Research into Production Cost Reduction by Energy Management of Houston's Surface and Groundwater Systems

Final Report

Part I

Introduction

by

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February 8, 1996

Prepared for

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City of Houston Project # 33100
University of Houston Project # 1558893

Contents

Summary

The project entitled "Research into Production Cost Reduction by Energy Management of Houston's Surface and Groundwater Systems" was to (1) identify strategies to reduce pumping costs associated with grondwater usage in the Southwest Houston Study Area and (2) develop software tools for strategic planning and selection of production policies. Additionally, several workshops and training sessions were conducted during software development and delivery.

The project involved the intgration of existing computer models and the collection and analysis of data. The models developed include the Southwest Houston Study Area distribution model, the Southwest Houston Study Area aquifer model, and a Geographic Information System (GIS) based demand estimation model.

The cost basis for all the modeling was based on electric utility bills, so the research considered only energy costs. Other factors of importance in the engineering-economic analysis include capital costs amortized over the early life of a project, labor, and O&M costs (except electricity).

The data were all combined into the various modeling softwares and special cases were run under two optimization objectives: (1) minimize production cost without regard to drawdown, and (2) minimize drawdown without regard to production cost. These cases used prescibed (but varying) demands.

The results of these simulation-optimization analyses showed that at low groundwater usage (as a percentage of 1994 demand), the minimum cost approach produces only slightly more maximum drawdown than a minimum drawdown approach. At higher usages the difference is much greater. Using an arbitrary value of 50 feet of drawdown, one can produce about 1200 million gallons per month from the study area and still achieve these acceptable drawdowns. Using a value of 20% of historical demand in the study area, one can produce 930 million gallons per month from the study area. This lower value represents the value that is required by a 20% groundwater/80% surface water allocation for 1994 high demand cases.

The simulation-optimization results were also interpreted to identify three categories of plants: base, peak, and reserve plants. Base plants appear to be the most cost effective plants to use routinely to produce the groundwater yield reported above, the peak plants should be used for peak demand situations such as fire-fighting. The reserve plants should either be decommissioned or rehabilitated to improve their production efficiency with respect to electric billing.

All the simulations suggest that the western edge of the study area will be a low pressure zone and, assuming our conceptualization of the network is reasonable correct, measures to increase surface water deliveries (at pressures around 95 psi.) to the western side of the study area, or measures to boost pressures should be implemented. We understand some of these measures are in progress, and these measures should produce improved system performance.

Simplified user instructions to the softwares are included in this report in the appendices. In addition to these instructions original instruction manuals for KYPIPE2, MODFLOW, ATLAS-GIS, and SURFER are supplied along with the various softwares. Several custm programs were also created and both source code and instructions are supplied for these products.

Introduction

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The project involved the intgration of existing computer models and the collection and analysis of data. The models developed include the Southwest Houston Study Area distribution model, the Southwest Houston Study Area aquifer model, and a Geographic Information System (GIS) based demand estimation model. Additional modeling was performed on the Chasewood Service Area to develop demand assignment techniques, and cost estimation modeling using data provided by Water Production.

The simulation models are incorporated as software files (included with this report on disks) for the following computer programs (to be installed by the researchers): KYPIPE2 (Water Distribution Network Model), ATLAS-GIS (Geographic Information System), USGS-MODFLOW (Ground Water Flow Model), and an optimization model based on the LSGRG2 code. Other models are spreadsheet based (the cost computations).

This report describes elements of the project and the simulation-optimization results. Users manuals and details of the models are incorporated as appendices to the report.

Purpose

The purpose of this research was to develop strategies to reduce water production costs associated with the groundwater component of water supply, and its distribution. An additional set of goals was to document a general analysis and simulation approach using Southwest Houston as a model area so that Planning and Operations Support staff can extend ideas to other areas, and to train these staff in the use of the software for its continued use or for further software refinement.

The costs considered were strictly electricity costs (which represents only the energy input into the water delivery analysis) and do not include other costs such as treatment (chemicals, etc.), routine maintenance, and labor.

Literature Review

The coupling of simulation and optimization models to address complex strategic issues in water utility management is relatively recent. Su et al. (1987) combined three models to develop the framework for a method to determine the optimal (minimum cost) design of a water distribution system subject to continuity, conservation of energy, nodal head bounds, and reliability constraints. The optimization model used is the generalized reduced-gradient model, GRG2, which solves an optimization problem with a nonlinear objective function and nonlinear constraints. The simulation model adopted is the University of Kentucky Model known as KYPIPE, which simulates steady-state flow in a water distribution system based upon the continuity and conservation of energy equations. A reliability model is used to determine the nodal and system reliabilities at each iteration of the optimization procedure using the minimum cut-set methods. The authors sucessfully demonstrated that the approach (1) included the reliability aspects into an optimization model; and (2) it can given an optimal design of a water distribution system while simultaneously satisfying the continuity, conservation of energy, nodal-pressure head bound, and reliability constraints. The current limitations of the methods are that the resulting pipe diameters may not be commercially available pipe sizes so that these resulting pipe diameters must be rounded to the appropriate sizes, and that the model requires considerable computational effort to determine the optimal design of large looped networks.

Lansey and Mays (1989) extended this work to address the limitations of most optimal water distribution system design models that arise because of the size of the network, the number of loading conditions analyzed, and the types of components designed. They developed a method to determine the optimal (minimum cost) design of water distribution systems. The design components can be sized are the pipe network, pumps or pump stations, and tanks. In fact, two major difficult components, pumps and tanks, can be the constraints in this methods. This method unfortunately shared the same limits as the earlier work.

Duan et al. (1990) extended this prior design work to the design of operational strategies for pumping systems. They developed a computer model that designs the pipe network including the number, location, and size of pumps and tanks, and designs of the pumping system operation strategy using a reliability-based procedure considering both hydraulic failures of the entire network and mechanical failure of the pumping system. GRG2, KYPIPE, and a reliability-based model system were used in this study.

Cullinane et al. (1992) continued the work on component sizing, and used GRG2, KYPIPE, and a custom availability-optimization model to search for and identify optimal solutions. This study is similar to that presented in Lansey and Mays (1989). However, the solution technique reduces the previous-study problem by writing some variables called state variables, which are dependent in terms of other control variables using the equality constraints. This step results in a smaller, reduced problem with a new objective and a smaller set of constraints, and can be efficiently solved by existing GRG2. The results from applying the method have shown the expected relationship between increased cost with higher reliability requirements. The advantages of this method: (1) Computation times for these methods have been significantly reduced. (2) The methods allow the inclusion of all types of component failure (tanks, pumps, and pipes), which no other previously published model was capable of considering. (3) This methodology more closely follows the standard design procedure of a new distribution system or the extension of an existing system.

Ormsbee at al. (1989) present a methodology for improving pump efficiency by mainly focusing on three operational problems: inefficient pumps, inefficient pump combinations, and inefficient pump scheduling. The optimum pump operation methodology involves two basic phases: determining the optimal pump combination required to produce a desired change in the water level, determining the optimal water level trajectory over a specific period of time for a given set of conditions (e.g. system demands, electric rate). The optimal tank trajectory problem is solved using dynamic programming by breaking it into a series of subproblems. The boundary conditions for the problem include both the initial and the final tank levels and a set of average system demands. The associated pump policy is determined using an explicit enumeration scheme. The methodology was applied to the Washington, D. C. water system, to test its applicability. To examine the variable electric rate schedule and the system demand schedule, the methodology was applied for four different rates. Annual energy usage cost savings of approximately 6.7% were projected. This methodology is directly applicable to complete water distribution systems or isolated pressure zones with a single dominant storage facility and multiple pump stations. The methodology uses tank level versus flow rate (TLF) curves and tank level versus unit energy (TLE) curves to determine the flow supplied by a pump combination and the unit energy requirement by a pump combination respectively. These curves have a high degree of accuracy in representing the hydraulics of the system, but the optimal pump operation policy for a particular system will change from day to day depending on the electric rate schedule and the system demand schedule.

Little and McCrodden (1989) describes the development and application of a model that includes commercial demand and energy charges as well as costs associated with on-site generation in lieu of commercial power. A study was performed for the city of Raliegh, North Carolina to determine cost effective raw water pumping by taking advantage of the existing storage and the newly available time-of-use power rates. The problem was formulated as a mixed-integer linear-programming (MILP) model. The model's objective is to prescribe the hours of operation of each pump or pump combination, whether power is purchased commercially or generated on site. Optimal ending storage levels in the raw water reservoir for each time period are considered. Binary integer variables are used to model commercial demand charges, energy charges, standby generator costs. The model is currently being used by the city of Raleigh and significant cost savings have been reported. Inclusion of demand charges in the optimization requires that the optimization period cover the entire billing period in order that demand and other charges are weighted properly. Some difficulties arise out of this requirement.

Brion and Mays (1991) present a methodology to improve pump operation efficiency, using a large-scale non-linear programming, has been presented. In this model the problem is formulated in an optimal framework where an optimal solution to the problem is obtained by interfacing a hydraulic simulation code with a non-linear optimization code. The hydraulic simulation model is used to implicitly solve the hydraulic constraints that define the flow phenomena each time the optimizer needs to evaluate these constraints. The hydraulic simulation code KYPIPE has been used to solve the hydraulic constraint equations. The use of both the hydraulic simulation model and the optimization model is essential as the hydraulic model does not readily imply a systematic determination of an efficient pump operation policy and the optimization code can handle only a limited number of decision variables. The development of the new methodology and the computer code PMPOPR (Pump Operation) are the results of this study. This program is capable of handling very large systems. This methodology evaluates gradients using an analytical approach rather than a finite difference approach thereby making it computationally efficient.

Generally, most of the research concentrated on the hydraulics of the networks only, and did not include limitations on the supply sources to the pumps. Other researchers have studied the conjunctive operation of groundwater and surface water supplies but from a relatively regional emphasis at a lerger spatial scale than the proble studied in this project.

A crucial underlying theme of all this prior work is the coupling of the reduced gradient algorithm with various simulation models and optimization objectives. This approach was adopted for this research, as were the simulation codes GRG2, KYPIPE (and its derivatives), and MODFLOW. The principal advantage of these codes is their acceptance and relative ease of use compared to custom simulation software. The principal disadvantage is their age - newer codes availaible after this work started may be superior (e.g. EPA NET is a far easier to implement network simulator that was not available when this project was started).

General Approach

Several methods were employed to achieve the purpose of the research. A network simulation model was constructed to predict pressures in the distribution system as a function of different supply and demand configurations. An aquifer simulation (drawdown simulator) model was constructed to predict drawdown as a function of different supply configurations that draw water from the underliying aquifers. A production cost analysis was performed to determine unit costs associated with groundwater production. These unit costs are in-turn used to calculate the cost of a particular supply configuration. A procedure using a Geographical Information System (GIS) was developed to estimate actual water demands based on water billing data to be assigned to different nodes of the network simulation model. A relatively simple interface program was developed to integrate the network simulator, the drawdown simulator, and the cost calculations to facilitate decision making and to conduct "what-if" simulations. User instructions (included as appendices) were developed to facilitate the extension of the methods to other parts of the City's system. Training sessions on the software were conducted to familarize the City staff with the tools, and, more importantly, the concepts behind the tools. Selected test cases were run using an optimizer program and are reported in the results section.

Study Area

Figure 1.1 depicts the Southwest Houston Study Area. The figure shows freeways in bold lines and the pipeline network model configuration that simulates distribution system behavior in the study area. The network model was developed by considering water supply pipelines of 12-inch or larger diameter. The network shown is not an exact replica of the actual pipeline configuration, just a useful and detailed approximation.

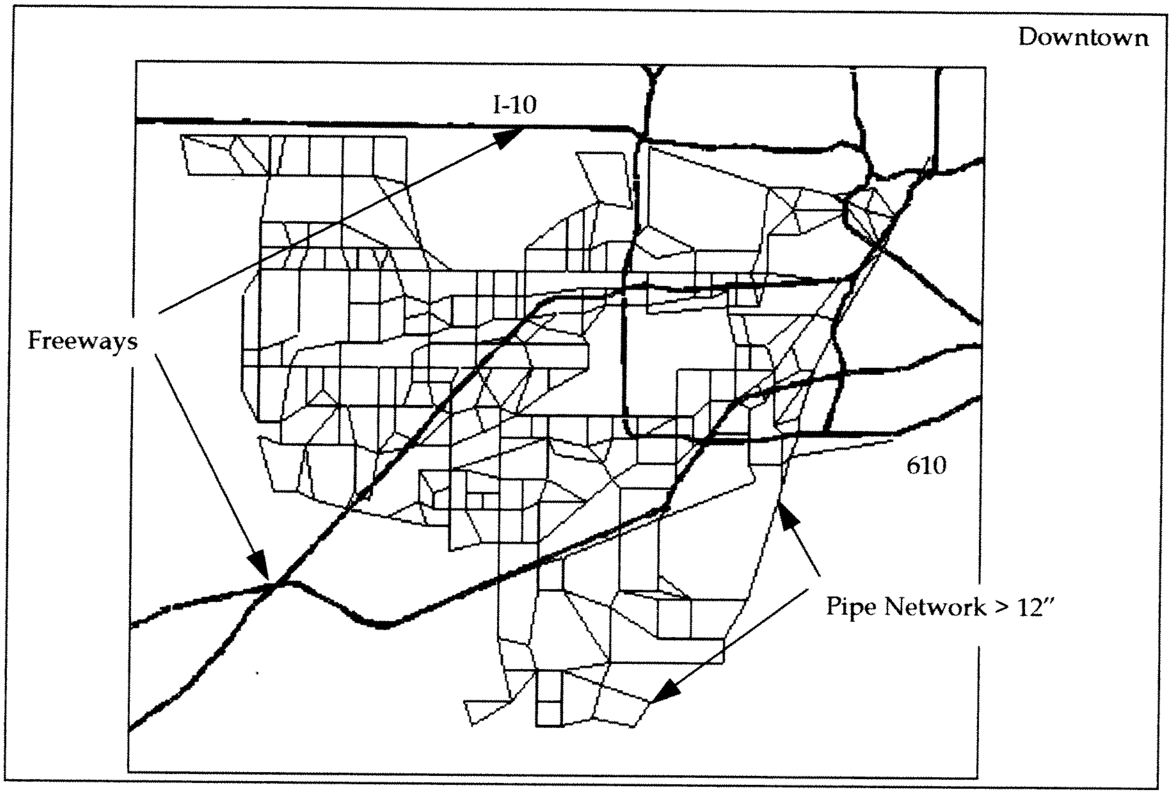

Figure 1.1. Study Area - Southwest Houston

Software

The software tools used were KYPIPE2 (1992) for the network simulations. USGS MODFLOW (1989) for the drawdown simulator, ATLAS-GIS (1993) for water demand estimation, and EXCEL(1990) for the unit cost analysis. The integrated interface program is a custom module written in Visual BASIC(1994). Parts of the KYPIPE2 source code were provided by the University of Kentucky and Dr. Donald Woods and were incorporated into the integrated modeling shell. ATLAS-GIS was selected for its availability (at relatively low cost) and its compatability with data used by the City of Houston Research and Data Services Dicision (who also use ATLAS-GIS).

Relationship of Supply, Demands, Costs, and Hydraulics

Supply, demands, and costs are related to each other through the water transmission system. Water can be supplied to this system from different locations as shown below in Figure 1.2.

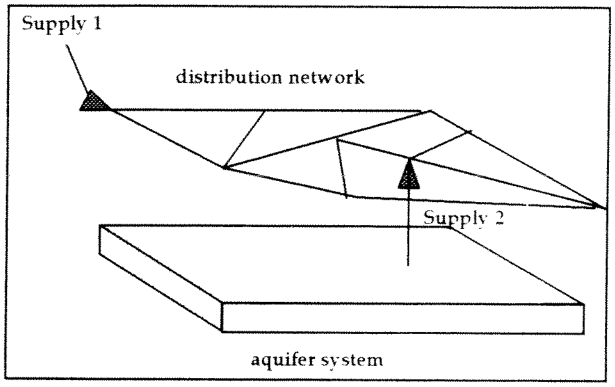

Figure 1.2. Schematic of Multiple Supply Locations in a Water Distribution System

Likewise, demand for water also occurs at different geographic locations as shown in Figure 1.3.

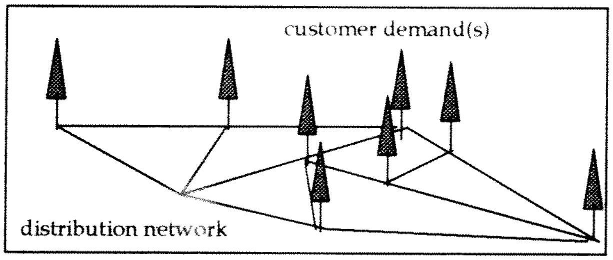

Figure 1.3. Schematic of Geographically Dispersed Demands

Conceptually these two diagrams are linked to each other through the distribution network. The network is governed by the system's hydraulics. Because of different pumping capacities, supply locations, and water treatment protocols, each supply point will have a unique cost associated with supplying a unit of water. Figure 1.4. schematically shows the supply-demand relationship.

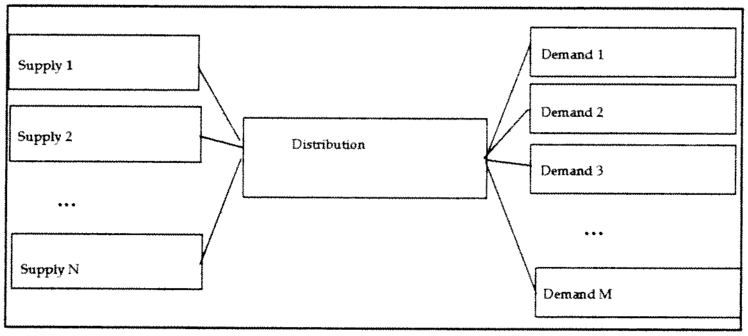

Figure 1.4. Schematic of Supply-Distribution-Demand Relationship.

The right side of the figure has a set of boxes that represent the geographically disperse demands. Not only do these demands have different locations, their values are temporally variable. The distribution system links these boxes to the various potential supply points. For a given demand configuration, there may be many different supply allocations (the left column of the diagram) that can satisfy the demand. Ideally, there should be a small subset of these supply allocations that satisfy the demand configuration for lower costs than all the other supply allocations. This particular set will be referred to an the set of non-inferior solutions. If the set contains one allocation that is less expensive than all the others, it will be refered to as the optimal allocation.

The modeling of the distribution system is important because not only do we need to identify non-inferior solutions, but we also need to be sure that the water pressure in the distribution system is neither too high or too low for a particular suppply allocation and demand configuration. From a strategic point of view one needs a tool to answer two questions: Given a demand configuration for a particular a transmission system (the network), what is a low cost supply allocation? Secondly, we want to ask: How well does this allocation perform compared to historical allocations?

Research into Production Cost Reduction by Energy Management of Houston's Surface and Groundwater Systems

Final Report

Part II

Production Cost Analysis

by

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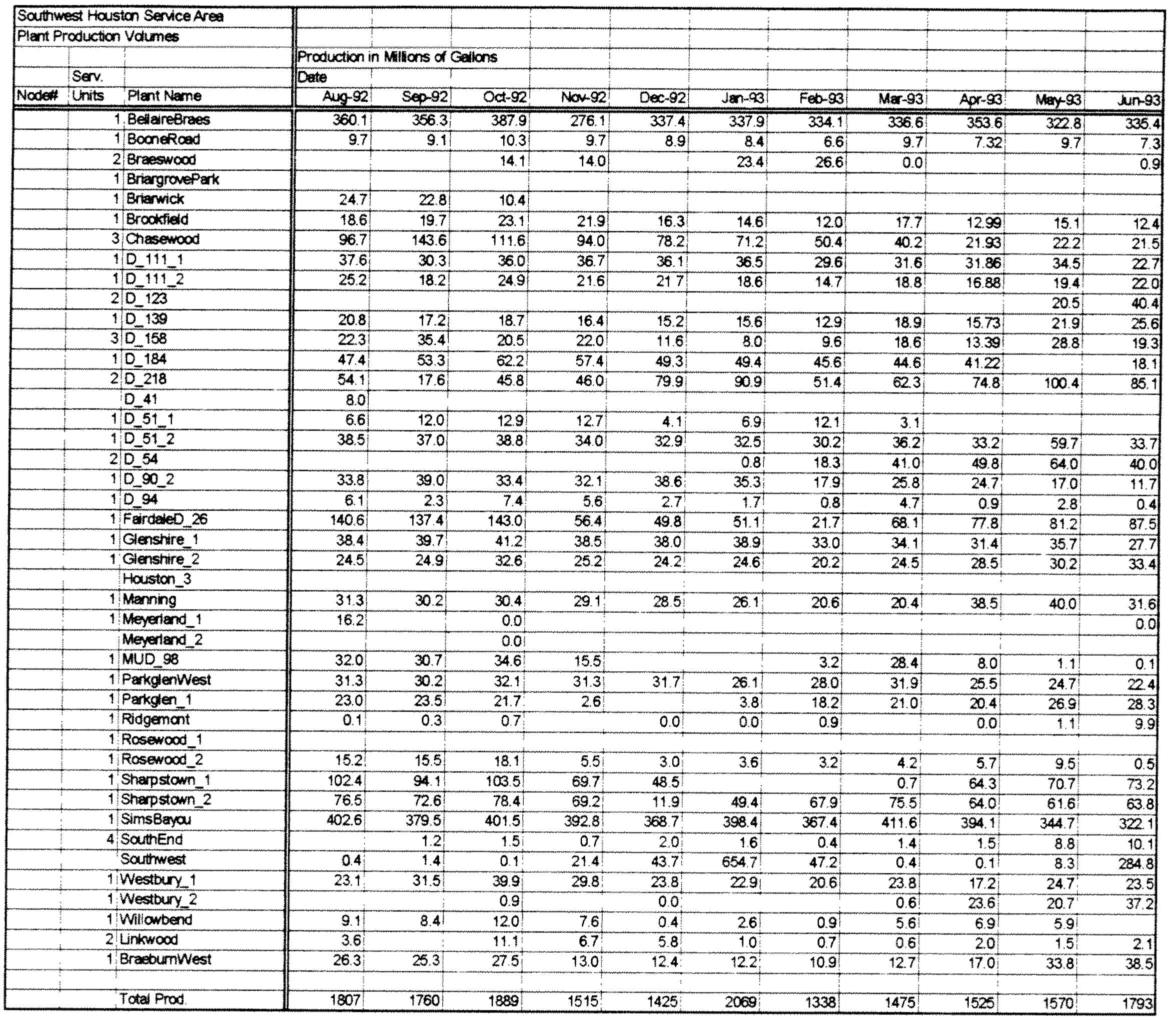
Figure 2.2 shows a completed production volume spreadsheet (after calculations) for August 1992 to June 1993. The figure is typical of the spreadsheets that were used as the basis for unit cost calculations in this research.



