55.44	54.71	0.73
39	48	53.29	52.81	0.48
24	34	54.75	54.36	0.40
42	43	52.15	51.90	0.25
51	44	50.77	50.67	0.10
52	48	50.09	50.00	0.09
7	12	47.89	47.82	0.07
19	75	59.45	59.38	0.07
17	11	48.26	48.20	0.06
54	26	46.40	46.34	0.06
57	66	48.65	48.59	0.06
10	80	62.43	62.39	0.04
74	6	33.48	33.46	0.02
5	90	64.54	64.54	0.01
73	**68**	43.24	43.24	0.00
70	**74**	40.40	40.40	0.01
73	**80**	40.39	40.39	0.01
76	**72**	40.37	40.37	0.00
77	**66**	41.65	41.65	0.01
80	**67**	40.35	40.35	0.00
83	**71**	38.04	38.04	0.00
19	**12**	48.77	48.71	0.06
24	**14**	49.51	49.45	0.06
26	**18**	50.99	50.91	0.07

Among these locations, a maximum drawdown of approximately 1.8 feet was found at the intersection of row 18 and column 47 within the model grid. Not surprisingly, this location lies between wells 03EW2102 and 03EW2110, which pump at the highest and second highest rates, respectively. However, this is less than the regional maximum drawdown of 2.9 ft found in the wellfield design Run 95 model, which was determined to lie within the threshold of permissible impact (Jacobs Engineering Group Inc., 1999g, B-46).

For all of the test locations that are located in or adjacent to Ashumet, Edwards, or Osborne ponds, the change in water table elevation is at least an order of magnitude below the 0.5-foot threshold. Water table mounding, which was looked at in the Run 95 study was not considered in the current analysis because, unlike the pumping configuration, the infiltration scheme did not vary from Run 95. Mounding in Run 95 did not significantly affect any of the local ponds or violate any ecological threshold. (Jacobs Engineering Group Inc., 1999g, B-46). These results lead to the conclusion that the hydrologic impacts of the pumping scheme developed in this study are within acceptable limits.

5.5 Summary and Conclusions

The analysis presented in the current study demonstrates the applicability of a much simpler MODFLOW model than the one actually applied in the SSRD design process. The modified representation of the CS-10 system applied here reduces computational time and logistical difficulty while maintaining the hydrologic integrity of the original model. Therefore, the adaptation of the model developed herein, a grid comprised of 85 rows, 96 columns, and 8 layers, is proposed as an alternative tool for further investigation into the behavior of the system.

In addition, the work described here shows that modeling this aquifer as a confined unit is a feasible alternative. The size and hydrogeology of the system result in minimal variation in aquifer thickness in response to the range of extraction levels that are applied. Use of the confined model confers the advantage of more rapid simulation, as well as ease of implementation into an optimization algorithm, as is clearly demonstrated in this case.

The crux of this analysis, the optimization study, led to the recommendation that the total extraction of the combined SSRD and in-plume systems be distributed as is shown in Table 5.6. Of the three SSRD wells, the only well that is activated, 03EW2110, is located in an in-plume region of high contaminant concentration. The other two SSRD wells, which are to remain inactive, are situated at leading edge locations. Well 03EW2107 is in the southwestern lobe, adjacent to the southwest infiltration trench. Well 03EW2109 is in the southern lobe of the plume, just north of the Sandwich Road extraction fence.

Table 5.6. The final recommended pumping scheme for the SSRD and in-plume systems enacts six of the eight wells of concern.

Well ID	**Flow Rate (ft/day)**	**Flow Rate (gpm)**	**System**
03EW2102	1.43E+05	740.00	In-Plume
03EW2103	9.74E+04	505.96	In-Plume
03EW2104	5.15E+04	267.25	In-Plume
03EW2105	9.96E+04	517.50	In-Plume
03EW2106	2.44E+04	126.50	In-Plume
03EW2107	0.00E+00	0.00	SSRD
03EW2109	0.00E+00	0.00	SSRD
03EW2110	1.04E+05	541.68	SSRD
Total	**5.19E+05**	**2700.02**	

In contrast to this outcome, the final SSRD design developed in 1999 resulted in the construction of all three of the SSRD wells. Therefore, since construction activities have already taken place, the likelihood is high that these wells will be active. In light of the results found here, then, it is recommended that additional transport and mass capture analysis be performed based on the pumping distribution given in Table 5.6. This will provide further insight regarding the efficiency of these wells, and may ultimately lead to an adjustment in their extraction rates, or even their long-term operation schedules.