Southwest Houston Service Area													
Plant Production Volumes													
			Production in Millions of Gallons										
	Serv.		Date										
Node#	Units	Plant Name	Aug-92	Sep-92	Oct-92	Nov-92	Dec-92	Jan-93	Feb-93	Mar-93	Apr-93	May-93	Jun-93
	1	BellaireBraes	360.1	356.3	387.9	276.1	337.4	337.9	334.1	336.6	353.6	322.8	335.4
	1	BooneRoad	9.7	9.1	10.3	9.7	8.9	8.4	6.6	9.7	7.32	9.7	7.3
	2	Braeswood			14.1	14.0		23.4	26.6	0.0			0.9
	1	BriargrovePark											
	1	Briarwick	24.7	22.8	10.4								
	1	Brookfield	18.6	19.7	23.1	21.9	16.3	14.6	12.0	17.7	12.99	15.1	12.4
	3	Chasewood	96.7	143.6	111.6	94.0	78.2	71.2	50.4	40.2	21.93	22.2	21.5
	1	D_111_1	37.6	30.3	36.0	36.7	36.1	36.5	29.6	31.6	31.86	34.5	22.7
	1	D_111_2	25.2	18.2	24.9	21.6	21.7	18.6	14.7	18.8	16.88	19.4	22.0
	2	D_123										20.5	40.4
	1	D_139	20.8	17.2	18.7	16.4	15.2	15.6	12.9	18.9	15.73	21.9	25.6
	3	D_158	22.3	35.4	20.5	22.0	11.6	8.0	9.6	18.6	13.39	28.8	19.3
	1	D_184	47.4	53.3	62.2	57.4	49.3	49.4	45.6	44.6	41.22		18.1
	2	D_218	54.1	17.6	45.8	46.0	79.9	90.9	51.4	62.3	74.8	100.4	85.1
		D_41	8.0										
	1	D_51_1	6.6	12.0	12.9	12.7	4.1	6.9	12.1	3.1			
	1	D_51_2	38.5	37.0	38.8	34.0	32.9	32.5	30.2	36.2	33.2	59.7	33.7
	2	D_54						0.8	18.3	41.0	49.8	64.0	40.0
	1	D_90_2	33.8	39.0	33.4	32.1	38.6	35.3	17.9	25.8	24.7	17.0	11.7
	1	D_94	6.1	2.3	7.4	5.6	2.7	1.7	0.8	4.7	0.9	2.8	0.4
	1	FairdaleD_26	140.6	137.4	143.0	56.4	49.8	51.1	21.7	68.1	77.8	81.2	87.5
	1	Glenshire_1	38.4	39.7	41.2	38.5	38.0	38.9	33.0	34.1	31.4	35.7	27.7
	1	Glenshire_2	24.5	24.9	32.6	25.2	24.2	24.6	20.2	24.5	28.5	30.2	33.4
		Houston_3											
	1	Manning	31.3	30.2	30.4	29.1	28.5	26.1	20.6	20.4	38.5	40.0	31.6
	1	Meyerland_1	16.2		0.0								0.0
		Meyerland_2			0.0								
	1	MUD_98	32.0	30.7	34.6	15.5			3.2	28.4	8.0	1.1	0.1
	1	ParkglenWest	31.3	30.2	32.1	31.3	31.7	26.1	28.0	31.9	25.5	24.7	22.4
	1	Parkglen_1	23.0	23.5	21.7	2.6		3.8	18.2	21.0	20.4	26.9	28.3
	1	Ridgemont	0.1	0.3	0.7		0.0	0.0	0.9		0.0	1.1	9.9
	1	Rosewood_1											
	1	Rosewood_2	15.2	15.5	18.1	5.5	3.0	3.6	3.2	4.2	5.7	9.5	0.5
	1	Sharpstown_1	102.4	94.1	103.5	69.7	48.5			0.7	64.3	70.7	73.2
	1	Sharpstown_2	76.5	72.6	78.4	69.2	11.9	49.4	67.9	75.5	64.0	61.6	63.8
	1	SimsBayou	402.6	379.5	401.5	392.8	368.7	398.4	367.4	411.6	394.1	344.7	322.1
	4	SouthEnd		1.2	1.5	0.7	2.0	1.6	0.4	1.4	1.5	8.8	10.1
		Southwest	0.4	1.4	0.1	21.4	43.7	654.7	47.2	0.4	0.1	8.3	284.8
	1	Westbury_1	23.1	31.5	39.9	29.8	23.8	22.9	20.6	23.8	17.2	24.7	23.5
	1	Westbury_2			0.9		0.0			0.6	23.6	20.7	37.2
	1	Willowbend	9.1	8.4	12.0	7.6	0.4	2.6	0.9	5.6	6.9	5.9	
	2	Linkwood	3.6		11.1	6.7	5.8	1.0	0.7	0.6	2.0	1.5	2.1
	1	BraeburnWest	26.3	25.3	27.5	13.0	12.4	12.2	10.9	12.7	17.0	33.8	38.5
		Total Prod.	1807	1760	1889	1515	1425	2069	1338	1475	1525	1570	1793

Figure 2.2. Typical Complete Production Volume Spreadsheet

The production costs are calculated using data contained in the "Monthly Electricity Costs of Major and Minor Groundwater Plants and Wells" also produced by Water Production. Figure 2.3 below shows the format of this report that can be used directly.

```
Plant Name  Aug 1992 Sep 1992 ...
----------  -------- -------- ...
CHASEWOOD#2  $5100    $6268   ...
```

Figure 2.3. Electricity Cost Report (Typical Format)

Again, the principal complications are the treatment of missing data, and the computation of a fixed cost for plants that produce zero water yet will have a non-zero electric bill. Once the production volume spreadsheet is completed, the electricity cost data are entered onto the same sheet just below the production volumes. The ratio of actual costs to the actual production volume produces a result that constitutes the unit cost for a particular plant in a particular month.

Figure 2.4 is the production cost spreadsheet used as the basis for unit cost calculations for this research. The values in the spreadsheet were transferred from the "Monthly Electricity Costs of Major and Minor Groundwater Plants and Wells."

Southwest Houston Service Area
Production Costs (in Dollars)

Node#	Serv. Units	Plant Name	Aug-92	Sep-92	Oct-92	Nov-92	Dec-92	Jan-93	Feb-93	Mar-93	Apr-93	May-93	Jun-93
	1	BellaireBraes	43172	51625	55328	52893	53661	53609	51354	50338	54217	54487	51785
	1	BooneRoad	1622	1802	1771	1746	2037	1826	1327	1835	1801	1984	1855
	2	Braeswood	68	179	1563	5992	28	28	28	28	28	57	1254
	1	BriargrovePark	28	28	28	28	28	28	28	28	28	28	28
	1	Briarwick	3730	4187	4824	28	28	38	101	28	58	101	101
	1	Brookfield	2641	2928	3029	3256	3196	2887	2533	2769	2851	2867	2772
	3	Chasewood	11320	13681	13525	22430	21703	20353	14742	14882	9117	6493	6940
	1	D_111_1	4737	5721	5197	5345	5840	5997	4922	5226	5158	6147	5449
	1	D_111_2	4068	4059	4043	3582	4468	3906	3315	3307	3440	4147	3614
	2	D_123	377	289	124	57	68	76	68	68	111	2075	6485
	1	D_139	4220	5038	4622	4941	4847	4791	4354	4154	5329	4370	5280
	3	D_158	4529	11801	8975	8408	5794	5016	3846	8449	6799	8174	7697
	1	D_184	8438	10644	10432	10940	11143	9975	9627	10136	9176	7025	3854
	2	D_218	11627	9751	9026	7788	14282	14738	15013	12107	13745	16487	15292
		D_41	2667										
	1	D_51_1	2019	2936	3116	3332	3341	1576	3189	3041		584	28
	1	D_51_2	5361	7032	6605	6434	6503	6781	6080	6347	6291	6629	6187
	2	D_54	149	150	165	123	80	82	146	5527	8280	11557	12512
	1	D_90_2	4580	5402	5606	5218	5186	6117	4829	4115	4381	4759	2969
	1	D_94	1028	1760	1178	2100	1052	1290	668	920	1064	883	787
	1	FairdaleD_26		17564	39079	30034	6536		6439	4833	12292	13008	13811
	1	Glenshire_1	4430	5000	5520	5604	5278	5559	5120	5064	4724	5002	5049
	1	Glenshire_2	3186	3982	4797	3791	3791	3844	3575	3449	4292	3018	4767
		Houston_3											
	1	Manning	4297	5006	5107	5207	4986	5217	4185	4273	5080	5472	5528
	1	Meyerland_1	5011	5086	91	91	91	28	28	28	28	28	28
		Meyerland_2											
	1	MUD_98 (D41-2)	3392	3974	4294	4035	1479	28	28	3158	3379	964	667
	1	ParkglenWest	4279	4803	4942	5019	5002	5197	4367	4806	4918	4911	4401
	1	Parkglen_1	3529	4918	4822	4396	178	136	3108	4204	4800	5658	5670
	1	Ridgemont	1835	759	758	753		1258	766	964	268	316	1617
	1	Rosewood_1	28	28	28	28	97	152	97	56	72	72	72
	1	Rosewood_2	3291	4609	4139	3833	2268	2645	3021	1788	2164	1690	3284
	1	Sharpstown_1	12592	15057	16731	14972	12247	7018	4587	4576	9928	12590	13457
	1	Sharpstown_2	11143	12770	13660	12958	12625	11927	12705	13315	12965	12175	12507
	1	SimsBayou	43716	48801	47949	47826	50880	49993	48987	50395	50138	50142	45771
	4	SouthEnd	10935	5930	7881	5516	4640	5138	5181	4680	5046	5801	7297
		Southwest	1316	10289	110	2549	6134	98294	11717	1114	576	2062	42245
	1	Westbury_1	5596	9668	6058	7664		6486	5587	6112	5837	5265	6905
	1	Westbury_2	1298		28	28						6380	6336
	1	Willowbend	1902	1586	1761	1930	1539	442	734	723	1069	1571	1055
	2	Linkwood	3975	3221	37	3346		3150	1154	1590	1535	1954	1811
	1	BraeburnWest	4661	4851	4966	4910	3515	3457	2958	3107	3074	4205	5470

Notes:
Service units = number of billing units
May include isolated wells etc.

Figure 2.4. Production Cost Spreadsheet (for August 1993 to June 1994)

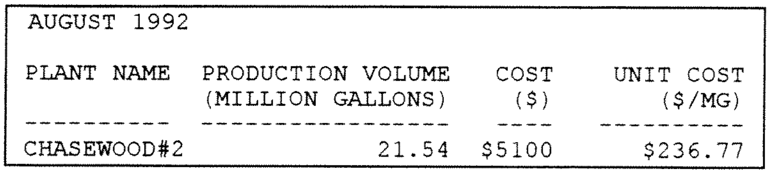
Individual Plant Analysis

Thirty-two of the plants in the above figures were analysed using the three cost models described above. The goal was to determine which model described the data, and how well the models could be expected to perform. Some of the plants had insufficient data to justify a complete analysis, and the average unit cost model was used.

The average unit cost for any plant was determined from the data using the following formula.

$$MC(\$/MG) = \frac{PC(\$)}{PV(MG)} \tag{2.4}$$

Figure 2.5 is a sample of the unit cost calculation showing the typical format used in this research.



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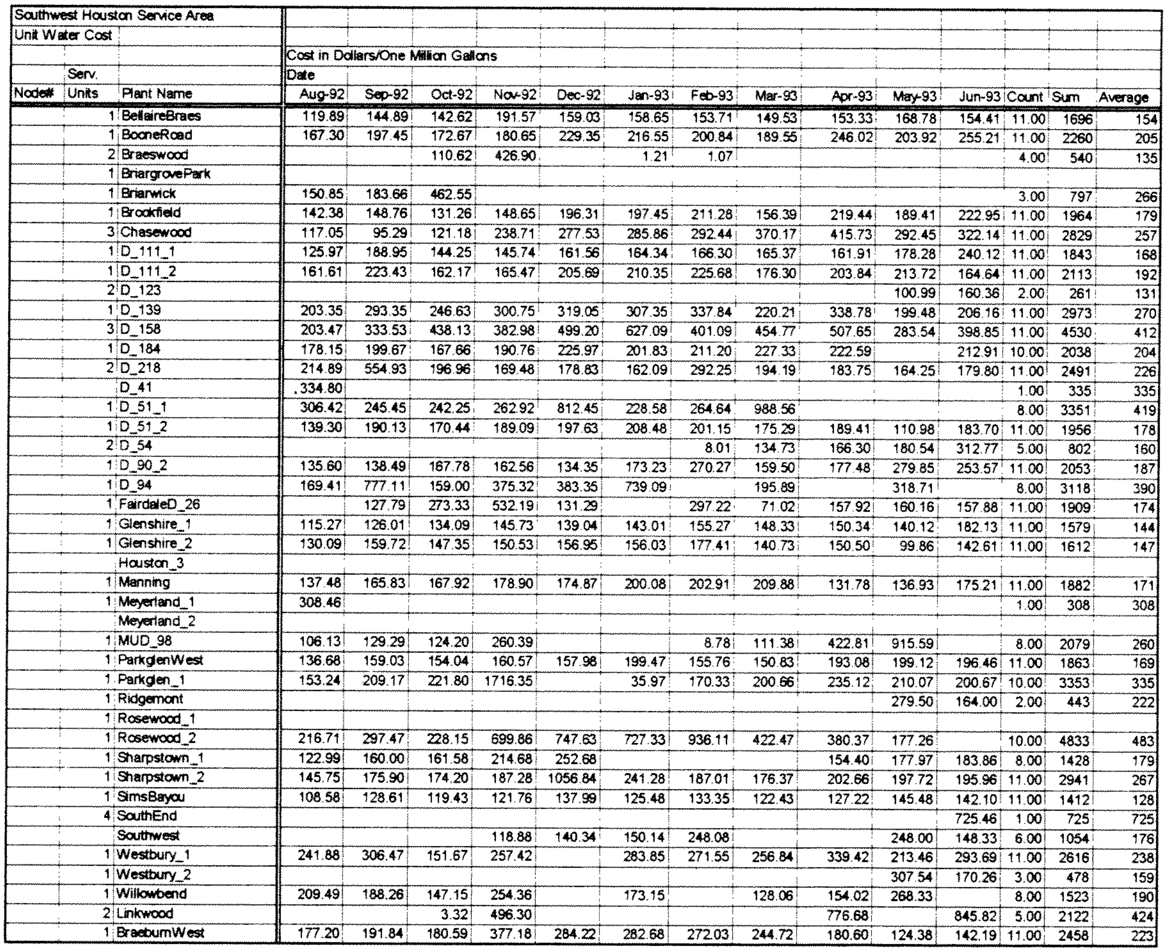
AUGUST 1992

PLANT NAME   PRODUCTION VOLUME    COST     UNIT COST
             (MILLION GALLONS)     ($)        ($/MG)
----------   -----------------    ----    ----------
CHASEWOOD#2              21.54   $5100       $236.77
```

Figure 2.5. Unit Cost Calculation (Typical)

Figure 2.6 is a typical unit cost spreadsheet showing monthly and average unit costs by plant in the study area. Certain plants were eliminated or merged into different names in subsequent analysis.



Southwest Houston Service Area																
Unit Water Cost																
			Cost in Dollars/One Million Gallons													
	Serv.		Date													
Node#	Units	Plant Name	Aug-92	Sep-92	Oct-92	Nov-92	Dec-92	Jan-93	Feb-93	Mar-93	Apr-93	May-93	Jun-93	Count	Sum	Average
	1	BellaireBraes	119.89	144.89	142.62	191.57	159.03	158.65	153.71	149.53	153.33	168.78	154.41	11.00	1696	154
	1	BooneRoad	167.30	197.45	172.67	180.65	229.35	216.55	200.84	189.55	246.02	203.92	255.21	11.00	2260	205
	2	Braeswood			110.62	426.90		1.21	1.07					4.00	540	135
	1	BriargrovePark														
	1	Briarwick	150.85	183.66	462.55									3.00	797	266
	1	Brookfield	142.38	148.76	131.26	148.65	196.31	197.45	211.28	156.39	219.44	189.41	222.95	11.00	1964	179
	3	Chasewood	117.05	95.29	121.18	238.71	277.53	285.86	292.44	370.17	415.73	292.45	322.14	11.00	2829	257
	1	D_111_1	125.97	188.95	144.25	145.74	161.56	164.34	166.30	165.37	161.91	178.28	240.12	11.00	1843	168
	1	D_111_2	161.61	223.43	162.17	165.47	205.69	210.35	225.68	176.30	203.84	213.72	164.64	11.00	2113	192
	2	D_123										100.99	160.36	2.00	261	131
	1	D_139	203.35	293.35	246.63	300.75	319.05	307.35	337.84	220.21	338.78	199.48	206.16	11.00	2973	270
	3	D_158	203.47	333.53	438.13	382.98	499.20	627.09	401.09	454.77	507.65	283.54	398.85	11.00	4530	412
	1	D_184	178.15	199.67	167.66	190.76	225.97	201.83	211.20	227.33	222.59		212.91	10.00	2038	204
	2	D_218	214.89	554.93	196.96	169.48	178.83	162.09	292.25	194.19	183.75	164.25	179.80	11.00	2491	226
		D_41	334.80											1.00	335	335
	1	D_51_1	306.42	245.45	242.25	262.92	812.45	228.58	264.64	988.56				8.00	3351	419
	1	D_51_2	139.30	190.13	170.44	189.09	197.63	208.48	201.15	175.29	189.41	110.98	183.70	11.00	1956	178
	2	D_54							8.01	134.73	166.30	180.54	312.77	5.00	802	160
	1	D_90_2	135.60	138.49	167.78	162.56	134.35	173.23	270.27	159.50	177.48	279.85	253.57	11.00	2053	187
	1	D_94	169.41	777.11	159.00	375.32	383.35	739.09		195.89		318.71		8.00	3118	390
	1	FairdaleD_26		127.79	273.33	532.19	131.29		297.22	71.02	157.92	160.16	157.88	11.00	1909	174
	1	Glenshire_1	115.27	126.01	134.09	145.73	139.04	143.01	155.27	148.33	150.34	140.12	182.13	11.00	1579	144
	1	Glenshire_2	130.09	159.72	147.35	150.53	156.95	156.03	177.41	140.73	150.50	99.86	142.61	11.00	1612	147
		Houston_3														
	1	Manning	137.48	165.83	167.92	178.90	174.87	200.08	202.91	209.88	131.78	136.93	175.21	11.00	1882	171
	1	Meyerland_1	308.46											1.00	308	308
		Meyerland_2														
	1	MUD_98	106.13	129.29	124.20	260.39			8.78	111.38	422.81	915.59		8.00	2079	260
	1	ParkglenWest	136.68	159.03	154.04	160.57	157.98	199.47	155.76	150.83	193.08	199.12	196.46	11.00	1863	169
	1	Parkglen_1	153.24	209.17	221.80	1716.35		35.97	170.33	200.66	235.12	210.07	200.67	10.00	3353	335
	1	Ridgemont										279.50	164.00	2.00	443	222
	1	Rosewood_1														
	1	Rosewood_2	216.71	297.47	228.15	699.86	747.63	727.33	936.11	422.47	380.37	177.26		10.00	4833	483
	1	Sharpstown_1	122.99	160.00	161.58	214.68	252.68				154.40	177.97	183.86	8.00	1428	179
	1	Sharpstown_2	145.75	175.90	174.20	187.28	1056.84	241.28	187.01	176.37	202.66	197.72	195.96	11.00	2941	267
	1	SimsBayou	108.58	128.61	119.43	121.76	137.99	125.48	133.35	122.43	127.22	145.48	142.10	11.00	1412	128
	4	SouthEnd											725.46	1.00	725	725
		Southwest				118.88	140.34	150.14	248.08			248.00	148.33	6.00	1054	176
	1	Westbury_1	241.88	306.47	151.67	257.42		283.85	271.55	256.84	339.42	213.46	293.69	11.00	2616	238
	1	Westbury_2										307.54	170.26	3.00	478	159
	1	Willowbend	209.49	188.26	147.15	254.36		173.15		128.06	154.02	268.33		8.00	1523	190
	2	Linkwood			3.32	496.30					776.68		845.82	5.00	2122	424
	1	BraeburnWest	177.20	191.84	180.59	377.18	284.22	282.68	272.03	244.72	180.60	124.38	142.19	11.00	2458	223

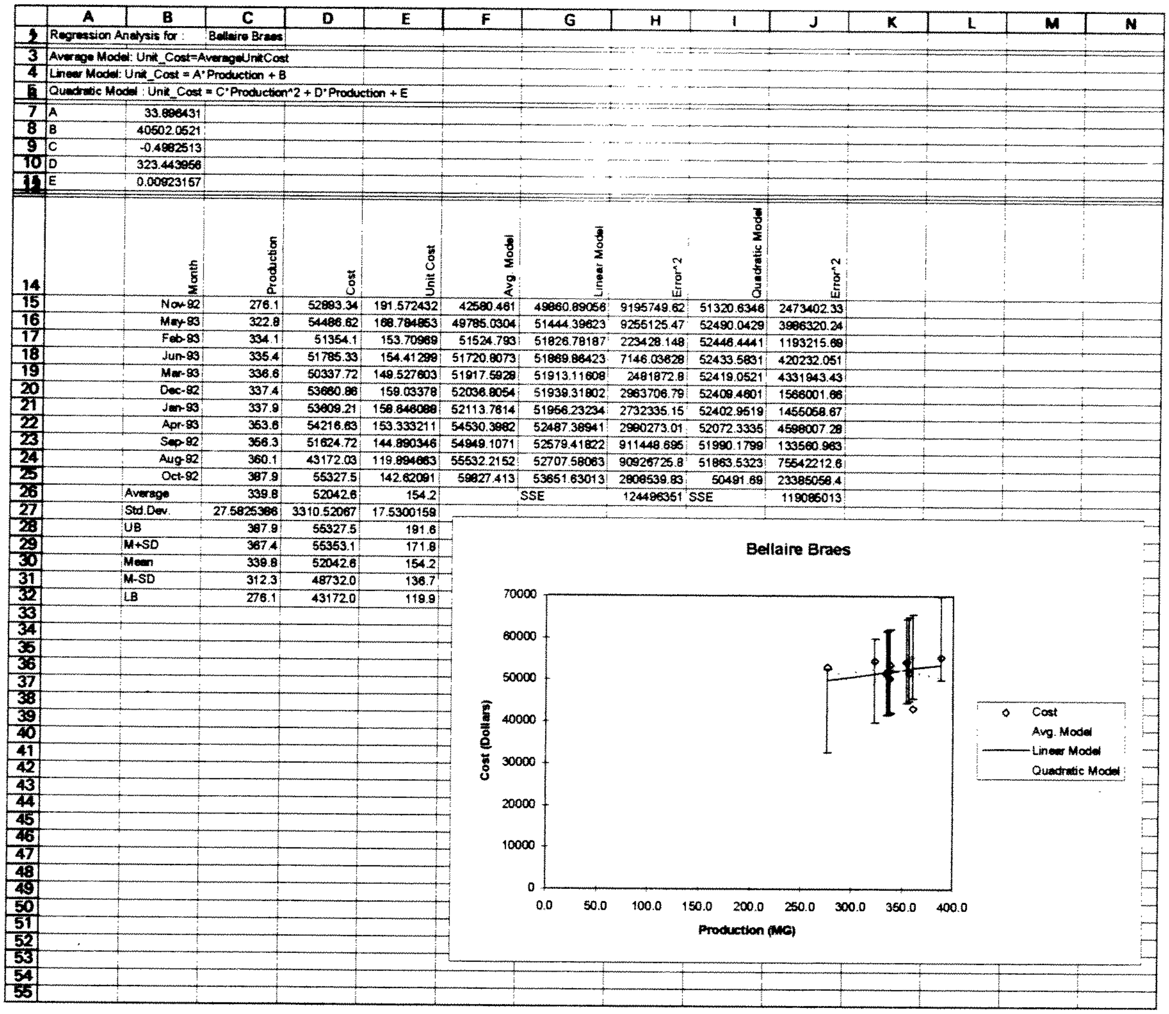
Figure 2.6 Monthly and Average Unit Costs for Producing One Million Gallons in the Southwest Houston Study Area.

The other two models were fitted to the plant data using the SOLVER package in Excel 5.0. The SOLVER is a spreadsheet version of the GRG-2 Model that was used for creating the optimization model for joint cost minimization and hydraulic analysis. The SOLVER package is limited in the size of the problems it can solve and in the complexity of the spreadsheet models it can use. Nevertheless, it is quite useful for curve fitting.

The principle of curve fitting is to create a model prediction and compute the squared error of this rpediction from the actual data based on the predictor variable. In this case the predictor variable is production volume. These squared errors are summed for a plant, and the solver is instructed to minimize this sum by changing the fitting parameters.

The "goodness" of fit for this research was determined by plotting the model curves and the data points and qualitatively assessing the goodness of fit. Rigorous "goodness-of-fit" teste were not applied because in most cases that data were too scattered for any model to satisfy any of these tests with confidence. The linear model was plotted with a variation about its prediction of no more than 20% and this value is shown on the plots. In most cases the data was within the band described by this variation model.

The following pages show the fitting analysis for each of the selected plants and the plots of the fitted models and the data.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Regression Analysis for :		Bellaire Braes											
3	Average Model: Unit_Cost=AverageUnitCost													
4	Linear Model: Unit_Cost = A*Production + B													
5	Quadratic Model : Unit_Cost = C*Production^2 + D*Production + E													
7	A	33.896431												
8	B	40502.0521												
9	C	-0.4982513												
10	D	323.443956												
11	E	0.00923157												
14		Month	Production	Cost	Unit Cost	Avg. Model	Linear Model	Error^2	Quadratic Model	Error^2				
15		Nov-92	276.1	52893.34	191.572432	42580.461	49860.89056	9195749.62	51320.6346	2473402.33				
16		May-93	322.8	54486.62	168.784853	49785.0304	51444.39623	9255125.47	52490.0429	3986320.24				
17		Feb-93	334.1	51354.1	153.70969	51524.793	51826.78187	223428.148	52446.4441	1193215.69				
18		Jun-93	335.4	51785.33	154.41299	51720.8073	51869.86423	7146.03628	52433.5831	420232.051				
19		Mar-93	336.6	50337.72	149.527603	51917.5928	51913.11608	2481872.8	52419.0521	4331943.43				
20		Dec-92	337.4	53680.86	159.03378	52036.8054	51939.31802	2963706.79	52409.4601	1566001.66				
21		Jan-93	337.9	53609.21	158.646088	52113.7614	51956.23234	2732335.15	52402.9519	1455058.67				
22		Apr-93	353.6	54216.63	153.333211	54530.3982	52487.38941	2990273.01	52072.3335	4598007.28				
23		Sep-92	356.3	51624.72	144.890346	54949.1071	52579.41822	911448.695	51990.1799	133560.963				
24		Aug-92	360.1	43172.03	119.894863	55532.2152	52707.58063	90926725.8	51863.5323	75542212.6				
25		Oct-92	387.9	55327.5	142.62091	59827.413	53651.63013	2808539.83	50491.69	23385058.4				
26		Average	339.8	52042.6	154.2		SSE	124496351	SSE	119086013				
27		Std.Dev.	27.5825386	3310.52067	17.5300159									
28		UB	387.9	55327.5	191.6									
29		M+SD	367.4	55353.1	171.8									
30		Mean	339.8	52042.6	154.2									
31		M-SD	312.3	48732.0	136.7									
32		LB	276.1	43172.0	119.9									
33														
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37														
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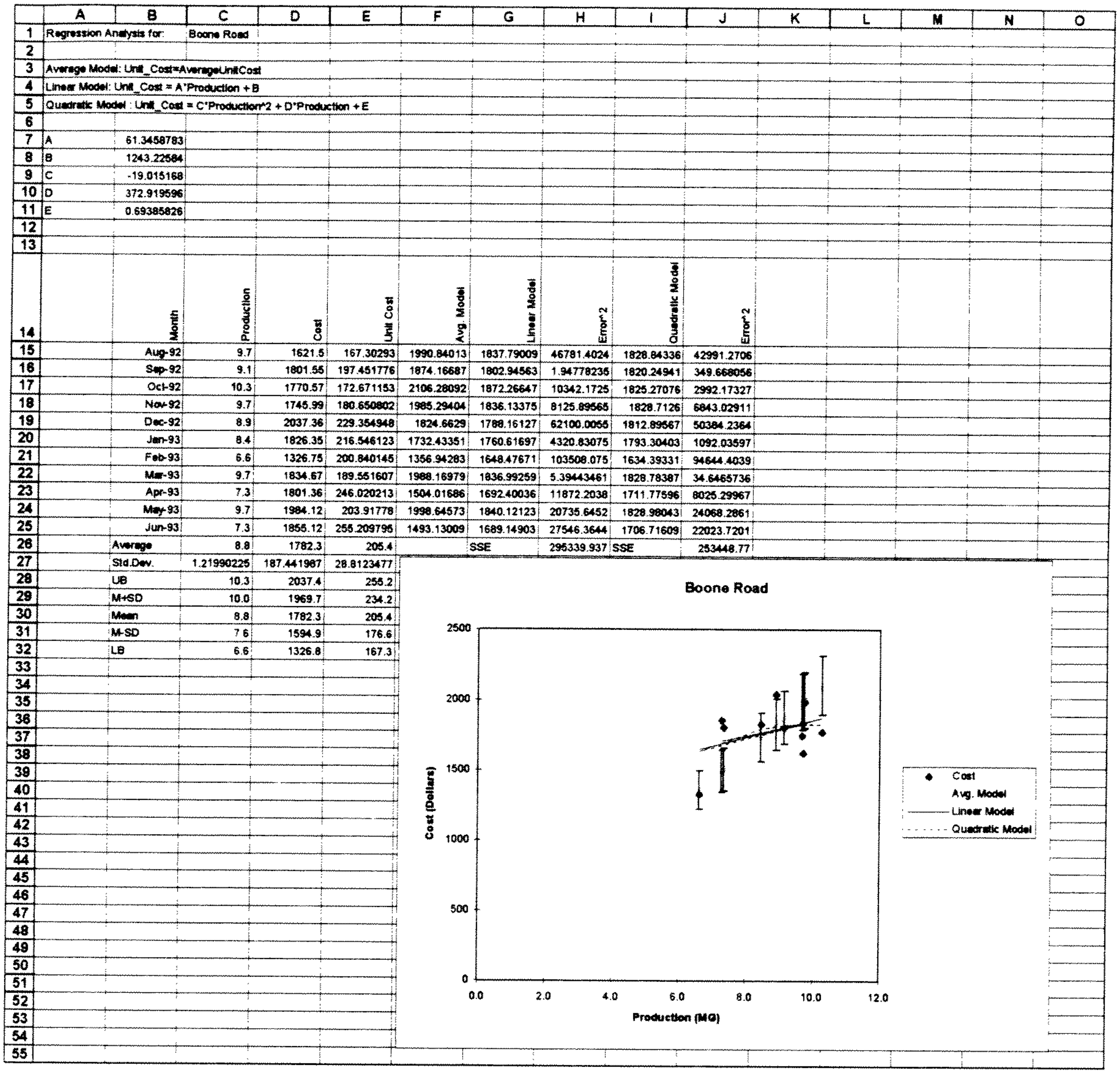
Figure 2.7 Bellaire Braes Production Cost Analysis



	A	B	C	D	E	F	G	H	I	J
1	Regression Analysis for:		Boone Road							
2										
3	Average Model: Unit_Cost=AverageUnitCost									
4	Linear Model: Unit_Cost = A*Production + B									
5	Quadratic Model : Unit_Cost = C*Production^2 + D*Production + E									
6										
7	A	61.3458783								
8	B	1243.22584								
9	C	-19.015168								
10	D	372.919596								
11	E	0.69385826								
12										
13										
14		Month	Production	Cost	Unit Cost	Avg. Model	Linear Model	Error^2	Quadratic Model	Error^2
15		Aug-92	9.7	1621.5	167.30293	1990.84013	1837.79009	46781.4024	1828.84336	42991.2706
16		Sep-92	9.1	1801.55	197.451776	1874.16687	1802.94563	1.94778236	1820.24941	349.668056
17		Oct-92	10.3	1770.57	172.671153	2106.28092	1872.26647	10342.1725	1825.27076	2992.17327
18		Nov-92	9.7	1745.99	180.650802	1985.29404	1836.13375	8125.89565	1828.7126	6843.02911
19		Dec-92	8.9	2037.36	229.354948	1824.6629	1788.16127	62100.0056	1812.89567	50384.2364
20		Jan-93	8.4	1826.35	216.546123	1732.43351	1760.61697	4320.83075	1793.30403	1092.03597
21		Feb-93	6.6	1326.75	200.840145	1356.94283	1648.47671	103508.075	1634.39331	94644.4039
22		Mar-93	9.7	1834.67	189.551607	1988.16979	1836.99259	5.39443461	1828.78387	34.6465736
23		Apr-93	7.3	1801.36	246.020213	1504.01686	1692.40036	11872.2038	1711.77596	8025.29967
24		May-93	9.7	1984.12	203.91778	1998.64573	1840.12123	20735.6452	1828.98043	24068.2861
25		Jun-93	7.3	1855.12	255.209796	1493.13009	1689.14903	27546.3644	1706.71609	22023.7201
26		Average	8.8	1782.3	205.4		SSE	295339.937	SSE	253448.77
27		Std.Dev.	1.21990225	187.441987	28.8123477					
28		UB	10.3	2037.4	255.2					
29		M+SD	10.0	1969.7	234.2					
30		Mean	8.8	1782.3	205.4					
31		M-SD	7.6	1594.9	176.6					
32		LB	6.6	1326.8	167.3					

Figure 2.8 Boone Road Production Cost Analysis

The figure for Boone Road shows that the linear cost model is a reasonable predictor of the cost-production relationship for this plant. 70% of the historical values are captured within the 20% variation range of the model. The average cost model is fair for this plant and most of the historical data fall within the 20% variation band for tha average cost model.

General Approach

The general approach used was to analyze the production costs of each selected plant in the study area. Initially three cost models were proposed; an average unit cost model, a linear cost model, and a quadratic cost model. Production volume (*PV*) in this report refers to the total volume (in millions of gallons) produced by a supply point. In the present work this supply point will be a groundwater production plant, in some cases a single well. Production cost (*PC*) in this report refers to the cost in dollars to produce the production volume of water.

The average unit cost model computes total production cost as

$$PC(\$) = MC(\$ / MG) * PV(MG) \tag{2.1}$$

The linear cost model computes the total production cost as

$$PC(\$) = A * PV(MG) + B \tag{2.2}$$

where A and B are coefficients determined by least-squares fitting of a line through the data for each plant. This model reflects the fact that cost is non-zero at zero production, and tends to increase as production increases.

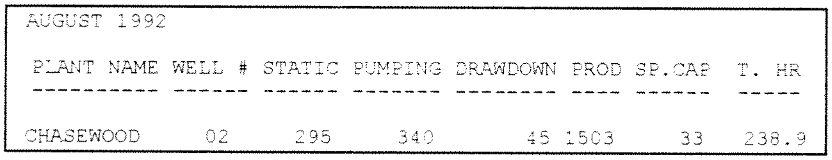
The quadratic cost model computes total production cost as

$$PC(\$) = C * PV(MG)^2 + D * PV(MG) + E \tag{2.3}$$

where C.D. and E are coefficients detemrined by least squares fitting of a curve through the data for each plant. This model was proposed to reflect economies of scale that are exprectd in producing large volumes of water from efficient plants.

Description of Data

Data from the monthly well reports prepared by Water Production is used to determine the production volume for each plant at a monthly time scale. The monthly well report format is shown below in Figure 2.1.



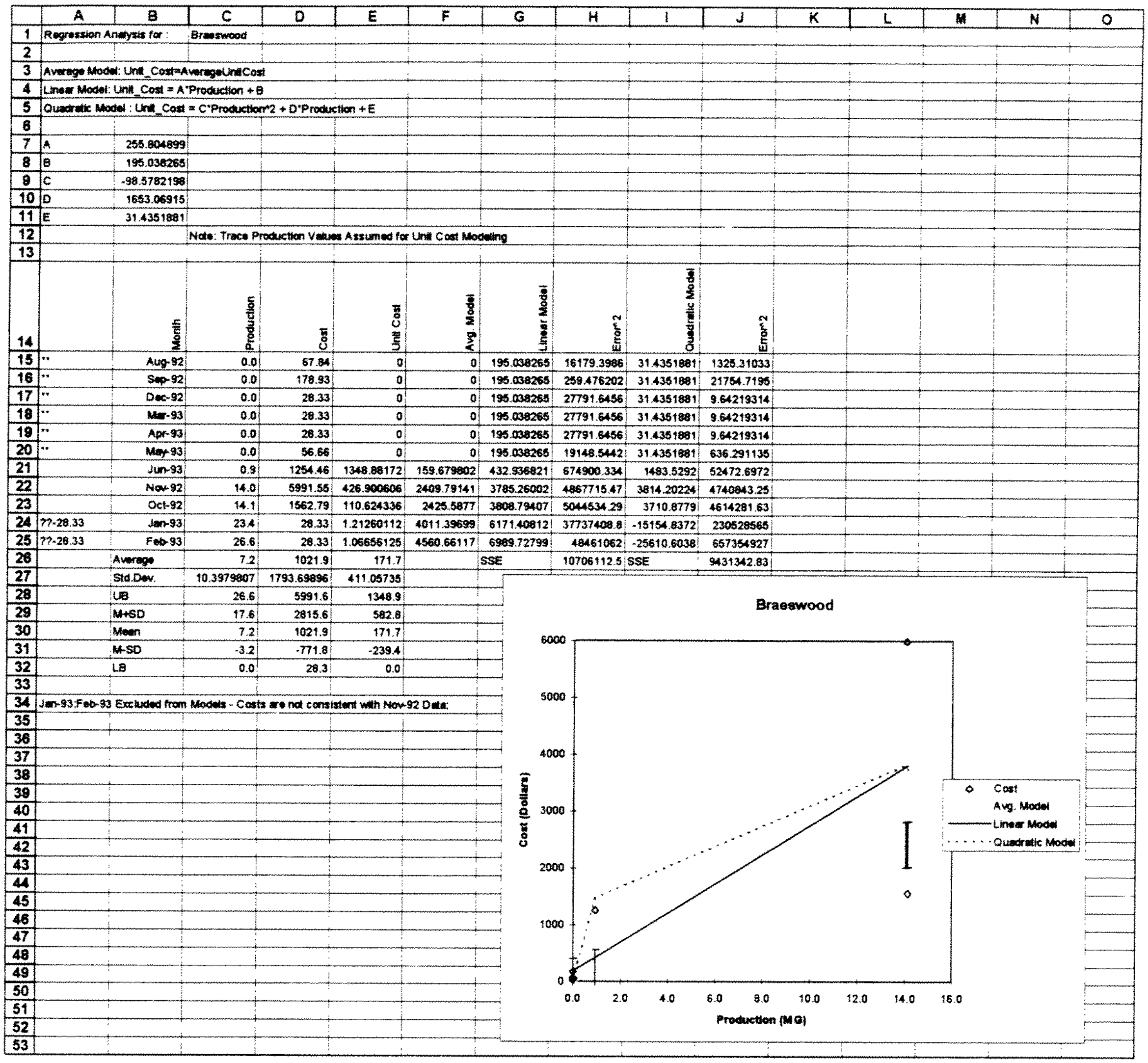
```
AUGUST 1992

 PLANT NAME WELL # STATIC PUMPING DRAWDOWN PROD SP.CAP  T. HR
 ---------- ------ ------ ------- -------- ---- ------  -----