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Appendix

Final MODOFC Input File (Opt.in)

```
MODOFC 2.1 Run95:CS-10 SSRD System
  8           : number of candidate wells
  1           : number of pumping constraints
  0           : number of head bounds
  0           : number of head difference constraints
  0           : number of capture zones
  0  0  00    : x,y coordinates of origin and angle of rotation of grid
  0           : Jacobian: 0= read existing, 1= compute & save, 2= compute only
5000000       : maximum number of LP iterations
-1e4 -50  5   : first, last, and scaling for perturbation (neg is extraction)
  2           : minimum thickness allowed in unconfined aquifers
 0.1          : convergence criteria for pump rates with unconfined iteration
 1            : print unconfined iterations? (0-no, 1-yes)
 1            : input echo? (1-yes, 0-no)
 01  01  00   : base run;           input echo, convergence, head (>0 then print)
 00  01  00   : base iteration run; input echo, convergence, head (>0 then print)
 00  01  00   : response matrix;    input echo, convergence, head (>0 then print)
 00  01  00   : final run;          input echo, convergence, head (>0 then print)
Run95.nam     : MODFLOW names file
*** Wells and Point Recharge ***
0             : include min/max # wells, inst cost or min pump rate (1-y,0-n)
0             : print relaxed solutions (0-no, 1-yes)
0     8       : min and max number of wells to use
Name  On Row Col L  #L E/I  Min        Max       PCst ICst StressPeriods
w-58  t  18  47  0  4  e  112909.1   152759.3   5.0   0.  '1'
               .01  5
               .53  6
               .40  7
               .06  8
w-59  t  34  48  0  2  e    71995      97405.    5.0  2000. '1'
               .67  5
               .33  6
w-60  t  20  41  0  6  e   38028.15  51449.85   5.0  2000. '1'
               .09  3
               .25  4
               .28  5
```

```
              .24  6
              .11  7
              .03  8
w-61  t  24  50  0  3  e   73636.35  99625.65   5.0  2000. '1'
              .47  4
              .53  5
              .00  6
w-62  t  27  52  0  4  e   18000.03  24352.98   5.0  2000. '1'
              .19  3
              .38  4
              .43  5
              .00  6
w-63  f  22  36  0  3  e   27680.76  37450.44   5.0  2000. '1'
              .52  4
              .46  5
              .01  6
w-64  f  48  55  0  5  e   22475.28  30407.73   5.0  2000. '1'
              .12  4
              .46  5
              .40  6
              .01  7
              .00  8
w-65  t  14  53  0  3  e   77076.64  104280.2   5.0  2000. '1'
              .29  4
              .52  5
              .18  6
*** Forced Injection Constraint ***
0.0                              : a - (sum extraction) >= a * (sum injection)
0.0                              : b - (sum injection)  >= b * (sum extraction)
*** Total Extraction Constraints ***
Name  On?  SP  Minimum  Maximum
p01    t    1  519786.  539037.
*** Bounds on Heads ***
Name  On?  Row Col Lay  </>  Head    StressPeriods
*** Generalized Head Differences; Low HD(ijk), High HD(ijk)
Name  On? R1  C1  L1  R2  C2  L2  HeadD  StressPeriods
*** Capture Zone lines ***
```