CHASEWOOD     02      295     340         45 1503     33   238.9
```

Figure 2.1. Monthly Well Report Format (Typical)

The production volumes are calculated from this data as the product of the production rate (in gallons per minute), the production time (in hours), and the ratio (60/1,000,000) that converts the result into units of million gallons for the given month. These calculations are carried out using a spreadsheet program. Generally, the primary difficulties are the treatment of missing data, and in our case the initial data entry. Since these reports are originally prepared in spreadsheet format it should not be difficult to simply add the production volume calculation to the monthly well report format.



	A	B	C	D	E	F	G	H	I	J
1	Regression Analysis for :		Braeswood							
2										
3	Average Model: Unit_Cost=AverageUnitCost									
4	Linear Model: Unit_Cost = A*Production + B									
5	Quadratic Model : Unit_Cost = C*Production^2 + D*Production + E									
6										
7	A	255.804899								
8	B	195.038265								
9	C	-98.5782198								
10	D	1653.06915								
11	E	31.4351881								
12			Note: Trace Production Values Assumed for Unit Cost Modeling							
13										
14		Month	Production	Cost	Unit Cost	Avg. Model	Linear Model	Error^2	Quadratic Model	Error^2
15	**	Aug-92	0.0	67.84	0	0	195.038265	16179.3986	31.4351881	1325.31033
16	**	Sep-92	0.0	178.93	0	0	195.038265	259.476202	31.4351881	21754.7195
17	**	Dec-92	0.0	28.33	0	0	195.038265	27791.6456	31.4351881	9.64219314
18	**	Mar-93	0.0	28.33	0	0	195.038265	27791.6456	31.4351881	9.64219314
19	**	Apr-93	0.0	28.33	0	0	195.038265	27791.6456	31.4351881	9.64219314
20	**	May-93	0.0	56.66	0	0	195.038265	19148.5442	31.4351881	636.291135
21		Jun-93	0.9	1254.46	1348.88172	159.679802	432.936821	674900.334	1483.5292	52472.6972
22		Nov-92	14.0	5991.55	426.900606	2409.79141	3785.26002	4867715.47	3814.20224	4740843.25
23		Oct-92	14.1	1562.79	110.624336	2425.5877	3808.79407	5044534.29	3710.8779	4614281.63
24	??-28.33	Jan-93	23.4	28.33	1.21260112	4011.39699	6171.40812	37737408.8	-15154.8372	230528565
25	??-28.33	Feb-93	26.6	28.33	1.06656125	4560.66117	6989.72799	48461062	-25610.6038	657354927
26		Average	7.2	1021.9	171.7		SSE	10706112.5	SSE	9431342.83
27		Std.Dev.	10.3979807	1793.69896	411.05735					
28		UB	26.6	5991.6	1348.9					
29		M+SD	17.6	2815.6	582.8					
30		Mean	7.2	1021.9	171.7					
31		M-SD	-3.2	-771.8	-239.4					
32		LB	0.0	28.3	0.0					
33										
34	Jan-93;Feb-93 Excluded from Models - Costs are not consistent with Nov-92 Data:									

Figure 2.9 Braeswood Production Cost Analysis

The figure for Braeswood shows that none of the models is really appliciable to this plant. The average cost model is selected as being as useful as any other.

Regression Analysis for : Brookfield

Average Model: Unit_Cost=AverageUnitCost

Linear Model: Unit_Cost = A*Production + B

Quadratic Model : Unit_Cost = C*Production^2 + D*Production + E

A	32.1646055
B	2345.32386
C	-7.89975565
D	310.387599
E	0.01256584

Month	Production	Cost	Unit Cost	Avg. Model	Linear Model	Error^2	Quadratic Model	Error^2
Aug-92	18.6	2641.47	142.381953	3312.88147	2942.04162	90343.2994	3039.41143	158357.384
Sep-92	19.7	2927.96	148.763337	3514.66866	2978.38763	2542.94538	3048.84506	14613.1971
Oct-92	23.1	3028.72	131.26116	4120.38739	3087.48997	3453.90902	2955.99125	5289.47132
Nov-92	21.9	3256.11	148.653671	3911.45729	3049.85738	42540.1439	3008.55655	61282.7089
Dec-92	16.3	3196.36	196.312492	2907.52135	2869.02797	107146.26	2959.49038	56107.2149
Jan-93	14.6	2886.97	197.453663	2610.91203	2815.60256	5093.31193	2849.43012	1409.24287
Feb-93	12.0	2532.66	211.283891	2140.55143	2730.88099	39291.5593	2585.52729	2794.94985
Mar-93	17.7	2769.44	156.39485	3162.16607	2914.89469	21157.068	3019.204	62382.0543
Apr-93	13.0	2851.18	219.439698	2320.19561	2763.23858	7733.69348	2699.2573	23080.5074
May-93	15.1	2866.66	189.406013	2702.69841	2832.13516	1191.96429	2888.14587	461.64242
Jun-93	12.4	2771.93	222.949409	2220.19487	2745.2264	713.082243	2637.92139	17958.3082
Average	16.8	2884.5	178.6		SSE	321207.237	SSE	403736.681
Std.Dev.	3.76980835	216.388354	33.6477829					
UB	23.1	3256.1	222.9					
M+SD	20.5	3100.9	212.2					
Mean	16.8	2884.5	178.6					
M-SD	13.0	2668.1	144.9					
LB	12.0	2532.7	131.3					

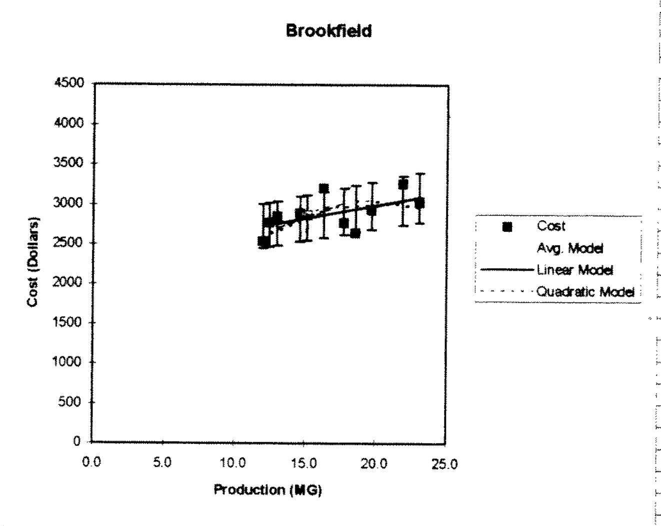
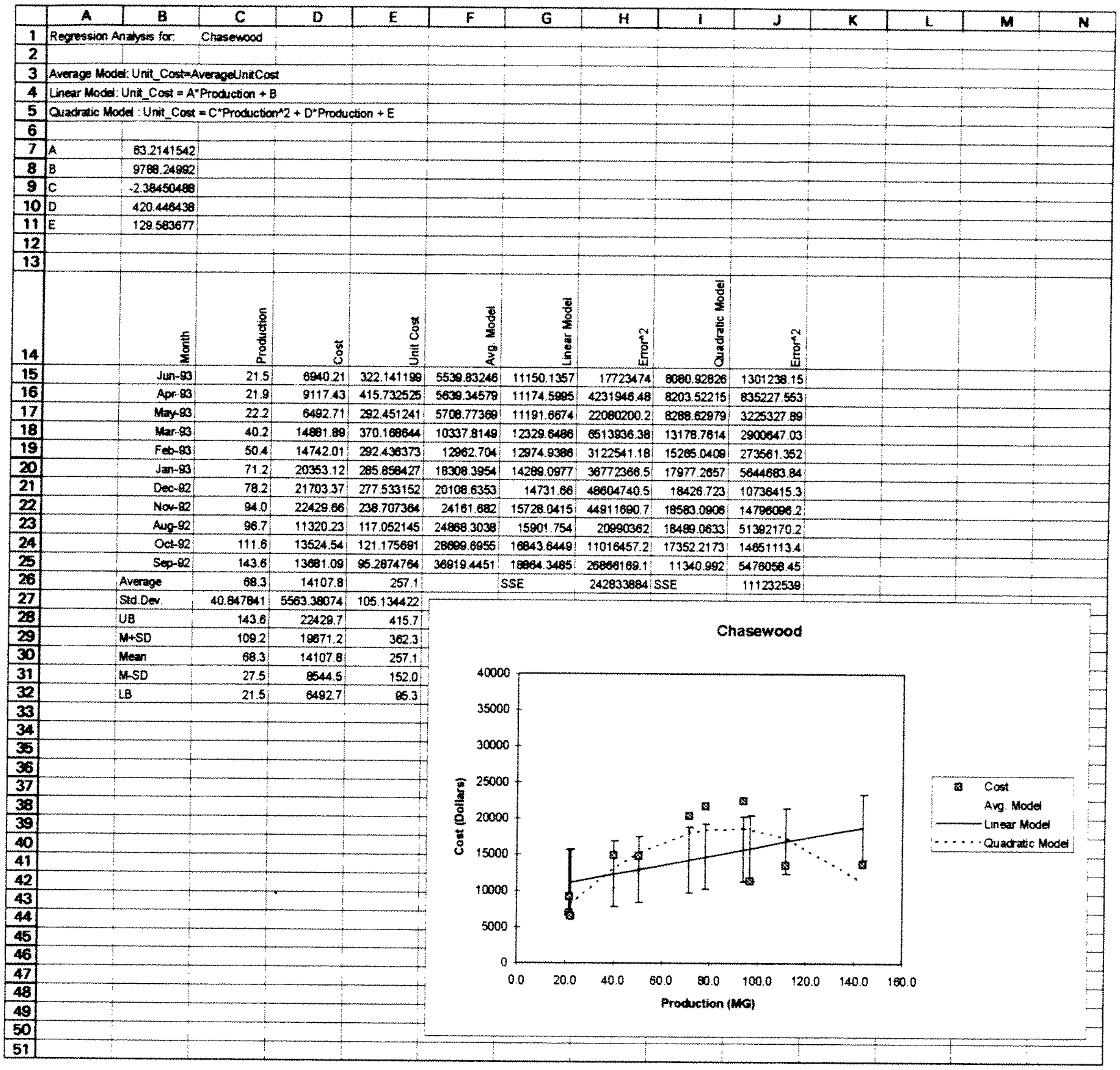


Figure 2.10 Brookfield Production Cost Analysis

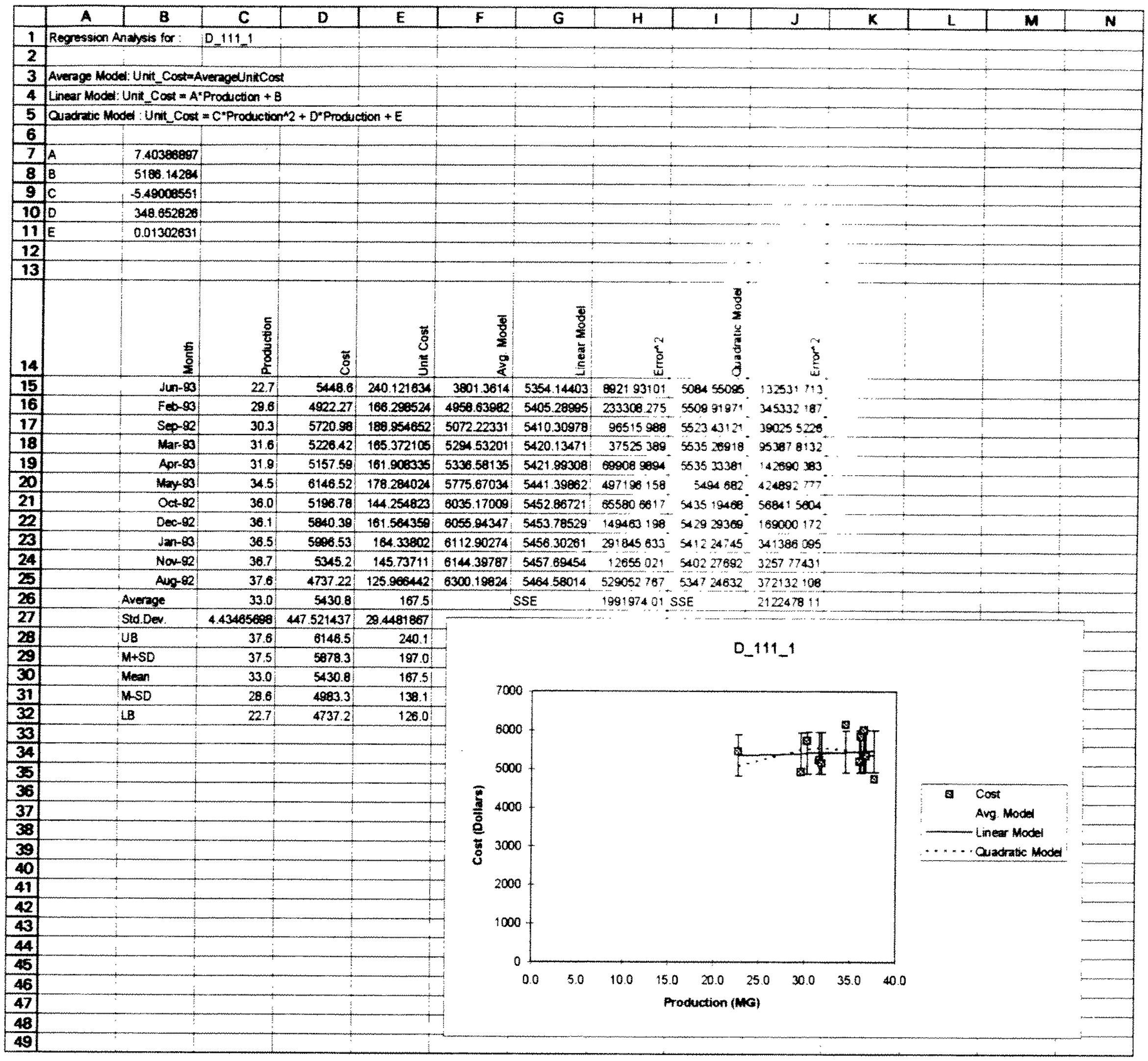
The figure for Brookfield shows that the linear cost model is a reasonable predictor of the cost-production relationship for this plant. 80% of the historical values are captured within the 20% variation range of the model.



	A	B	C	D	E	F	G	H	I	J
1	Regression Analysis for:		Chasewood							
2										
3	Average Model: Unit_Cost=AverageUnitCost									
4	Linear Model: Unit_Cost = A*Production + B									
5	Quadratic Model : Unit_Cost = C*Production^2 + D*Production + E									
6										
7	A	63.2141542								
8	B	9788.24992								
9	C	-2.38450488								
10	D	420.446438								
11	E	129.583677								
12										
13										
14		Month	Production	Cost	Unit Cost	Avg. Model	Linear Model	Error^2	Quadratic Model	Error^2
15		Jun-93	21.5	6940.21	322.141199	5539.83246	11150.1357	17723474	8080.92826	1301238.15
16		Apr-93	21.9	9117.43	415.732525	5639.34579	11174.5995	4231946.48	8203.52215	835227.553
17		May-93	22.2	6492.71	292.451241	5708.77369	11191.6674	22080200.2	8288.62979	3225327.89
18		Mar-93	40.2	14881.89	370.168644	10337.8149	12329.6486	6513936.38	13178.7614	2900647.03
19		Feb-93	50.4	14742.01	292.436373	12962.704	12974.9386	3122541.18	15265.0409	273561.352
20		Jan-93	71.2	20353.12	285.858427	18308.3954	14289.0977	36772366.5	17977.2657	5644683.84
21		Dec-92	78.2	21703.37	277.533152	20108.6353	14731.66	48604740.5	18426.723	10736415.3
22		Nov-92	94.0	22429.66	238.707364	24161.682	15728.0415	44911690.7	18583.0906	14796096.2
23		Aug-92	96.7	11320.23	117.052145	24868.3038	15901.754	20990362	18489.0633	51392170.2
24		Oct-92	111.6	13524.54	121.175691	28699.6955	16843.6449	11016457.2	17352.2173	14651113.4
25		Sep-92	143.6	13681.09	95.2874764	36919.4451	18864.3485	26866169.1	11340.992	5476058.45
26		Average	68.3	14107.8	257.1		SSE	242833884	SSE	111232539
27		Std.Dev.	40.847641	5563.38074	105.134422					
28		UB	143.6	22429.7	415.7					
29		M+SD	109.2	19671.2	362.3					
30		Mean	68.3	14107.8	257.1					
31		M-SD	27.5	8544.5	152.0					
32		LB	21.5	6492.7	95.3					

Figure 2.11 Chasewood Production Cost Analysis

The figure for Chasewood shows that the average cost model performs well for all but the three highest historical production volumes. The linear cost model exhibits the same type of performance but poorly predicts middel range production volume-cost relationships.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Regression Analysis for :		D_111_1											
2														
3	Average Model: Unit_Cost=AverageUnitCost													
4	Linear Model: Unit_Cost = A*Production + B													
5	Quadratic Model : Unit_Cost = C*Production^2 + D*Production + E													
6														
7	A	7.40386897												
8	B	5186.14284												
9	C	-5.49008551												
10	D	348.652826												
11	E	0.01302631												
12														
13														
14		Month	Production	Cost	Unit Cost	Avg. Model	Linear Model	Error^2	Quadratic Model	Error^2				
15		Jun-93	22.7	5448.6	240.121634	3801.3614	5354.14403	8921.93101	5084.55095	132531.713				
16		Feb-93	29.6	4922.27	166.298524	4958.63982	5405.28995	233308.275	5509.91971	345332.187				
17		Sep-92	30.3	5720.98	188.954652	5072.22331	5410.30978	96515.988	5523.43121	39025.5226				
18		Mar-93	31.6	5226.42	165.372105	5294.53201	5420.13471	37525.389	5535.26918	95387.8132				
19		Apr-93	31.9	5157.59	161.908335	5336.58135	5421.99308	69908.9894	5535.33381	142690.383				
20		May-93	34.5	6146.52	178.284024	5775.67034	5441.39862	497196.158	5494.682	424892.777				
21		Oct-92	36.0	5196.78	144.254823	6035.17009	5452.86721	65580.6617	5435.19468	56841.5604				
22		Dec-92	36.1	5840.39	161.564359	6055.94347	5453.78529	149463.198	5429.29369	169000.172				
23		Jan-93	36.5	5996.53	164.33802	6112.90274	5456.30261	291845.633	5412.24745	341386.095				
24		Nov-92	36.7	5345.2	145.73711	6144.39787	5457.69454	12655.021	5402.27692	3257.77431				
25		Aug-92	37.6	4737.22	125.966442	6300.19824	5464.58014	529052.767	5347.24632	372132.108				
26		Average	33.0	5430.8	167.5		SSE	1991974.01	SSE	2122478.11				
27		Std.Dev.	4.43465698	447.521437	29.4481867									
28		UB	37.6	6146.5	240.1									
29		M+SD	37.5	5878.3	197.0									
30		Mean	33.0	5430.8	167.5									
31		M-SD	28.6	4983.3	138.1									
32		LB	22.7	4737.2	126.0									
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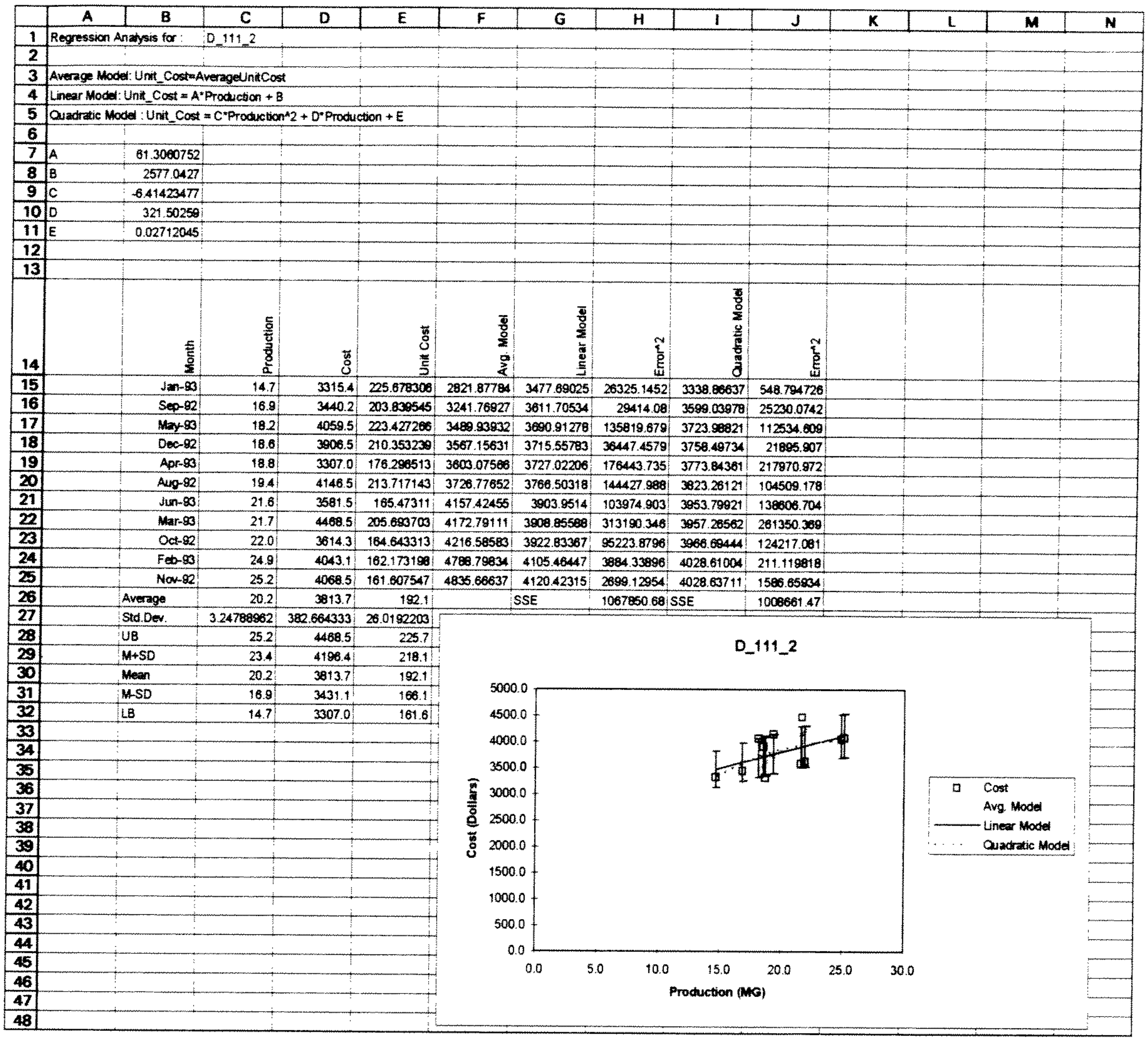
Figure 2.12 D-111-1 Production Cost Analysis

The figure for D-111-1 shows that the linear cost model is a reasonable predictor of the cost-production relationship for this plant. 80% of the historical values are captured within the 20% variation range of the model. The nearly flat slope of the linear cost model suggests that other costs are charged to this plant, since there is little variation in total costs over the entire range of production volumes.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Regression Analysis for :		D_111_2											
2														
3	Average Model: Unit_Cost=AverageUnitCost													
4	Linear Model: Unit_Cost = A*Production + B													
5	Quadratic Model : Unit_Cost = C*Production^2 + D*Production + E													
6														
7	A	61.3060752												
8	B	2577.0427												
9	C	-6.41423477												
10	D	321.50259												
11	E	0.02712045												
12														
13														
14		Month	Production	Cost	Unit Cost	Avg. Model	Linear Model	Error^2	Quadratic Model	Error^2				
15		Jan-93	14.7	3315.4	225.678306	2821.87784	3477.69025	26325.1452	3338.86637	548.794726				
16		Sep-92	16.9	3440.2	203.839545	3241.76927	3611.70534	29414.08	3599.03978	25230.0742				
17		May-93	18.2	4059.5	223.427266	3489.93932	3690.91278	135819.679	3723.98821	112534.609				
18		Dec-92	18.6	3906.5	210.353239	3567.15631	3715.55783	36447.4579	3758.49734	21895.907				
19		Apr-93	18.8	3307.0	176.296513	3603.07566	3727.02206	176443.735	3773.84361	217970.972				
20		Aug-92	19.4	4146.5	213.717143	3726.77652	3766.50318	144427.988	3823.26121	104509.178				
21		Jun-93	21.6	3581.5	165.47311	4157.42455	3903.9514	103974.903	3953.79921	138606.704				
22		Mar-93	21.7	4468.5	205.693703	4172.79111	3908.85588	313190.346	3957.26562	261350.369				
23		Oct-92	22.0	3614.3	164.643313	4216.58583	3922.83367	95223.8796	3966.69444	124217.081				
24		Feb-93	24.9	4043.1	162.173198	4788.79834	4105.46447	3884.33896	4028.61004	211.119818				
25		Nov-92	25.2	4068.5	161.607547	4835.66637	4120.42315	2699.12954	4028.63711	1586.65934				
26		Average	20.2	3813.7	192.1		SSE	1067850.68	SSE	1008661.47				
27		Std.Dev.	3.24788962	382.664333	26.0192203									
28		UB	25.2	4468.5	225.7									
29		M+SD	23.4	4196.4	218.1									
30		Mean	20.2	3813.7	192.1									
31		M-SD	16.9	3431.1	166.1									
32		LB	14.7	3307.0	161.6									
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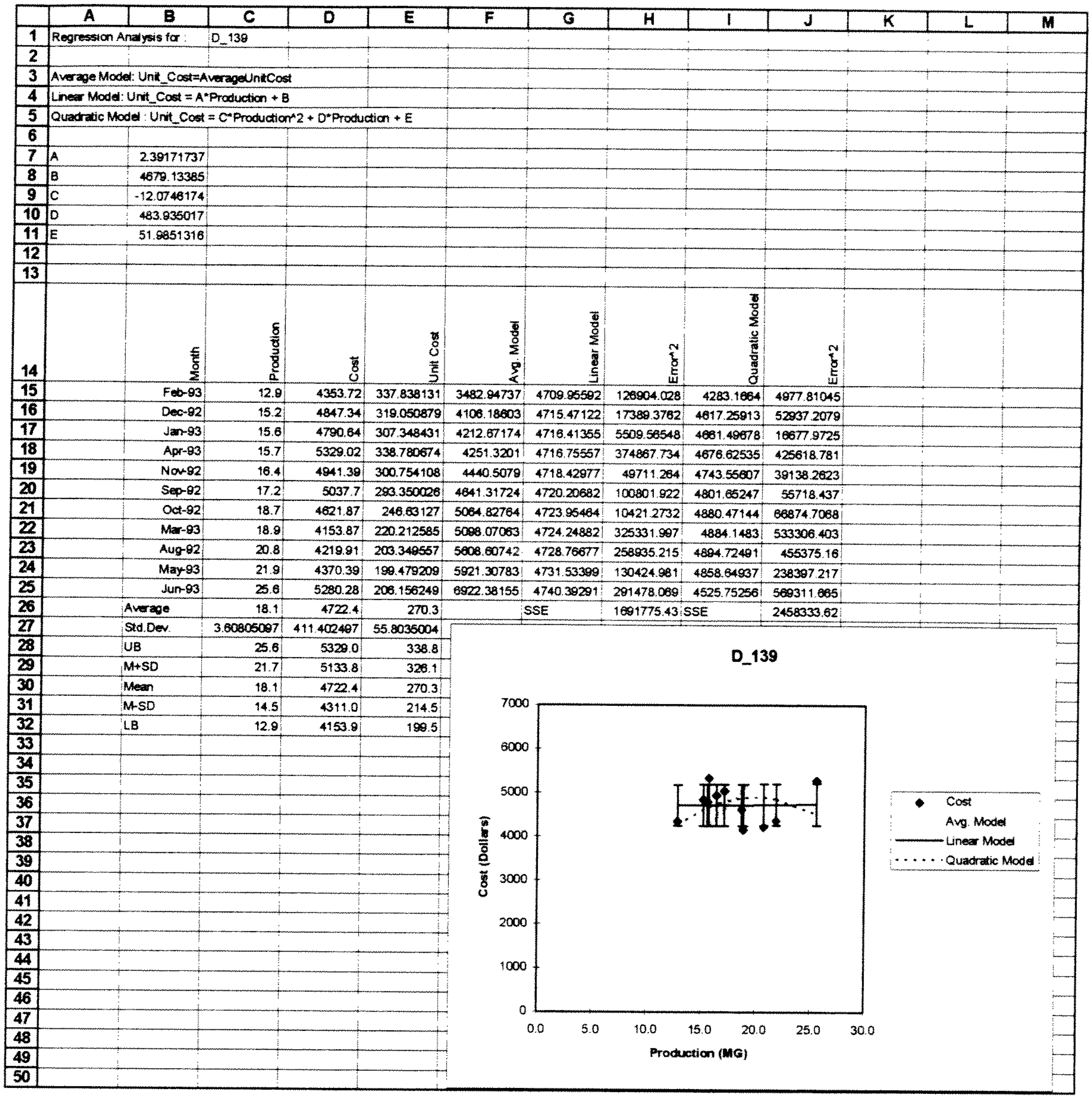
Figure 2.13 D-111-2 Production Cost Analysis

The figure for D-111-2 shows that the linear cost model is a reasonable predictor of the cost-production relationship for this plant. 70% of the historical values are captured within the 20% variation range of the model.



	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Regression Analysis for :		D_139										
2													
3	Average Model: Unit_Cost=AverageUnitCost												
4	Linear Model: Unit_Cost = A*Production + B												
5	Quadratic Model : Unit_Cost = C*Production^2 + D*Production + E												
6													
7	A	2.39171737											
8	B	4679.13385											
9	C	-12.0746174											
10	D	483.935017											
11	E	51.9851316											
12													
13													
14		Month	Production	Cost	Unit Cost	Avg. Model	Linear Model	Error^2	Quadratic Model	Error^2			
15		Feb-93	12.9	4353.72	337.838131	3482.94737	4709.95592	126904.028	4283.1664	4977.81045			
16		Dec-92	15.2	4847.34	319.050879	4106.18603	4715.47122	17389.3762	4617.25913	52937.2079			
17		Jan-93	15.6	4790.64	307.348431	4212.67174	4716.41355	5509.56548	4661.49678	16677.9725			
18		Apr-93	15.7	5329.02	338.780674	4251.3201	4716.75557	374867.734	4676.62535	425618.781			
19		Nov-92	16.4	4941.39	300.754108	4440.5079	4718.42977	49711.264	4743.55607	39138.2623			
20		Sep-92	17.2	5037.7	293.350026	4641.31724	4720.20682	100801.922	4801.65247	55718.437			
21		Oct-92	18.7	4621.87	246.63127	5064.82764	4723.95464	10421.2732	4880.47144	66874.7068			
22		Mar-93	18.9	4153.87	220.212585	5098.07063	4724.24882	325331.997	4884.1483	533306.403			
23		Aug-92	20.8	4219.91	203.349557	5608.60742	4728.76677	258935.215	4894.72491	455375.16			
24		May-93	21.9	4370.39	199.479209	5921.30783	4731.53399	130424.981	4858.64937	238397.217			
25		Jun-93	25.6	5280.28	206.156249	6922.38155	4740.39291	291478.069	4525.75256	569311.665			
26		Average	18.1	4722.4	270.3		SSE	1691775.43	SSE	2458333.62			
27		Std.Dev.	3.60805097	411.402497	55.8035004								
28		UB	25.6	5329.0	338.8								
29		M+SD	21.7	5133.8	326.1								
30		Mean	18.1	4722.4	270.3								
31		M-SD	14.5	4311.0	214.5								
32		LB	12.9	4153.9	199.5								
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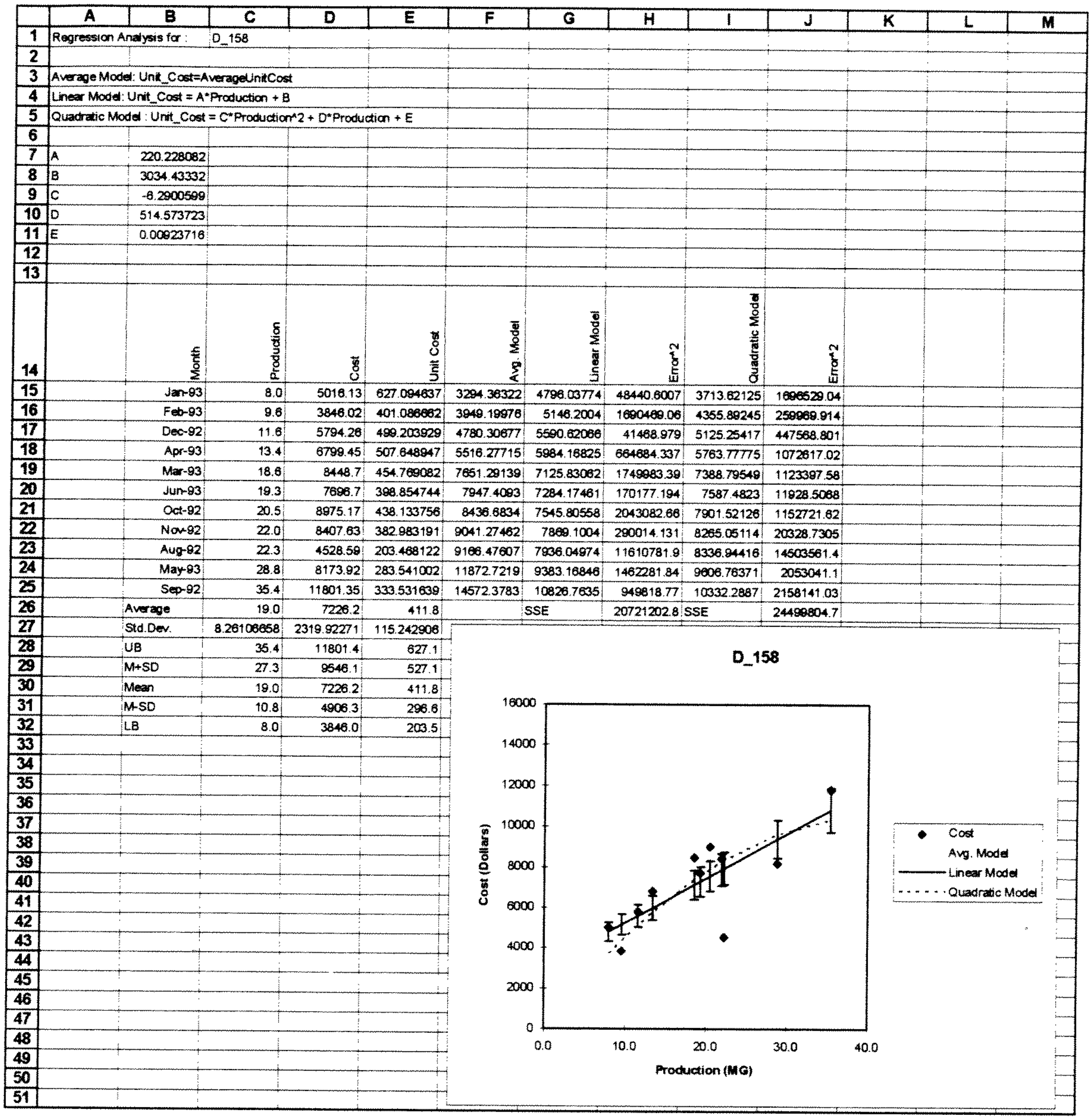
Figure 2.14 D-139 Production Cost Analysis

The figure for D-139 shows that the linear cost model is a reasonable predictor of the cost-production relationship for this plant. 70% of the historical values are captured within the 20% variation range of the model. The nearly flat slope of the linear cost model suggests that other costs are charged to this plant, since there is little variation in total costs over the entire range of production volumes.



	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Regression Analysis for :		D_158										
2													
3	Average Model: Unit_Cost=AverageUnitCost												
4	Linear Model: Unit_Cost = A*Production + B												
5	Quadratic Model : Unit_Cost = C*Production^2 + D*Production + E												
6													
7	A	220.228082											
8	B	3034.43332											
9	C	-6.2900599											
10	D	514.573723											
11	E	0.00923716											
12													
13													
14		Month	Production	Cost	Unit Cost	Avg. Model	Linear Model	Error^2	Quadratic Model	Error^2			
15		Jan-93	8.0	5016.13	627.094637	3294.36322	4796.03774	48440.6007	3713.62125	1696529.04			
16		Feb-93	9.6	3846.02	401.086662	3949.19976	5146.2004	1690469.06	4355.89245	259969.914			
17		Dec-92	11.6	5794.26	499.203929	4780.30677	5590.62066	41468.979	5125.25417	447568.801			
18		Apr-93	13.4	6799.45	507.648947	5516.27715	5984.16825	664684.337	5763.77775	1072617.02			
19		Mar-93	18.6	8448.7	454.769082	7651.29139	7125.83062	1749983.39	7388.79549	1123397.58			
20		Jun-93	19.3	7696.7	398.854744	7947.4093	7284.17461	170177.194	7587.4823	11928.5068			
21		Oct-92	20.5	8975.17	438.133756	8436.6834	7545.80558	2043082.66	7901.52126	1152721.62			
22		Nov-92	22.0	8407.63	382.983191	9041.27462	7869.1004	290014.131	8265.05114	20328.7305			
23		Aug-92	22.3	4528.59	203.468122	9166.47607	7936.04974	11610781.9	8336.94416	14503561.4			
24		May-93	28.8	8173.92	283.541002	11872.7219	9383.16846	1462281.84	9606.76371	2053041.1			
25		Sep-92	35.4	11801.35	333.531639	14572.3783	10826.7635	949818.77	10332.2887	2158141.03			
26		Average	19.0	7226.2	411.8		SSE	20721202.8	SSE	24498804.7			
27		Std.Dev.	8.26106658	2319.92271	115.242906								
28		UB	35.4	11801.4	627.1								
29		M+SD	27.3	9546.1	527.1								
30		Mean	19.0	7226.2	411.8								
31		M-SD	10.8	4906.3	296.6								
32		LB	8.0	3846.0	203.5								
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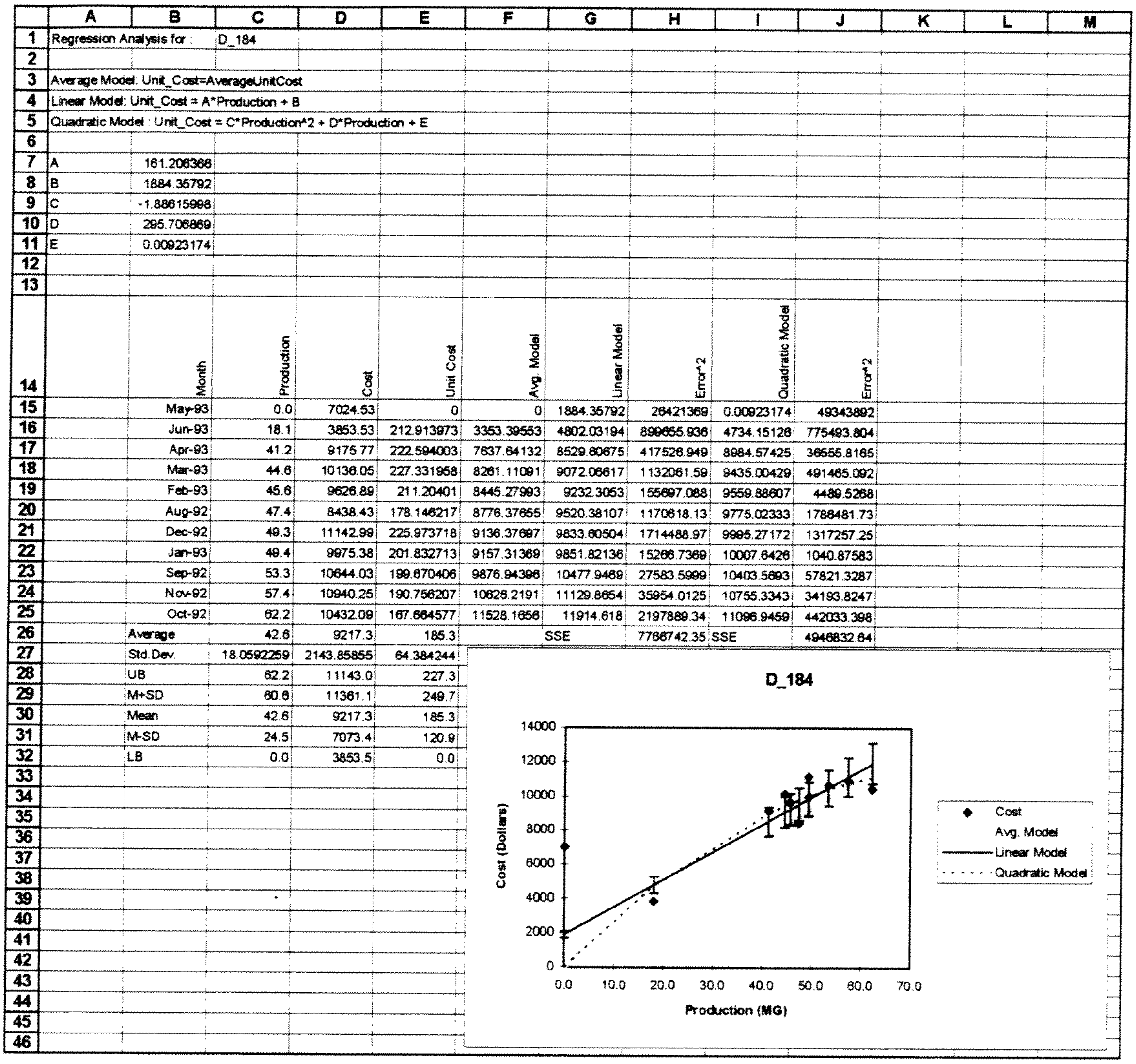
Figure 2.15 D-158 Production Cost Analysis

The figure for D-158 shows that the linear cost model is a reasonable predictor of the cost-production relationship for this plant. 60% of the historical values are captured within the 20% variation range of the model. The other two models are acceptable in the middle and lower ranges of historical production values. The average cost model overpredicts costs at the higher ranges.



	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Regression Analysis for :		D_184										
2													
3	Average Model: Unit_Cost=AverageUnitCost												
4	Linear Model: Unit_Cost = A*Production + B												
5	Quadratic Model : Unit_Cost = C*Production^2 + D*Production + E												
6													
7	A	161.206366											
8	B	1884.35792											
9	C	-1.88615998											
10	D	295.706869											
11	E	0.00923174											
12													
13													
14		Month	Production	Cost	Unit Cost	Avg. Model	Linear Model	Error^2	Quadratic Model	Error^2			
15		May-93	0.0	7024.53	0	0	1884.35792	26421369	0.00923174	49343892			
16		Jun-93	18.1	3853.53	212.913973	3353.39553	4802.03194	899655.936	4734.15126	775493.804			
17		Apr-93	41.2	9175.77	222.594003	7637.64132	8529.60675	417526.949	8984.57425	36555.8165			
18		Mar-93	44.6	10136.05	227.331958	8261.11091	9072.06617	1132061.59	9435.00429	491465.092			
19		Feb-93	45.6	9626.89	211.20401	8445.27993	9232.3053	155697.088	9559.88607	4489.5268			
20		Aug-92	47.4	8438.43	178.146217	8776.37655	9520.38107	1170618.13	9775.02333	1786481.73			
21		Dec-92	49.3	11142.99	225.973718	9136.37697	9833.60504	1714488.97	9995.27172	1317257.25			
22		Jan-93	49.4	9975.38	201.832713	9157.31369	9851.82136	15266.7369	10007.6426	1040.87583			
23		Sep-92	53.3	10644.03	199.670406	9876.94396	10477.9469	27583.5999	10403.5693	57821.3287			
24		Nov-92	57.4	10940.25	190.756207	10626.2191	11129.8654	35954.0125	10755.3343	34193.8247			
25		Oct-92	62.2	10432.09	167.664577	11528.1656	11914.618	2197889.34	11096.9459	442033.398			
26		Average	42.6	9217.3	185.3		SSE	7766742.35	SSE	4946832.64			
27		Std.Dev.	18.0592259	2143.85855	64.384244								
28		UB	62.2	11143.0	227.3								
29		M+SD	60.6	11361.1	249.7								
30		Mean	42.6	9217.3	185.3								
31		M-SD	24.5	7073.4	120.9								
32		LB	0.0	3853.5	0.0								
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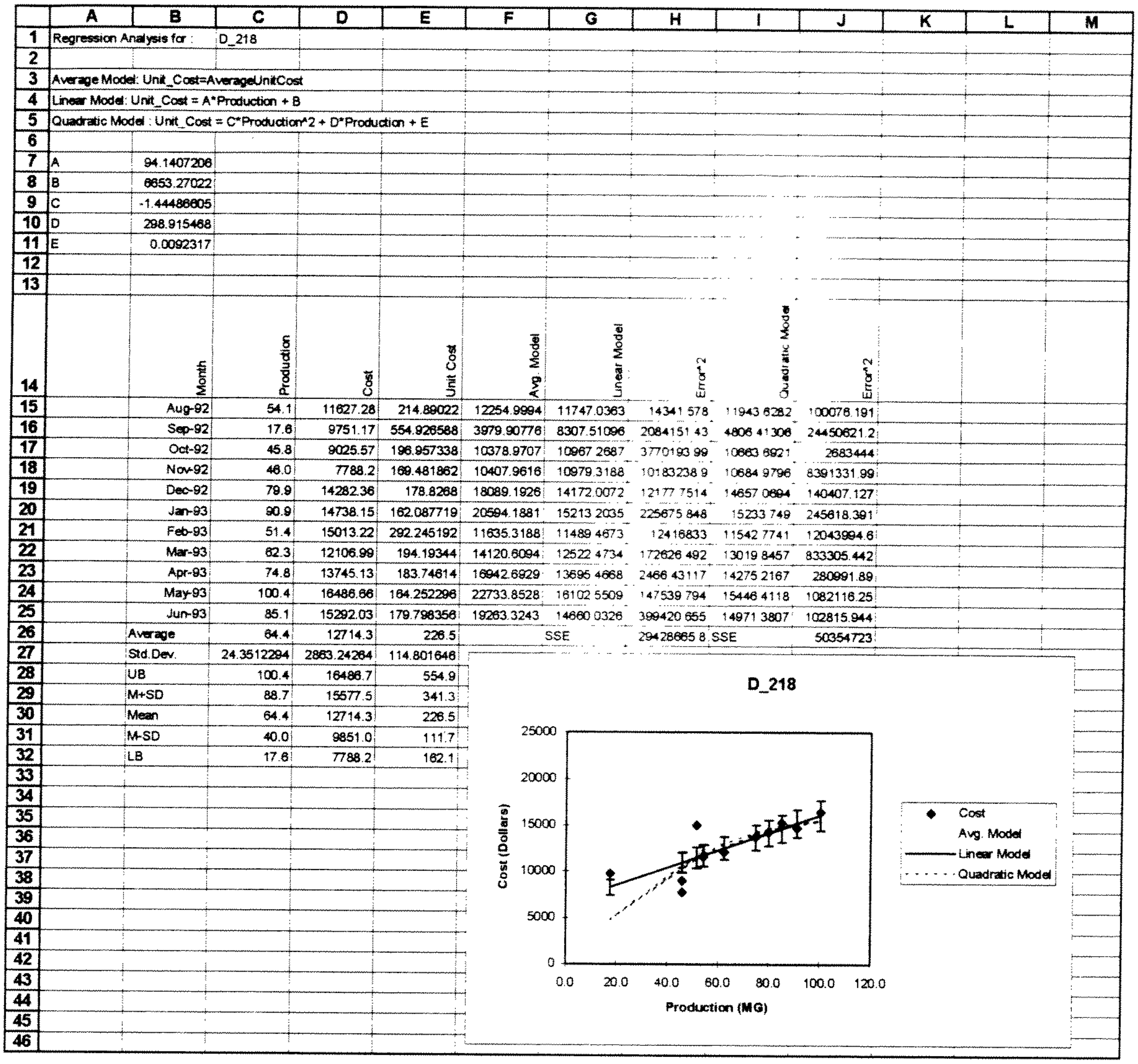
Figure 2.16 D-184 Production Cost Analysis

The figure for D-184shows that the linear cost model is a reasonable predictor of the cost-production relationship for this plant. 80% of the historical values are captured within the 20% variation range of the model. The other two models are reasonable predictors of the historical behavior except at the lowest production value.



	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Regression Analysis for :		D_218										
2													
3	Average Model: Unit_Cost=AverageUnitCost												
4	Linear Model: Unit_Cost = A*Production + B												
5	Quadratic Model : Unit_Cost = C*Production^2 + D*Production + E												
6													
7	A	94.1407206											