Final MODOFC Solution File (*Solution*)

```
MODOFC VERSION 2.1 - SOLUTION OUTPUT FILE
MODOFC 2.1 Run95:CS-10 SSRD System


+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
             MODOFC Version 2.1 Optimization Results
+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

 Optimal Solution Found

+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
                  PROBLEM SOLUTION
+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

 Objective Function Value                            2.5989E+06

 Pumping Rates Listed For Each Well

   Name          Stress periods          Extraction             Injection
--------------------------------------------------------------------


 w-58           1                        1.4267D+05
 w-59           1                        9.7405D+04
 w-60           1                        5.1450D+04
 w-61           1                        9.9626D+04
 w-62           1                        2.4353D+04
 w-63           1                        0.0000D+00
 w-64           1                        0.0000D+00
 w-65           1                        1.0428D+05

--------------------------------------------------------------------
 Total Rates                             5.1979D+05             0.0000D+00

+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

 Pumping Rates and Costs Listed For Each Stress Period

Name            i   j   k           Extraction   Injection        Cost
--------------------------------------------------------------------
```

```
--- Stress Period  1 ---   10.000E-01 days
w-58          18  47   m        1.4267E+05              7.1336E+05
w-59          34  48   m        9.7405E+04              4.8703E+05
w-60          20  41   m        5.1450E+04              2.5725E+05
w-61          24  50   m        9.9626E+04              4.9813E+05
w-62          27  52   m        2.4353E+04              1.2176E+05
w-65          14  53   m        1.0428E+05              5.2140E+05
---------------------------------------------------------------------
 Total Rates and Costs          5.1979E+05  0.0000E+00  2.5989E+06
=====================================================================


 Total Pumping Costs:           0.2599E+07
 Total Installation Costs:      0.0000E+00


 TOTAL COSTS:                   0.2599E+07

+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
                    BINDING CONSTRAINTS
+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

  Constraint type   Name         i   j   k   t        Shadow Price
---------------------------------------------------------------------

min total extract   p01        --- --- ---   1          5.0000E+00

+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
                    RANGE ANALYSIS
+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++



               CONSTRAINT INFORMATION - SLACKS, DUALS AND RANGES

           Lower/Upper Bound are the values of the RHS beyond which
                 basis will change.
           Leaving is the variable which will leave the basis.
           Entering is the variable which will enter the basis.
           If entering same as leaving a non-basic has hit its own bound -
                  no change in basis.
```

Name	Slack	Shadow Price	Original RHS	Lower/Upper Bound	Entering	Leaving
sv1	0.000D+00	5.00000D+00	5.19786D+05	3.77114D+05	dv8	dv1
				5.29873D+05	NA	dv1
sv2	1.925D+04	0.00000D+00	5.39037D+05	5.19786D+05	NA	sv2
				Infinity	No Change	

COST INFORMATION - REDUCED COST AND RANGES

Lower/Upper Bound are the values of the cost coefficient
beyond which basis will change
Leaving is the variable which will leave the basis
Entering is the variable which will enter the basis
If entering same as leaving a non-basic has hit its own bound
no change in basis

Name	Reduced Cost	Original Cost	Lower/Upper Bound	Entering	Leaving
dv1	0.00000D+00	5.00000D+00	5.00000D+00	dv8	dv8
			Infinity	No Change	
dv2	0.00000D+00	5.00000D+00	Infinity	No Change	
			5.00000D+00	dv2	dv2
dv3	0.00000D+00	5.00000D+00	Infinity	No Change	
			5.00000D+00	dv3	dv3
dv4	0.00000D+00	5.00000D+00	Infinity	No Change	
			5.00000D+00	dv4	dv4
dv5	0.00000D+00	5.00000D+00	Infinity	No Change	
			5.00000D+00	dv5	dv5
dv6	0.00000D+00	5.00000D+00	Infinity	No Change	

			5.00000D+00	dv6	dv6
dv7	0.00000D+00	5.00000D+00	Infinity		No Change
			5.00000D+00	dv7	dv7
dv8	0.00000D+00	5.00000D+00	Infinity		No Change
			5.00000D+00	dv8	dv8
sv1	5.00000D+00	0.00000D+00	-5.00000D+00	sv1	dv1
			Infinity		No Change
sv2	0.00000D+00	0.00000D+00	Infinity		No Change
			5.00000D+00	sv1	dv1

++

Key for Variable Name Relationships

Decision Variable/Candidate Well Relationship

Decision Variable	Well Name	Stress Period
dv1	w-58	1
dv2	w-59	1
dv3	w-60	1
dv4	w-61	1
dv5	w-62	1
dv6	w-63	1
dv7	w-64	1
dv8	w-65	1

Slack Variable/Constraint Relationship

Slack Variable	Constaint Type	Name	Stress Period
sv1	min total extraction	p01	1
sv2	max total extraction	p01	1