8	B	8653.27022											
9	C	-1.44486605											
10	D	298.915468											
11	E	0.0092317											
12													
13													
14		Month	Production	Cost	Unit Cost	Avg. Model	Linear Model	Error^2	Quadratic Model	Error^2			
15		Aug-92	54.1	11627.28	214.89022	12254.9994	11747.0363	14341.578	11943.6282	100078.191			
16		Sep-92	17.6	9751.17	554.926588	3979.90776	8307.51096	2084151.43	4806.41306	24450621.2			
17		Oct-92	45.8	9025.57	196.957338	10378.9707	10967.2687	3770193.99	10663.6921	2683444			
18		Nov-92	46.0	7788.2	169.481862	10407.9616	10979.3188	10183238.9	10684.9796	8391331.99			
19		Dec-92	79.9	14282.36	178.8268	18089.1926	14172.0072	12177.7514	14657.0694	140407.127			
20		Jan-93	90.9	14738.15	162.087719	20594.1881	15213.2035	225675.848	15233.749	245618.391			
21		Feb-93	51.4	15013.22	292.245192	11635.3188	11489.4673	12416833	11542.7741	12043994.6			
22		Mar-93	62.3	12106.99	194.19344	14120.6094	12522.4734	172626.492	13019.8457	833305.442			
23		Apr-93	74.8	13745.13	183.74614	16942.6929	13695.4668	2466.43117	14275.2167	280991.89			
24		May-93	100.4	16486.66	164.252296	22733.8528	16102.5509	147539.794	15446.4118	1082116.25			
25		Jun-93	85.1	15292.03	179.798356	19263.3243	14660.0326	399420.655	14971.3807	102815.944			
26		Average	64.4	12714.3	226.5	SSE		29428665.8	SSE	50354723			
27		Std.Dev.	24.3512294	2863.24264	114.801646								
28		UB	100.4	16486.7	554.9								
29		M+SD	88.7	15577.5	341.3								
30		Mean	64.4	12714.3	226.5								
31		M-SD	40.0	9851.0	111.7								
32		LB	17.6	7788.2	162.1								
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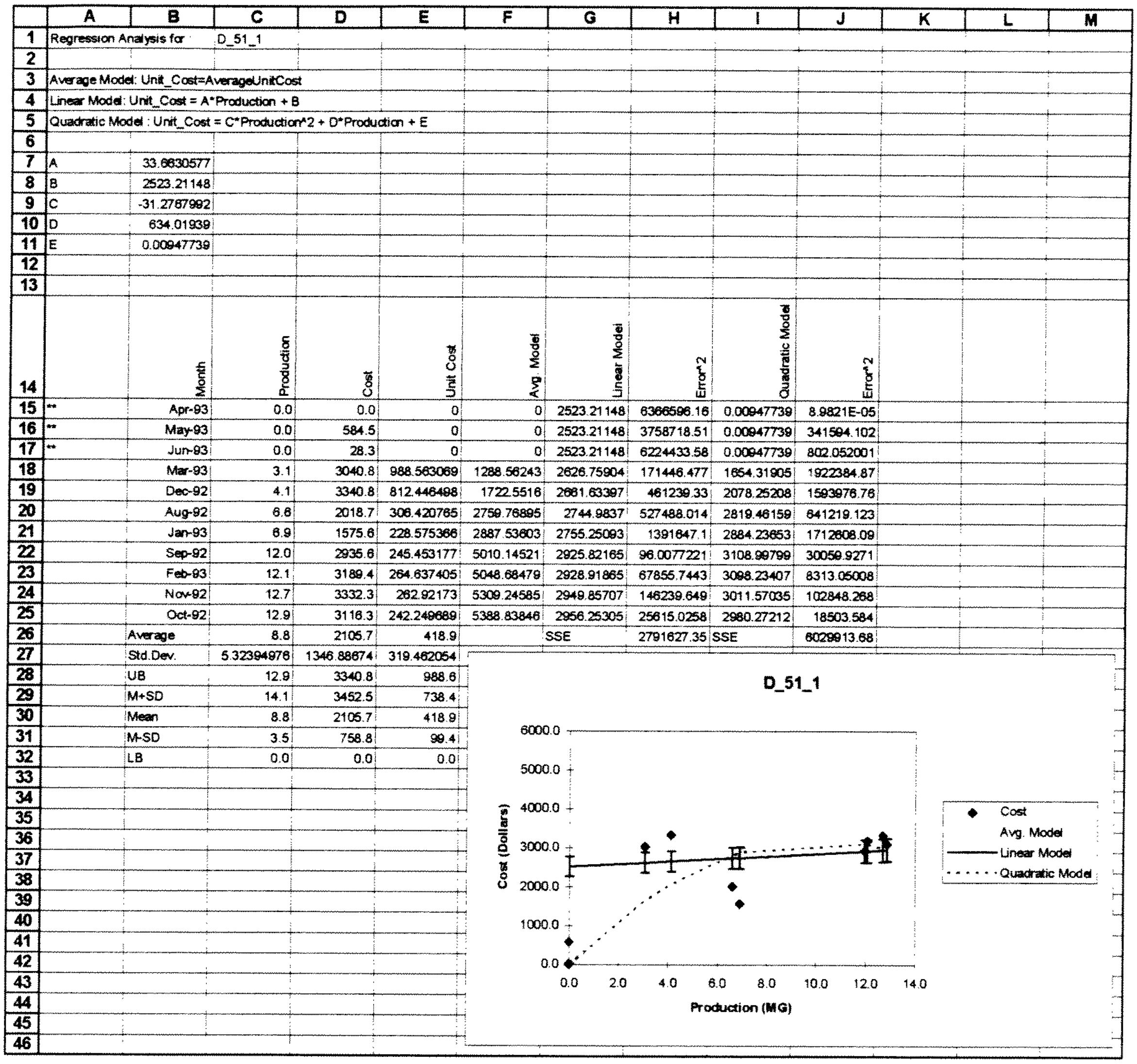
Figure 2.17 D-218 Production Cost Analysis

The figure for D-218 shows that the linear cost model is a reasonable predictor of the cost-production relationship for this plant. 70% of the historical values are captured within the 20% variation range of the model.



	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Regression Analysis for		D_51_1										
2													
3	Average Model: Unit_Cost=AverageUnitCost												
4	Linear Model: Unit_Cost = A*Production + B												
5	Quadratic Model : Unit_Cost = C*Production^2 + D*Production + E												
6													
7	A	33.6630577											
8	B	2523.21148											
9	C	-31.2767992											
10	D	634.01939											
11	E	0.00947739											
12													
13													
14		Month	Production	Cost	Unit Cost	Avg. Model	Linear Model	Error^2	Quadratic Model	Error^2			
15	**	Apr-93	0.0	0.0	0	0	2523.21148	6366596.16	0.00947739	8.9821E-05			
16	**	May-93	0.0	584.5	0	0	2523.21148	3758718.51	0.00947739	341594.102			
17	**	Jun-93	0.0	28.3	0	0	2523.21148	6224433.58	0.00947739	802.052001			
18		Mar-93	3.1	3040.8	988.563069	1288.56243	2626.75904	171446.477	1654.31905	1922384.87			
19		Dec-92	4.1	3340.8	812.446498	1722.5516	2661.63397	461239.33	2078.25208	1593976.76			
20		Aug-92	6.6	2018.7	306.420765	2759.76895	2744.9837	527488.014	2819.46159	641219.123			
21		Jan-93	6.9	1575.6	228.575366	2887.53603	2755.25093	1391647.1	2884.23653	1712608.09			
22		Sep-92	12.0	2935.6	245.453177	5010.14521	2925.82165	96.0077221	3108.99799	30059.9271			
23		Feb-93	12.1	3189.4	264.637405	5048.68479	2928.91865	67855.7443	3098.23407	8313.05008			
24		Nov-92	12.7	3332.3	262.92173	5309.24585	2949.85707	146239.649	3011.57035	102848.268			
25		Oct-92	12.9	3116.3	242.249689	5388.83846	2956.25305	25615.0258	2980.27212	18503.584			
26		Average	8.8	2105.7	418.9		SSE	2791627.35	SSE	6029913.68			
27		Std.Dev.	5.32394976	1346.88674	319.462054								
28		UB	12.9	3340.8	988.6								
29		M+SD	14.1	3452.5	738.4								
30		Mean	8.8	2105.7	418.9								
31		M-SD	3.5	758.8	99.4								
32		LB	0.0	0.0	0.0								
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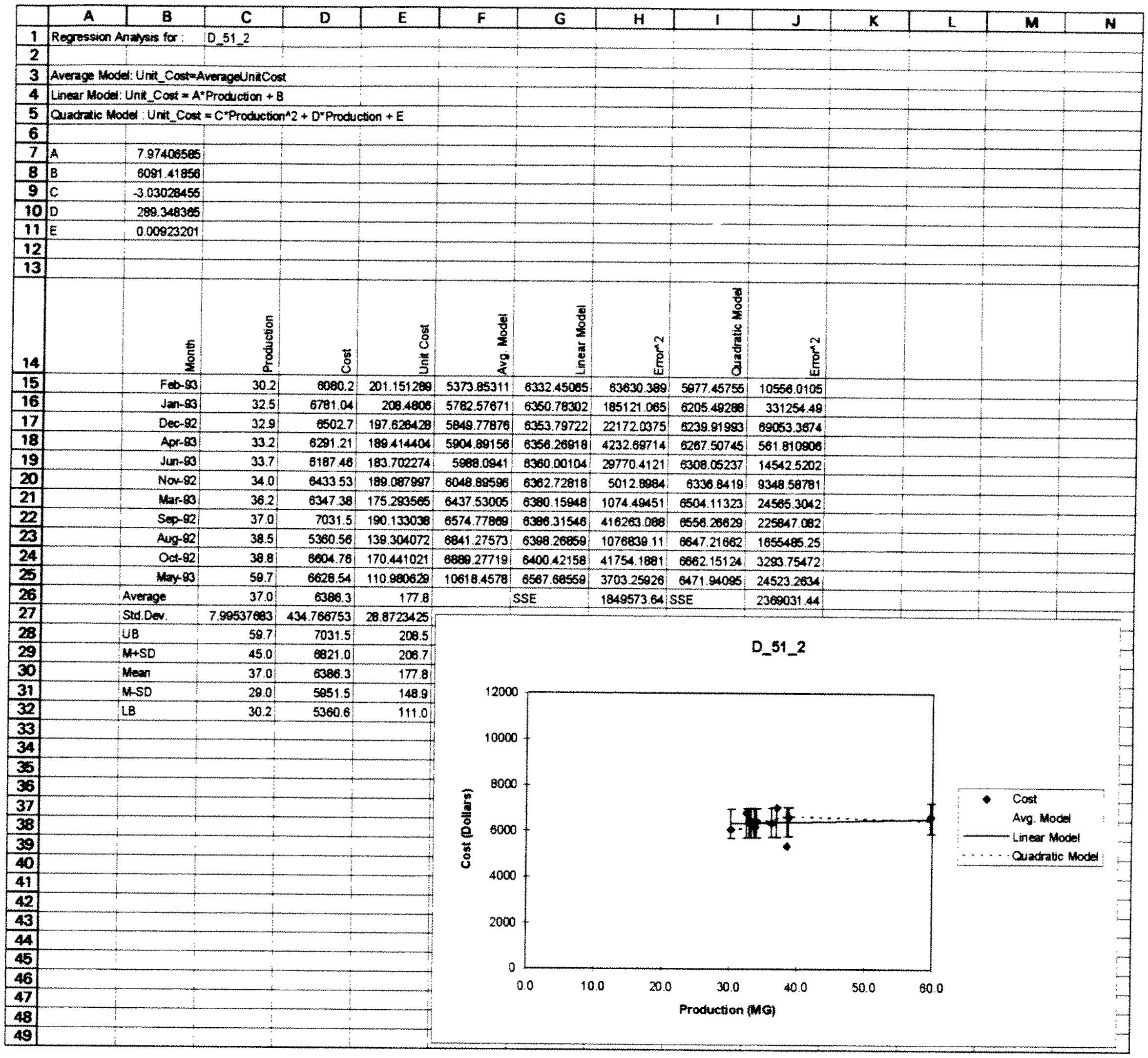
Figure 2.18 D-51-1 Production Cost Analysis

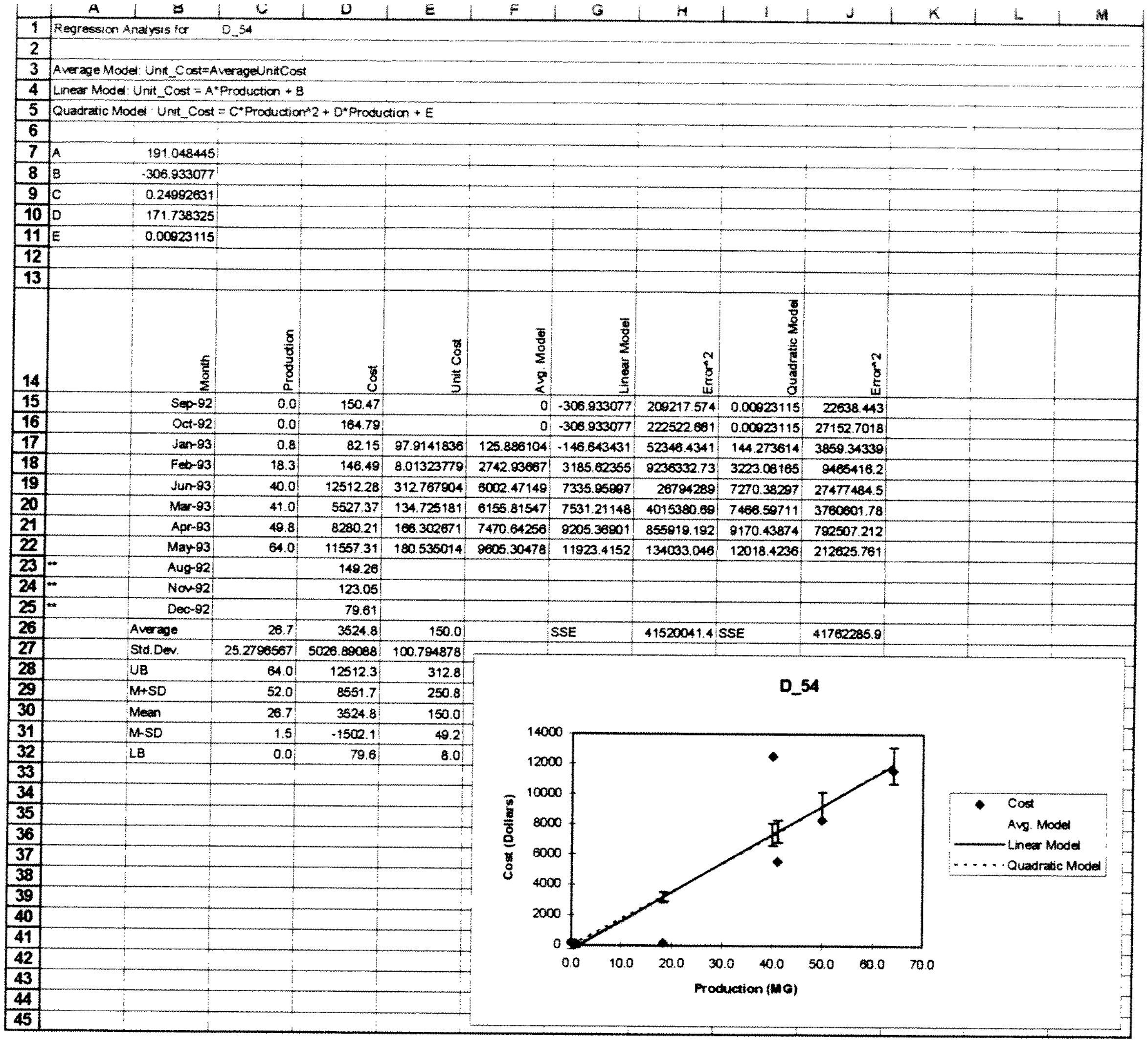
The figure for D-51-1 shows that none of the models perofrms well as a predictor for the cost-production relationship. The linear model does well at the high production rates, but only 40% of the historical values fall within the 20% variation bars for the linear model.



	A	B	C	D	E	F	G	H	I	J
1	Regression Analysis for :		D_51_2							
2										
3	Average Model: Unit_Cost=AverageUnitCost									
4	Linear Model: Unit_Cost = A*Production + B									
5	Quadratic Model : Unit_Cost = C*Production^2 + D*Production + E									
6										
7	A	7.97406585								
8	B	6091.41856								
9	C	-3.03028455								
10	D	289.348365								
11	E	0.00923201								
12										
13										
14		Month	Production	Cost	Unit Cost	Avg. Model	Linear Model	Error^2	Quadratic Model	Error^2
15		Feb-93	30.2	6080.2	201.151289	5373.85311	6332.45065	63630.389	5977.45755	10556.0105
16		Jan-93	32.5	6781.04	208.4806	5782.57671	6350.78302	185121.065	6205.49288	331254.49
17		Dec-92	32.9	6502.7	197.626428	5849.77876	6353.79722	22172.0375	6239.91993	69053.3674
18		Apr-93	33.2	6291.21	189.414404	5904.89156	6356.26918	4232.69714	6267.50745	561.810906
19		Jun-93	33.7	6187.46	183.702274	5988.0941	6360.00104	29770.4121	6308.05237	14542.5202
20		Nov-92	34.0	6433.53	189.087997	6048.89596	6362.72818	5012.8984	6336.8419	9348.58781
21		Mar-93	36.2	6347.38	175.293565	6437.53005	6380.15948	1074.49451	6504.11323	24565.3042
22		Sep-92	37.0	7031.5	190.133038	6574.77869	6386.31546	416263.088	6556.26629	225847.082
23		Aug-92	38.5	5360.56	139.304072	6841.27573	6398.26859	1076839.11	6647.21662	1655485.25
24		Oct-92	38.8	6604.76	170.441021	6889.27719	6400.42158	41754.1881	6662.15124	3293.75472
25		May-93	59.7	6628.54	110.980629	10618.4578	6567.68559	3703.25926	6471.94095	24523.2634
26		Average	37.0	6386.3	177.8		SSE	1849573.64	SSE	2369031.44
27		Std.Dev.	7.99537683	434.766753	28.8723425					
28		UB	59.7	7031.5	208.5					
29		M+SD	45.0	6821.0	206.7					
30		Mean	37.0	6386.3	177.8					
31		M-SD	29.0	5951.5	148.9					
32		LB	30.2	5360.6	111.0					

Figure 2.19 D-51-2 Production Cost Analysis

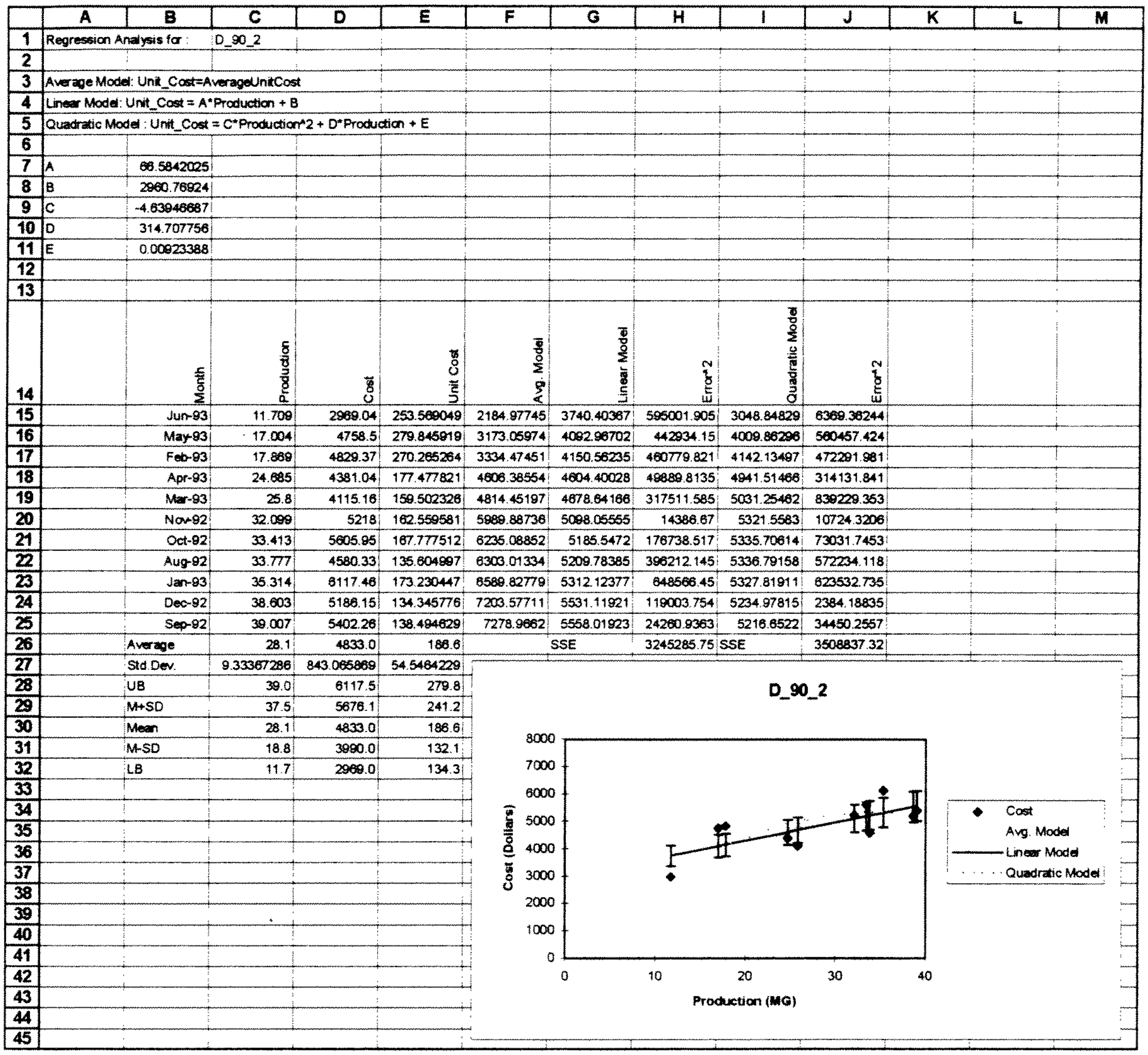
The figure shows that the linear cost model performs adequately for this plant. The average cost model performs adequately for most of the historical range of production values, but way overpredicts at the high production values (nearly 100% at the highest value).



	A	B	C	D	E	F	G	H	I	J
1	Regression Analysis for	D_54								
2										
3	Average Model: Unit_Cost=AverageUnitCost									
4	Linear Model: Unit_Cost = A*Production + B									
5	Quadratic Model : Unit_Cost = C*Production^2 + D*Production + E									
6										
7	A	191.048445								
8	B	-306.933077								
9	C	0.24992631								
10	D	171.738325								
11	E	0.00923115								
12										
13										
14		Month	Production	Cost	Unit Cost	Avg. Model	Linear Model	Error^2	Quadratic Model	Error^2
15		Sep-92	0.0	150.47		0	-306.933077	209217.574	0.00923115	22638.443
16		Oct-92	0.0	164.79		0	-306.933077	222522.681	0.00923115	27152.7018
17		Jan-93	0.8	82.15	97.9141836	125.886104	-146.643431	52346.4341	144.273614	3859.34339
18		Feb-93	18.3	146.49	8.01323779	2742.93667	3185.62355	9236332.73	3223.08165	9465416.2
19		Jun-93	40.0	12512.28	312.767904	6002.47149	7335.95997	26794289	7270.38297	27477484.5
20		Mar-93	41.0	5527.37	134.725181	6155.81547	7531.21148	4015380.69	7466.59711	3760601.78
21		Apr-93	49.8	8280.21	166.302671	7470.64256	9205.36901	855919.192	9170.43874	792507.212
22		May-93	64.0	11557.31	180.535014	9605.30478	11923.4152	134033.046	12018.4236	212625.761
23	**	Aug-92		149.26						
24	**	Nov-92		123.05						
25	**	Dec-92		79.61						
26		Average	26.7	3524.8	150.0		SSE	41520041.4	SSE	41762285.9
27		Std.Dev.	25.2796567	5026.89088	100.794878					
28		UB	64.0	12512.3	312.8					
29		M+SD	52.0	8551.7	250.8					
30		Mean	26.7	3524.8	150.0					
31		M-SD	1.5	-1502.1	49.2					
32		LB	0.0	79.6	8.0					

Figure 2.20 D-54 Production Cost Analysis

The figure shows that all three models perform that same, none really adequately. Thne number of data pairs for analysis of this plant are insufficient for the type of analysis performed and the average cost model is probably as good as any model for this case.



Regression Analysis for : D_90_2

Average Model: Unit_Cost=AverageUnitCost

Linear Model: Unit_Cost = A*Production + B

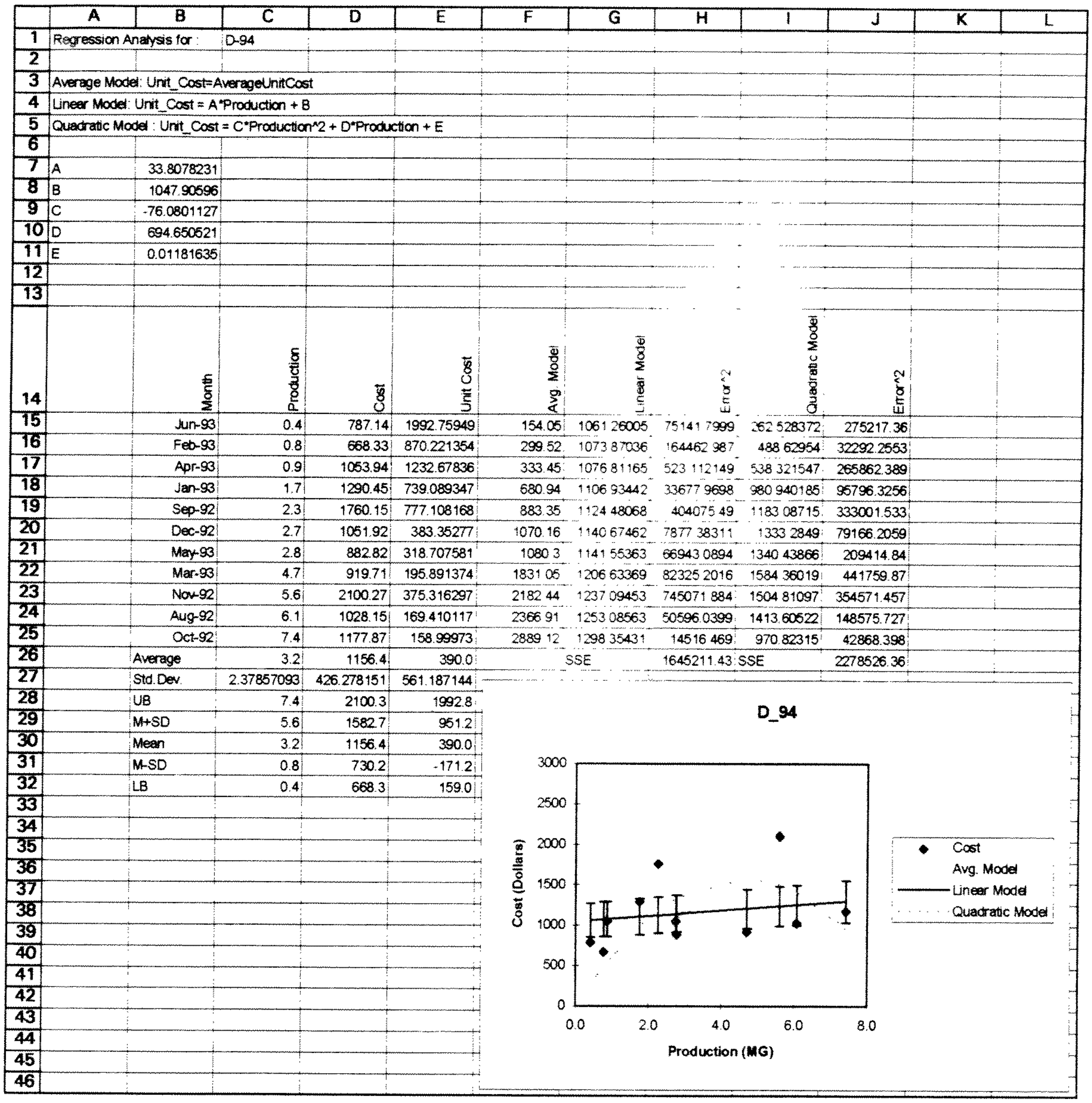
Quadratic Model : Unit_Cost = C*Production^2 + D*Production + E

A	66.5842025
B	2960.76924
C	-4.63946687
D	314.707756
E	0.00923388

Month	Production	Cost	Unit Cost	Avg. Model	Linear Model	Error^2	Quadratic Model	Error^2
Jun-93	11.709	2969.04	253.569049	2184.97745	3740.40367	595001.905	3048.84829	6369.38244
May-93	17.004	4758.5	279.845919	3173.05974	4092.96702	442934.15	4009.86296	560457.424
Feb-93	17.869	4829.37	270.265264	3334.47451	4150.56235	460779.821	4142.13497	472291.981
Apr-93	24.685	4381.04	177.477821	4606.38554	4604.40028	49889.8135	4941.51466	314131.841
Mar-93	25.8	4115.16	159.502326	4814.45197	4678.64166	317511.585	5031.25462	839229.353
Nov-92	32.099	5218	162.559581	5989.88736	5098.05555	14386.67	5321.5583	10724.3206
Oct-92	33.413	5605.95	167.777512	6235.08852	5185.5472	176738.517	5335.70614	73031.7453
Aug-92	33.777	4580.33	135.604997	6303.01334	5209.78385	396212.145	5336.79158	572234.118
Jan-93	35.314	6117.46	173.230447	6589.82779	5312.12377	648566.45	5327.81911	623532.735
Dec-92	38.603	5186.15	134.345776	7203.57711	5531.11921	119003.754	5234.97815	2384.18835
Sep-92	39.007	5402.26	138.494629	7278.9662	5558.01923	24260.9363	5216.6522	34450.2557
Average	28.1	4833.0	186.6		SSE	3245285.75	SSE	3508837.32
Std.Dev.	9.33367286	843.065869	54.5464229					
UB	39.0	6117.5	279.8					
M+SD	37.5	5676.1	241.2					
Mean	28.1	4833.0	186.6					
M-SD	18.8	3990.0	132.1					
LB	11.7	2969.0	134.3					

Figure 2.21 D-90-2 Production Cost Analysis

The figure for D-90-2 shows that all three models are good predictors of the cost-production relationship for this plant. The average cost model overpredicts by 40% at the extreme ranges of historical values. The linear cost model captures 70% of the historical data within a 20% variation range of the model.



	A	B	C	D	E	F	G	H	I	J	K	L
1	Regression Analysis for :		D-94									
2												
3	Average Model: Unit_Cost=AverageUnitCost											
4	Linear Model: Unit_Cost = A*Production + B											
5	Quadratic Model : Unit_Cost = C*Production^2 + D*Production + E											
6												
7	A	33.8078231										
8	B	1047.90596										
9	C	-76.0801127										
10	D	694.650521										
11	E	0.01181635										
12												
13												
14		Month	Production	Cost	Unit Cost	Avg. Model	Linear Model	Error^2	Quadratic Model	Error^2		
15		Jun-93	0.4	787.14	1992.75949	154.05	1061.26005	75141.7999	262.528372	275217.36		
16		Feb-93	0.8	668.33	870.221354	299.52	1073.87036	164462.987	488.62954	32292.2553		
17		Apr-93	0.9	1053.94	1232.67836	333.45	1076.81165	523.112149	538.321547	265862.389		
18		Jan-93	1.7	1290.45	739.089347	680.94	1106.93442	33677.9698	980.940185	95796.3256		
19		Sep-92	2.3	1760.15	777.108168	883.35	1124.48068	404075.49	1183.08715	333001.533		
20		Dec-92	2.7	1051.92	383.35277	1070.16	1140.67462	7877.38311	1333.2849	79166.2059		
21		May-93	2.8	882.82	318.707581	1080.3	1141.55363	66943.0894	1340.43866	209414.84		
22		Mar-93	4.7	919.71	195.891374	1831.05	1206.63369	82325.2016	1584.36019	441759.87		
23		Nov-92	5.6	2100.27	375.316297	2182.44	1237.09453	745071.884	1504.81097	354571.457		
24		Aug-92	6.1	1028.15	169.410117	2366.91	1253.08563	50596.0399	1413.60522	148575.727		
25		Oct-92	7.4	1177.87	158.99973	2889.12	1298.35431	14516.469	970.82315	42868.398		
26		Average	3.2	1156.4	390.0		SSE	1645211.43	SSE	2278526.36		
27		Std.Dev.	2.37857093	426.278151	561.187144							
28		UB	7.4	2100.3	1992.8							
29		M+SD	5.6	1582.7	951.2							
30		Mean	3.2	1156.4	390.0							
31		M-SD	0.8	730.2	-171.2							
32		LB	0.4	668.3	159.0							
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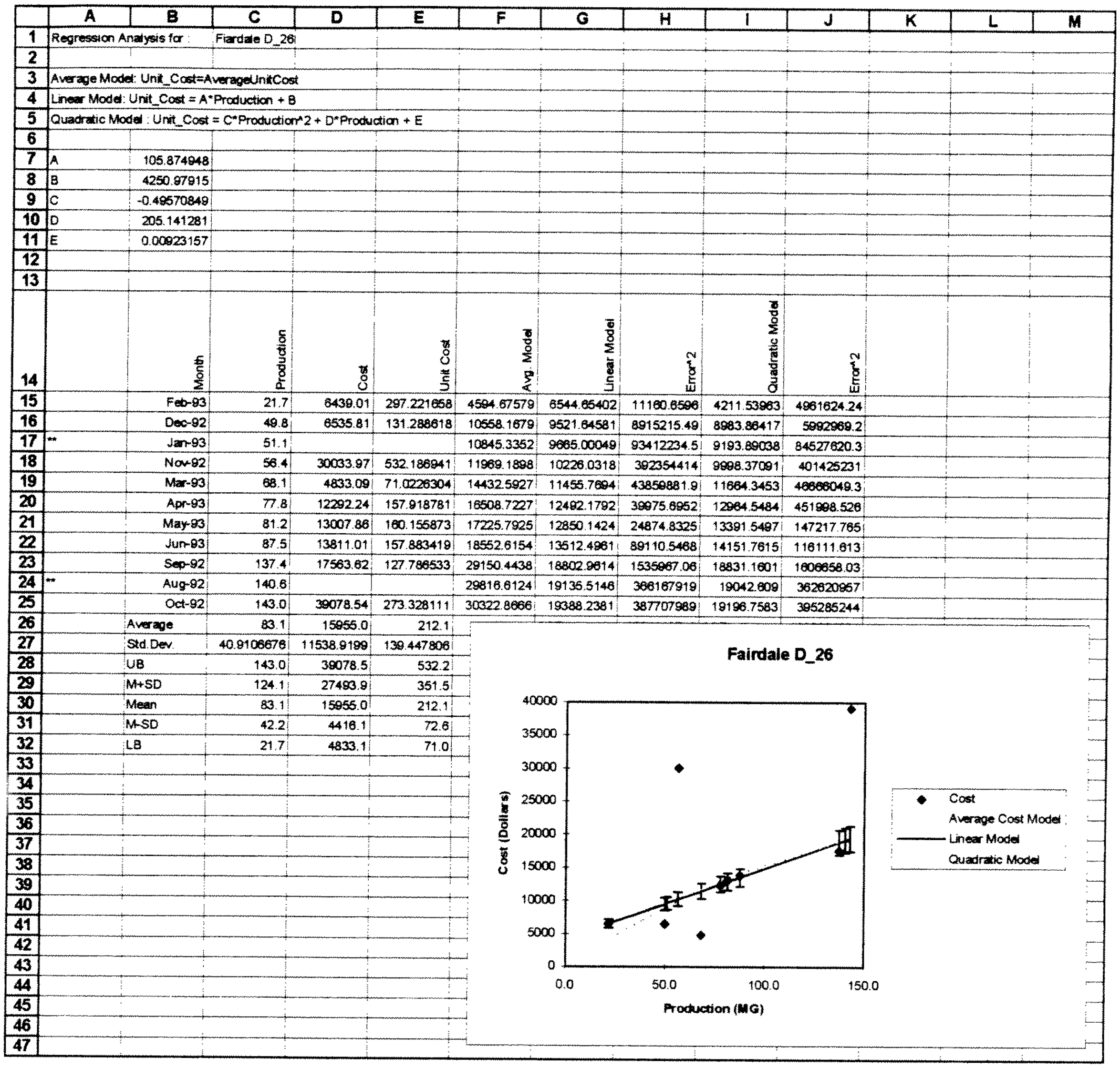
Figure 2.22 D-94 Production Cost Analysis

The figure for D-94 shows that the linear cost model is a reasonable predictor of the cost-production relationship for this plant. 70% of the data fall within the 20% variation range of the model. The average cost and quadratic cost model do perform well for this plant.



	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Regression Analysis for :		Fiardale D_26										
2													
3	Average Model: Unit_Cost=AverageUnitCost												
4	Linear Model: Unit_Cost = A*Production + B												
5	Quadratic Model : Unit_Cost = C*Production^2 + D*Production + E												
6													
7	A	105.874948											
8	B	4250.97915											
9	C	-0.49570849											
10	D	205.141281											
11	E	0.00923157											
12													
13													
14		Month	Production	Cost	Unit Cost	Avg. Model	Linear Model	Error^2	Quadratic Model	Error^2			
15		Feb-93	21.7	6439.01	297.221658	4594.67579	6544.65402	11160.6596	4211.53963	4961624.24			
16		Dec-92	49.8	6535.81	131.288618	10558.1679	9521.64581	8915215.49	8983.86417	5992969.2			
17	**	Jan-93	51.1			10845.3352	9665.00049	93412234.5	9193.89038	84527620.3			
18		Nov-92	56.4	30033.97	532.186941	11969.1898	10226.0318	392354414	9998.37091	401425231			
19		Mar-93	68.1	4833.09	71.0226304	14432.5927	11455.7694	43859881.9	11664.3453	46666049.3			
20		Apr-93	77.8	12292.24	157.918781	16508.7227	12492.1792	39975.6952	12964.5484	451998.526			
21		May-93	81.2	13007.86	160.155873	17225.7925	12850.1424	24874.8325	13391.5497	147217.765			
22		Jun-93	87.5	13811.01	157.883419	18552.6154	13512.4961	89110.5468	14151.7615	116111.613			
23		Sep-92	137.4	17563.62	127.786533	29150.4438	18802.9614	1535967.06	18831.1601	1606658.03			
24	**	Aug-92	140.6			29816.6124	19135.5146	366167919	19042.609	362620957			
25		Oct-92	143.0	39078.54	273.328111	30322.8666	19388.2381	387707989	19196.7583	395285244			
26		Average	83.1	15955.0	212.1								
27		Std.Dev.	40.9106676	11538.9199	139.447806								
28		UB	143.0	39078.5	532.2								
29		M+SD	124.1	27493.9	351.5								
30		Mean	83.1	15955.0	212.1								
31		M-SD	42.2	4416.1	72.6								
32		LB	21.7	4833.1	71.0								
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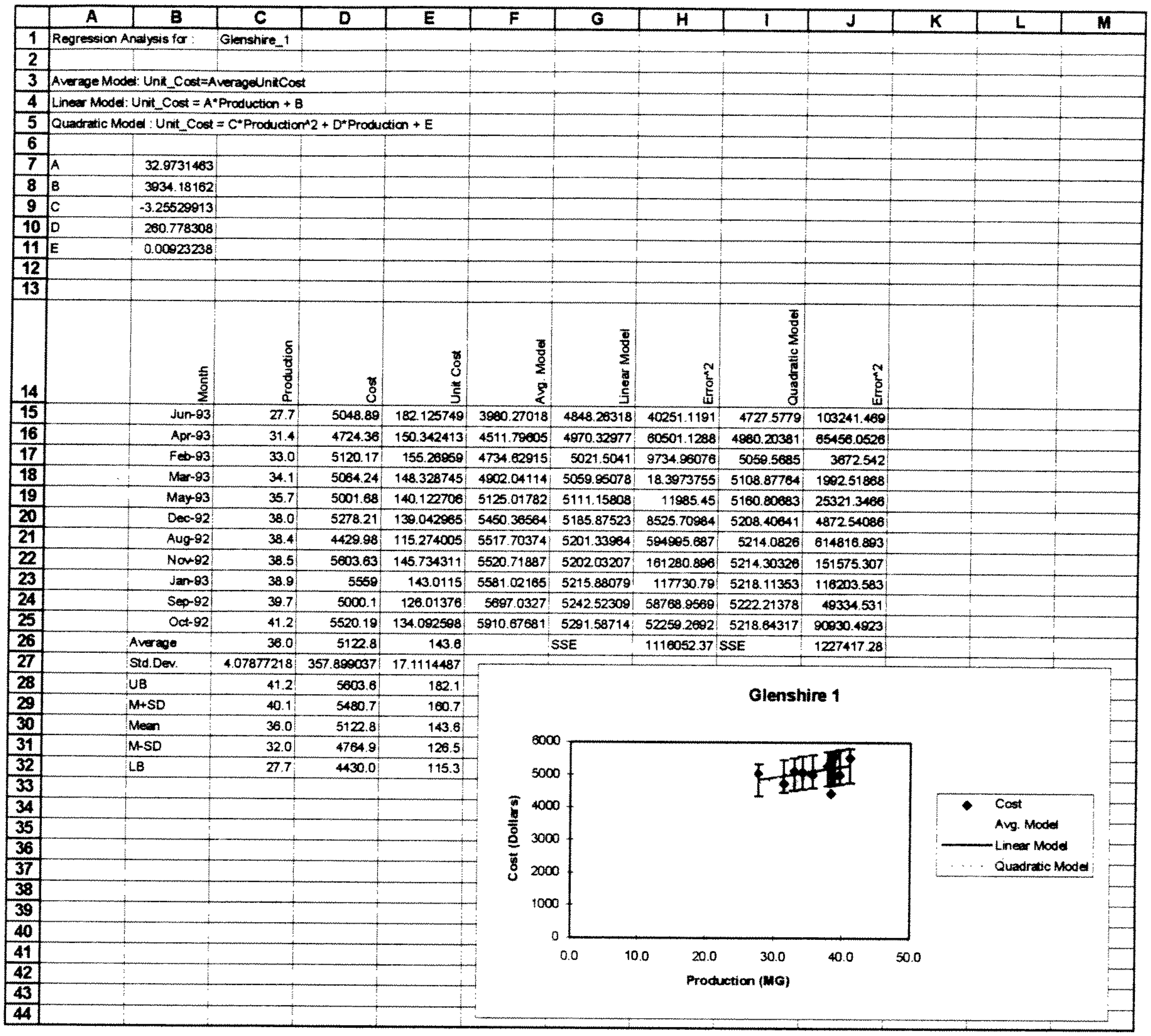
Figure 2.23 Fairdale D-26 Production Cost Analysis

The figure for Fairdale D-26 shows that none of the models are good predictors of the cost-production relationship. The historical data are scattered with three outlying points that suggest that costs were charged to other plants or incorrectly tabulated in three of the reviewed periods. Ignoring these three points, one would choose the linear or quadratic cost model as acceptable prediction models.



	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Regression Analysis for :		Glenshire_1										
2													
3	Average Model: Unit_Cost=AverageUnitCost												
4	Linear Model: Unit_Cost = A*Production + B												
5	Quadratic Model : Unit_Cost = C*Production^2 + D*Production + E												
6													
7	A	32.9731463											
8	B	3934.18162											
9	C	-3.25529913											
10	D	260.778308											
11	E	0.00923238											
12													
13													
14		Month	Production	Cost	Unit Cost	Avg. Model	Linear Model	Error^2	Quadratic Model	Error^2			
15		Jun-93	27.7	5048.89	182.125749	3980.27018	4848.26318	40251.1191	4727.5779	103241.469			
16		Apr-93	31.4	4724.36	150.342413	4511.79605	4970.32977	60501.1288	4960.20381	65456.0526			
17		Feb-93	33.0	5120.17	155.26959	4734.62915	5021.5041	9734.96076	5059.5685	3672.542			
18		Mar-93	34.1	5064.24	148.328745	4902.04114	5059.95078	18.3973755	5108.87764	1992.51868			
19		May-93	35.7	5001.68	140.122706	5125.01782	5111.15808	11985.45	5160.80683	25321.3466			
20		Dec-92	38.0	5278.21	139.042965	5450.36564	5185.87523	8525.70984	5208.40641	4872.54086			
21		Aug-92	38.4	4429.98	115.274005	5517.70374	5201.33964	594995.687	5214.0826	614816.893			
22		Nov-92	38.5	5603.63	145.734311	5520.71887	5202.03207	161280.896	5214.30326	151575.307			
23		Jan-93	38.9	5559	143.0115	5581.02165	5215.88079	117730.79	5218.11353	116203.583			
24		Sep-92	39.7	5000.1	126.01376	5697.0327	5242.52309	58768.9569	5222.21378	49334.531			
25		Oct-92	41.2	5520.19	134.092598	5910.67681	5291.58714	52259.2692	5218.64317	90930.4923			
26		Average	36.0	5122.8	143.8		SSE	1116052.37	SSE	1227417.28			
27		Std.Dev.	4.07877218	357.899037	17.1114487								
28		UB	41.2	5603.6	182.1								
29		M+SD	40.1	5480.7	160.7								
30		Mean	36.0	5122.8	143.6								
31		M-SD	32.0	4764.9	126.5								
32		LB	27.7	4430.0	115.3								
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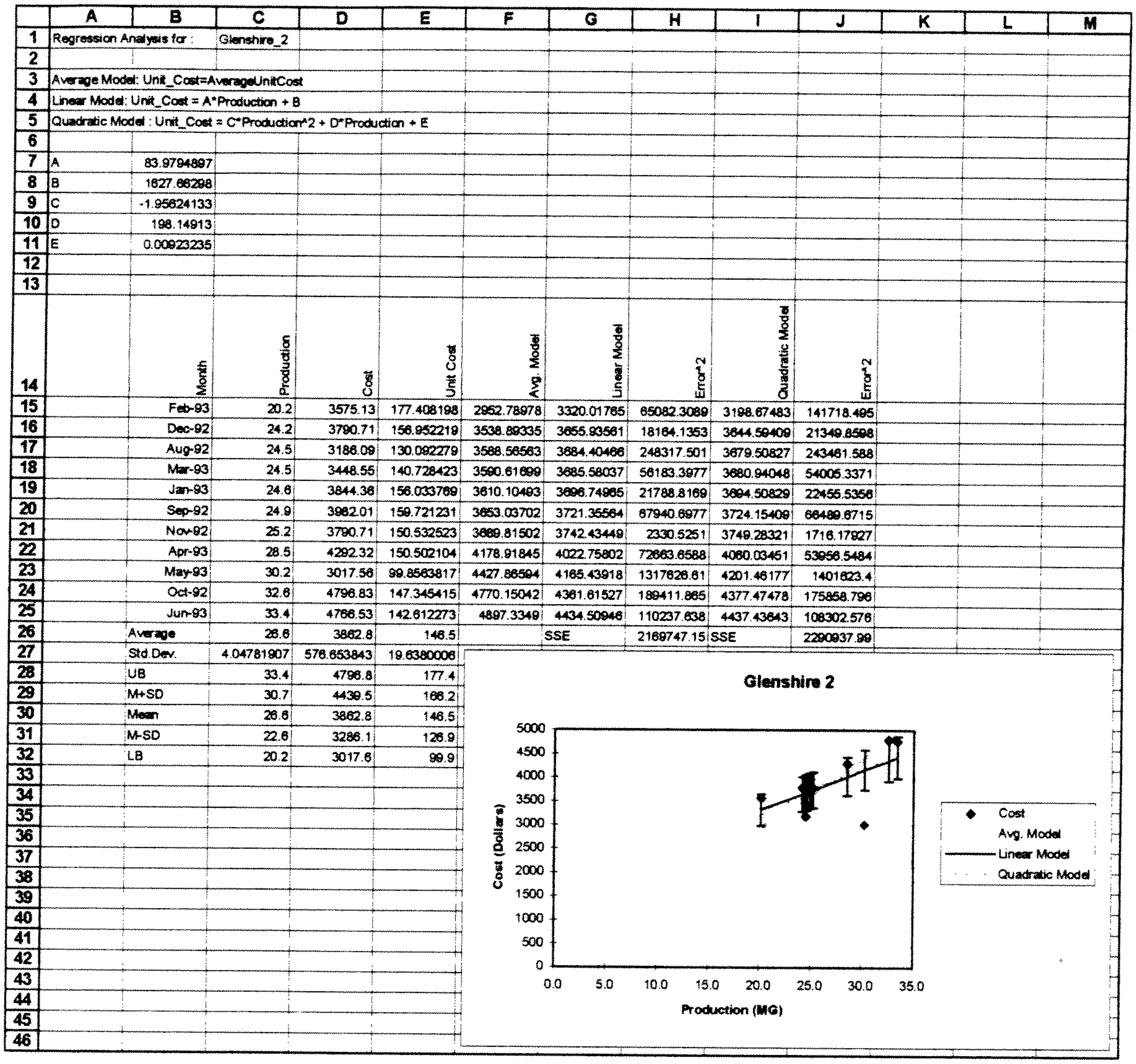
Figure 2.24 Glenshire 1 Production Cost Analysis

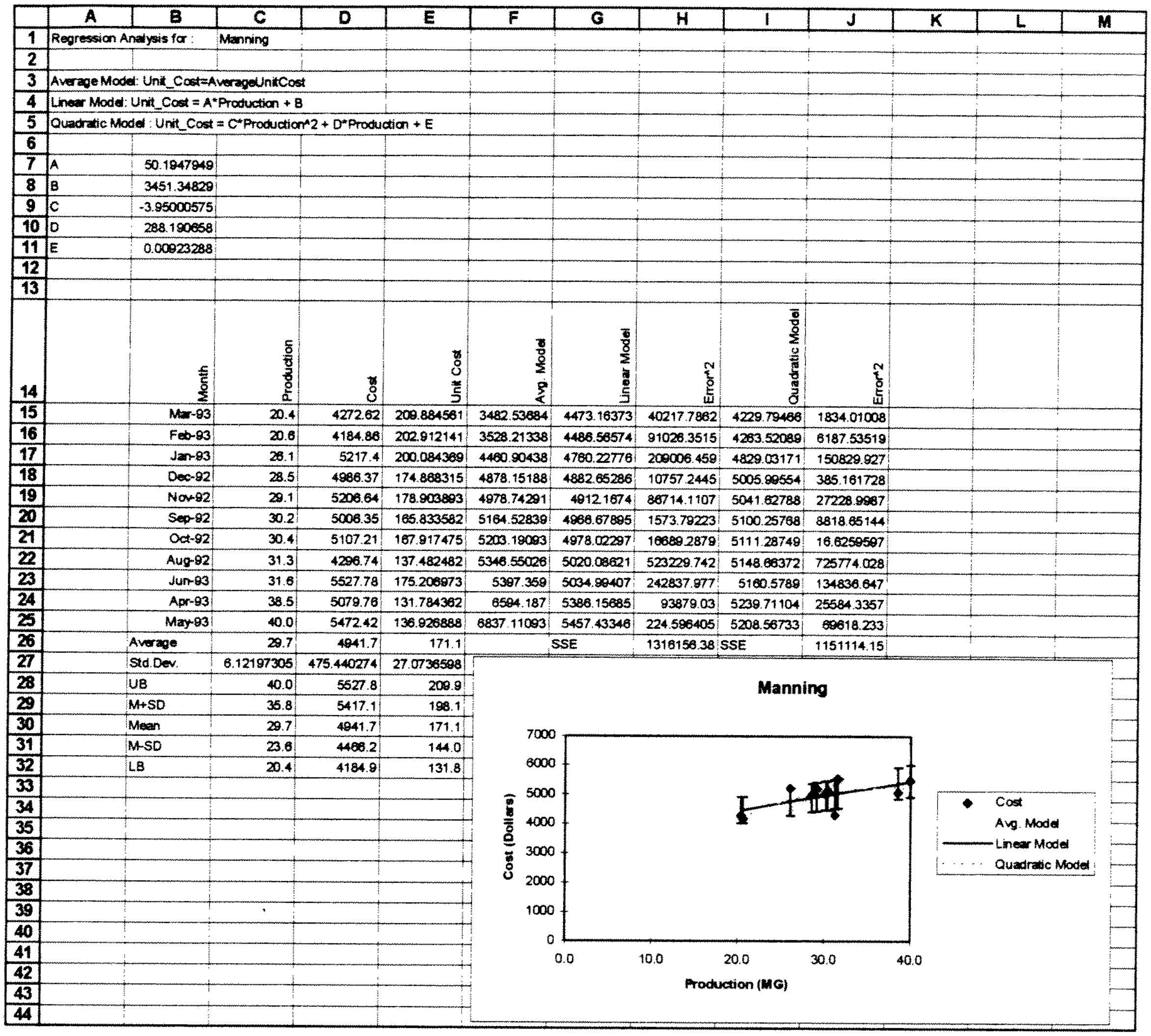
The figure for Glenshire 1 shows that all the linear cost and quadratic cost models are good predictors of the historical cost-production relationship. The average cost model is acceptable, underpredicting at the low end of historical production and overpredicting by about 30% at the extreme ranges of the historical production values.



	A	B	C	D	E	F	G	H	I	J
1	Regression Analysis for :		Glenshire_2							
2										
3	Average Model: Unit_Cost=AverageUnitCost									
4	Linear Model: Unit_Cost = A*Production + B									
5	Quadratic Model : Unit_Cost = C*Production^2 + D*Production + E									
6										
7	A	83.9794897								
8	B	1627.66298								
9	C	-1.95624133								
10	D	198.14913								
11	E	0.00923235								
12										
13										
14		Month	Production	Cost	Unit Cost	Avg. Model	Linear Model	Error^2	Quadratic Model	Error^2
15		Feb-93	20.2	3575.13	177.408198	2952.78978	3320.01765	65082.3089	3198.67483	141718.495
16		Dec-92	24.2	3790.71	156.952219	3538.89335	3655.93561	18164.1353	3644.59409	21349.8598
17		Aug-92	24.5	3186.09	130.092279	3588.56563	3684.40466	248317.501	3679.50827	243461.588
18		Mar-93	24.5	3448.55	140.728423	3590.61699	3685.58037	56183.3977	3680.94048	54005.3371
19		Jan-93	24.6	3844.36	156.033769	3610.10493	3696.74965	21788.8169	3694.50829	22455.5356
20		Sep-92	24.9	3982.01	159.721231	3653.03702	3721.35564	67940.6977	3724.15409	66489.6715
21		Nov-92	25.2	3790.71	150.532523	3689.81502	3742.43449	2330.5251	3749.28321	1716.17927
22		Apr-93	28.5	4292.32	150.502104	4178.91845	4022.75802	72663.6588	4060.03451	53956.5484
23		May-93	30.2	3017.56	99.8563817	4427.86594	4165.43918	1317628.61	4201.46177	1401623.4
24		Oct-92	32.6	4796.83	147.345415	4770.15042	4361.61527	189411.865	4377.47478	175858.796
25		Jun-93	33.4	4766.53	142.612273	4897.3349	4434.50946	110237.638	4437.43643	108302.576
26		Average	26.6	3862.8	146.5		SSE	2169747.15	SSE	2290937.99
27		Std.Dev.	4.04781907	576.653843	19.6380006					
28		UB	33.4	4796.8	177.4					
29		M+SD	30.7	4439.5	166.2					
30		Mean	26.6	3862.8	146.5					
31		M-SD	22.6	3286.1	126.9					
32		LB	20.2	3017.6	99.9					

Figure 2.25 Glenshire 2 Production Cost Analysis

The figure forGlenshire 2 shows that all the models are good predictors of the historical cost-production relationship.



	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Regression Analysis for :		Manning										
2													
3	Average Model: Unit_Cost=AverageUnitCost												
4	Linear Model: Unit_Cost = A*Production + B												
5	Quadratic Model : Unit_Cost = C*Production^2 + D*Production + E												
6													
7	A	50.1947949											
8	B	3451.34829											
9	C	-3.95000575											
10	D	288.190658											
11	E	0.00923288											
12													
13													
14		Month	Production	Cost	Unit Cost	Avg. Model	Linear Model	Error^2	Quadratic Model	Error^2			
15		Mar-93	20.4	4272.62	209.884561	3482.53684	4473.16373	40217.7862	4229.79466	1834.01008			
16		Feb-93	20.6	4184.86	202.912141	3528.21338	4486.56574	91026.3515	4263.52089	6187.53519			
17		Jan-93	26.1	5217.4	200.084369	4460.90438	4760.22776	209006.459	4829.03171	150829.927			
18		Dec-92	28.5	4986.37	174.868315	4878.15188	4882.65286	10757.2445	5005.99554	385.161728			
19		Nov-92	29.1	5206.64	178.903893	4978.74291	4912.1674	86714.1107	5041.62788	27228.9987			
20		Sep-92	30.2	5006.35	165.833582	5164.52839	4966.67895	1573.79223	5100.25768	8818.65144			
21		Oct-92	30.4	5107.21	167.917475	5203.19093	4978.02297	16689.2879	5111.28749	16.6259597			
22		Aug-92	31.3	4296.74	137.482482	5346.55026	5020.08621	523229.742	5148.66372	725774.028			
23		Jun-93	31.6	5527.78	175.208973	5397.359	5034.99407	242837.977	5160.5789	134836.647			
24		Apr-93	38.5	5079.76	131.784362	6594.187	5386.15685	93879.03	5239.71104	25584.3357			
25		May-93	40.0	5472.42	136.926888	6837.11093	5457.43346	224.596405	5208.56733	69618.233			
26		Average	29.7	4941.7	171.1		SSE	1316156.38	SSE	1151114.15			
27		Std.Dev.	6.12197305	475.440274	27.0736598								
28		UB	40.0	5527.8	209.9								
29		M+SD	35.8	5417.1	198.1								
30		Mean	29.7	4941.7	171.1								
31		M-SD	23.6	4466.2	144.0								
32		LB	20.4	4184.9	131.8								
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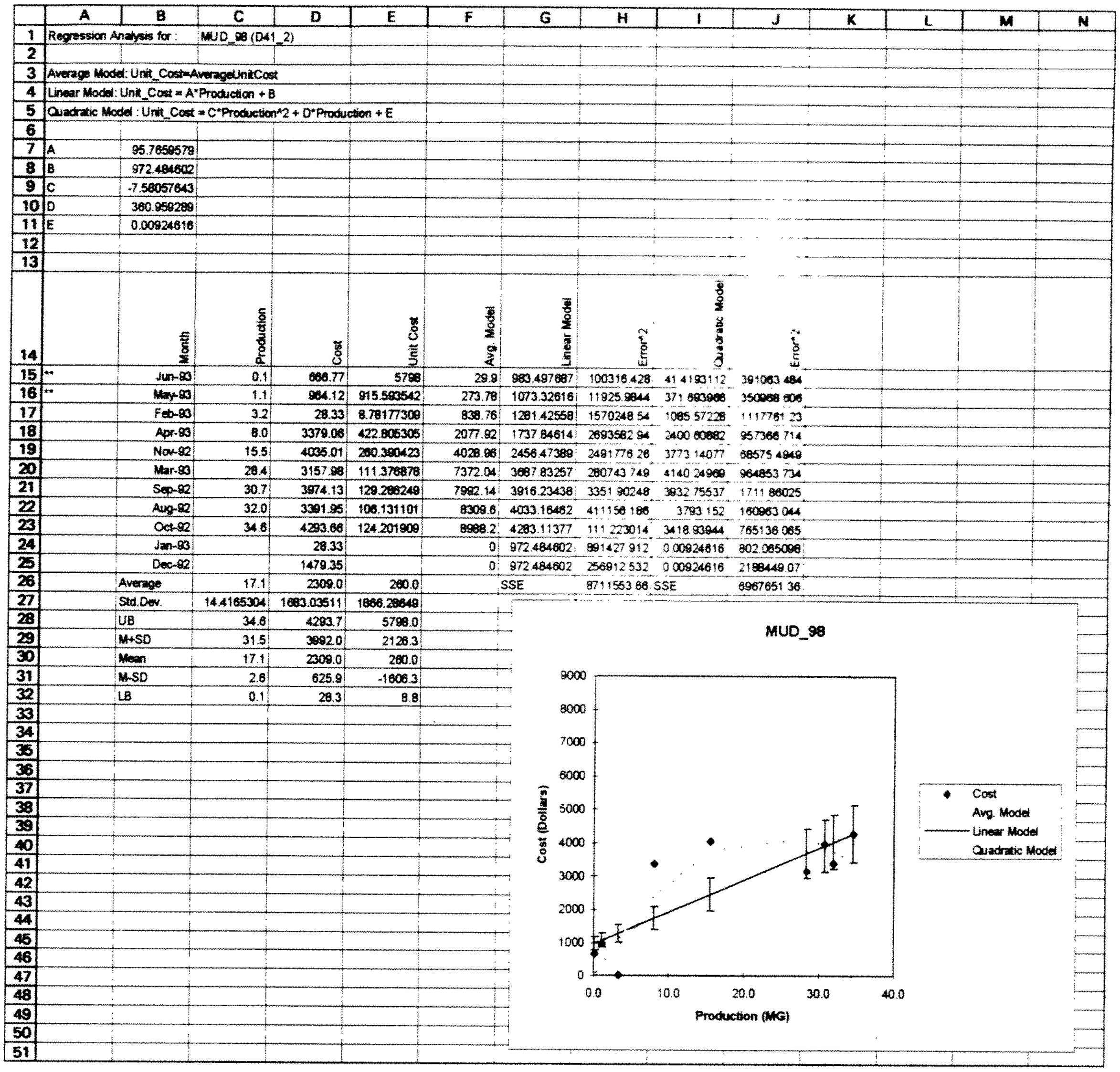
Figure 2.26 Manning Production Cost Analysis

The figure for Manning shows that all the linear cost and quadratic cost models are good predictors of the historical cost-production relationship. The average cost model is acceptable, underpredicting at the low end of historical production and overpredicting by about 40% at the extreme ranges of the historical operation values.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Regression Analysis for :		MUD_98 (D41_2)											
2														
3	Average Model: Unit_Cost=AverageUnitCost													
4	Linear Model: Unit_Cost = A*Production + B													
5	Quadratic Model : Unit_Cost = C*Production^2 + D*Production + E													
6														
7	A	95.7659579												
8	B	972.484602												
9	C	-7.58057643												
10	D	360.959289												
11	E	0.00924616												
12														
13														
14		Month	Production	Cost	Unit Cost	Avg. Model	Linear Model	Error^2	Quadratic Model	Error^2				
15	**	Jun-93	0.1	666.77	5798	29.9	983.497687	100316.428	41.4193112	391063.484				
16	**	May-93	1.1	984.12	915.593542	273.78	1073.32616	11925.9844	371.693966	350968.606				
17		Feb-93	3.2	28.33	8.78177309	838.76	1281.42558	1570248.54	1085.57228	1117761.23				
18		Apr-93	8.0	3379.06	422.805305	2077.92	1737.84614	2693582.94	2400.80882	957366.714				
19		Nov-92	15.5	4035.01	260.390423	4028.96	2456.47389	2491776.26	3773.14077	68575.4949				
20		Mar-93	28.4	3157.98	111.376876	7372.04	3687.83257	280743.749	4140.24969	964853.734				
21		Sep-92	30.7	3974.13	129.286249	7982.14	3916.23438	3351.90248	3932.75537	1711.86025				
22		Aug-92	32.0	3391.95	106.131101	8309.6	4033.16462	411158.186	3793.152	160963.044				
23		Oct-92	34.6	4293.66	124.201909	8988.2	4283.11377	111.223014	3418.93944	765138.065				
24		Jan-93		28.33		0	972.484602	891427.912	0.00924616	802.065098				
25		Dec-92		1479.35		0	972.484602	256912.532	0.00924616	2188449.07				
26		Average	17.1	2309.0	260.0		SSE	8711553.66	SSE	6967651.36				
27		Std.Dev.	14.4165304	1683.03511	1866.28649									
28		UB	34.6	4293.7	5798.0									
29		M+SD	31.5	3992.0	2126.3									
30		Mean	17.1	2309.0	260.0									
31		M-SD	2.6	625.9	-1606.3									
32		LB	0.1	28.3	8.8									
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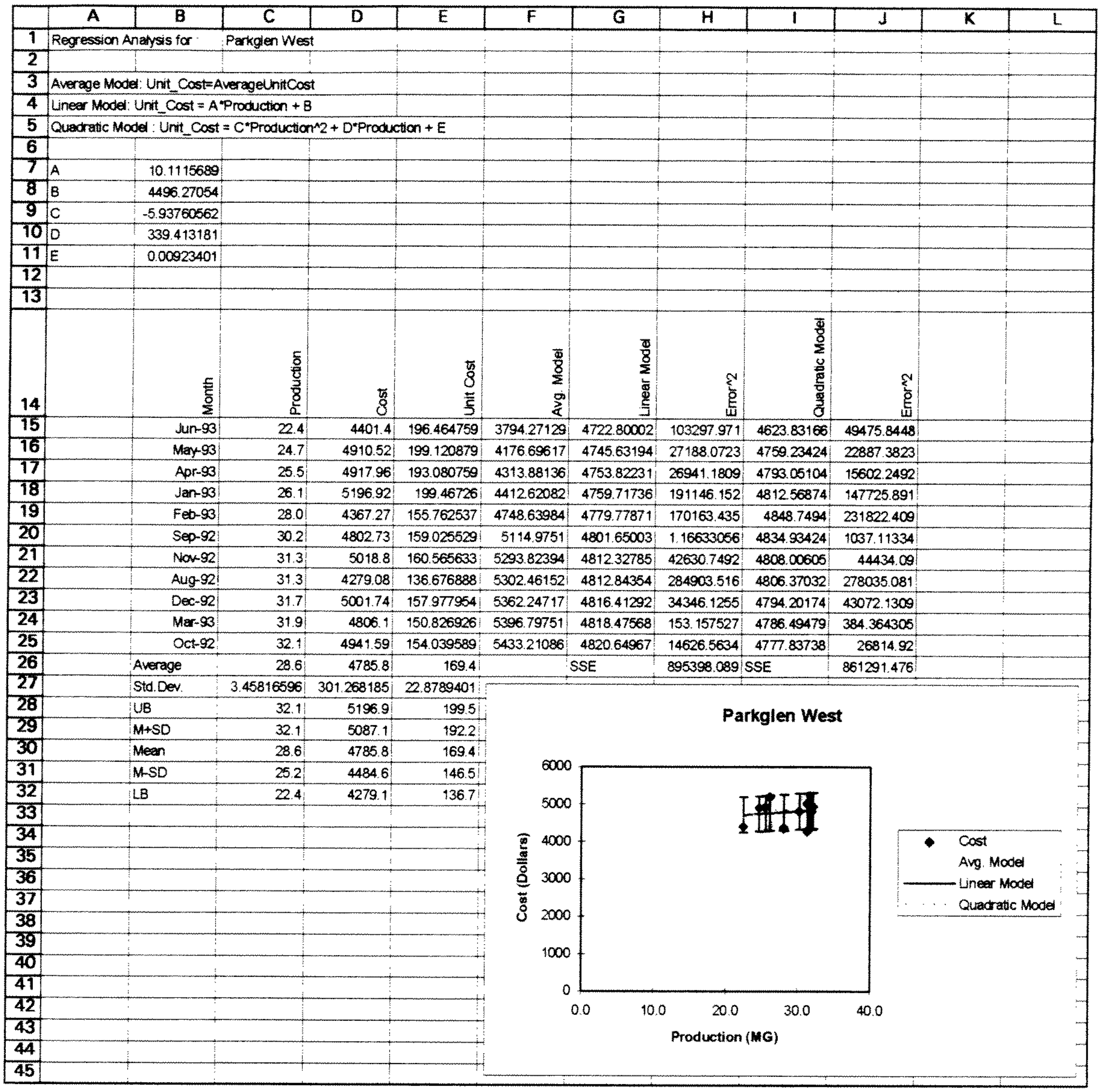
Figure 2.27 MUD 98 Production Cost Analysis

The figure for MUD 98 shows that the linear cost model is a good approximation of the production-cost relationship for this plant. 60% of the historical data fall within the 20% variation range of the model. For this plant, the other two models are poor predictors of the cost-production relationship at the high production value ranges.



	A	B	C	D	E	F	G	H	I	J	K	L
1	Regression Analysis for	Parkglen West										
2												
3	Average Model: Unit_Cost=AverageUnitCost											
4	Linear Model: Unit_Cost = A*Production + B											
5	Quadratic Model : Unit_Cost = C*Production^2 + D*Production + E											
6												
7	A	10.1115689										
8	B	4496.27054										
9	C	-5.93760562										
10	D	339.413181										
11	E	0.00923401										
12												
13												
14		Month	Production	Cost	Unit Cost	Avg. Model	Linear Model	Error^2	Quadratic Model	Error^2		
15		Jun-93	22.4	4401.4	196.464759	3794.27129	4722.80002	103297.971	4623.83166	49475.8448		
16		May-93	24.7	4910.52	199.120879	4176.69617	4745.63194	27188.0723	4759.23424	22887.3823		
17		Apr-93	25.5	4917.96	193.080759	4313.88136	4753.82231	26941.1809	4793.05104	15602.2492		
18		Jan-93	26.1	5196.92	199.46726	4412.62082	4759.71736	191146.152	4812.56874	147725.891		
19		Feb-93	28.0	4367.27	155.762537	4748.63984	4779.77871	170163.435	4848.7494	231822.409		
20		Sep-92	30.2	4802.73	159.025529	5114.9751	4801.65003	1.16633056	4834.93424	1037.11334		
21		Nov-92	31.3	5018.8	160.565633	5293.82394	4812.32785	42630.7492	4808.00605	44434.09		
22		Aug-92	31.3	4279.08	136.676888	5302.46152	4812.84354	284903.516	4806.37032	278035.081		
23		Dec-92	31.7	5001.74	157.977954	5362.24717	4816.41292	34346.1255	4794.20174	43072.1309		
24		Mar-93	31.9	4806.1	150.826926	5396.79751	4818.47568	153.157527	4786.49479	384.364305		
25		Oct-92	32.1	4941.59	154.039589	5433.21086	4820.64967	14626.5634	4777.83738	26814.92		
26		Average	28.6	4785.8	169.4		SSE	895398.089	SSE	861291.476		
27		Std.Dev.	3.45816596	301.268185	22.8789401							
28		UB	32.1	5196.9	199.5							
29		M+SD	32.1	5087.1	192.2							
30		Mean	28.6	4785.8	169.4							
31		M-SD	25.2	4484.6	146.5							
32		LB	22.4	4279.1	136.7							
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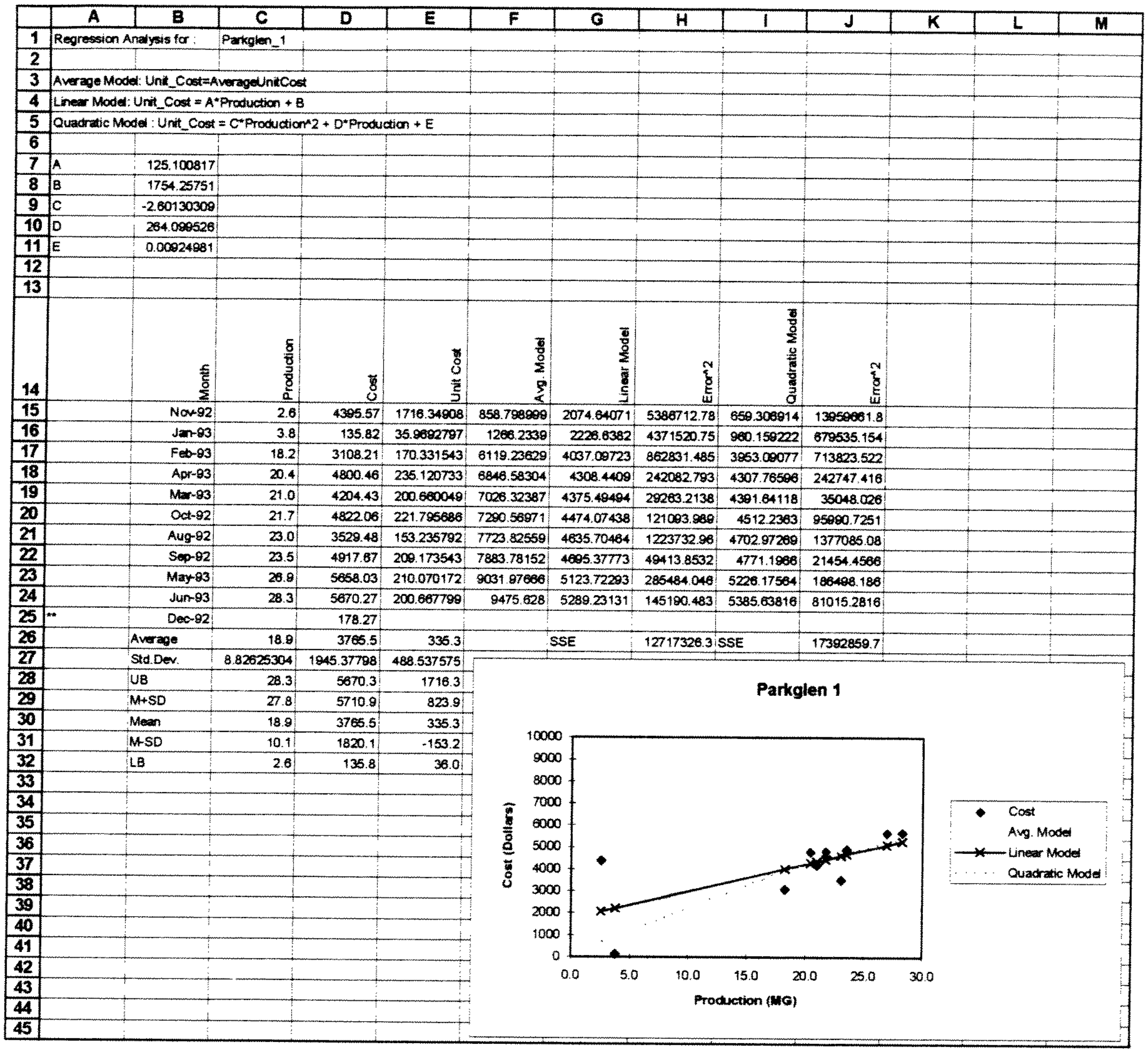
Figure 2.28 Parkglen West Production Cost Analysis

The figure for Parkglen West shows that all the linear cost and quadratic cost models are good predictors of the historical cost-production relationship. The average cost model is acceptable, underpredicting at the low end of historical production and overpredicting by about 20% at the high end.



	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Regression Analysis for :		Parkglen_1										
2													
3	Average Model: Unit_Cost=AverageUnitCost												
4	Linear Model: Unit_Cost = A*Production + B												
5	Quadratic Model : Unit_Cost = C*Production^2 + D*Production + E												
6													
7	A	125.100817											
8	B	1754.25751											
9	C	-2.60130309											
10	D	264.099526											
11	E	0.00924981											
12													
13													
14		Month	Production	Cost	Unit Cost	Avg. Model	Linear Model	Error^2	Quadratic Model	Error^2			
15		Nov-92	2.6	4395.57	1716.34908	858.798999	2074.64071	5386712.78	659.306914	13959661.8			
16		Jan-93	3.8	135.82	35.9692797	1266.2339	2226.6382	4371520.75	960.159222	679535.154			
17		Feb-93	18.2	3108.21	170.331543	6119.23629	4037.09723	862831.485	3953.09077	713823.522			
18		Apr-93	20.4	4800.46	235.120733	6846.58304	4308.4409	242082.793	4307.76596	242747.416			
19		Mar-93	21.0	4204.43	200.660049	7026.32387	4375.49494	29263.2138	4391.64118	35048.026			
20		Oct-92	21.7	4822.06	221.795686	7290.56971	4474.07438	121093.989	4512.2363	95990.7251			
21		Aug-92	23.0	3529.48	153.235792	7723.82559	4635.70464	1223732.96	4702.97269	1377085.08			
22		Sep-92	23.5	4917.67	209.173543	7883.78152	4695.37773	49413.8532	4771.1966	21454.4566			
23		May-93	26.9	5658.03	210.070172	9031.97666	5123.72293	285484.046	5226.17564	186498.186			
24		Jun-93	28.3	5670.27	200.667799	9475.628	5289.23131	145190.483	5385.63816	81015.2816			
25	**	Dec-92		178.27									
26		Average	18.9	3765.5	335.3		SSE	12717326.3	SSE	17392859.7			
27		Std.Dev.	8.82625304	1945.37798	488.537575								
28		UB	28.3	5670.3	1716.3								
29		M+SD	27.8	5710.9	823.9								
30		Mean	18.9	3765.5	335.3								
31		M-SD	10.1	1820.1	-153.2								
32		LB	2.6	135.8	36.0								
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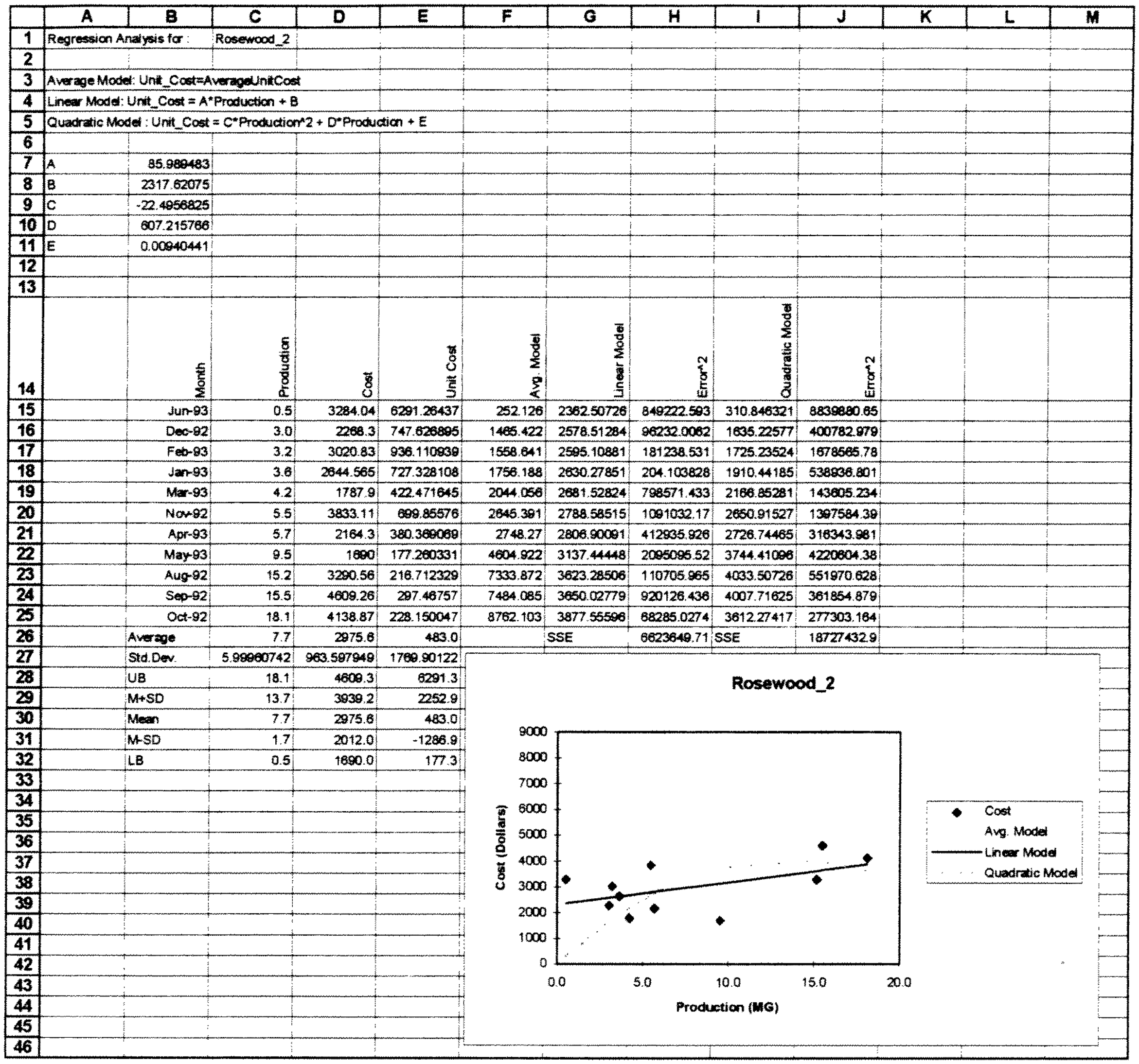
Figure 2.29 Parkglen 1 Production Cost Analysis

The figure for Parkglen 1 shows that the linear cost model is a good approximation of the production-cost relationship for this plant. 60% of the historical data fall within the 20% variation range of the model. For this plant, the other two models are poor predictors of the cost-production relationship.



	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Regression Analysis for :		Rosewood_2										
2													
3	Average Model: Unit_Cost=AverageUnitCost												
4	Linear Model: Unit_Cost = A*Production + B												
5	Quadratic Model : Unit_Cost = C*Production^2 + D*Production + E												
6													
7	A	85.989483											
8	B	2317.62075											
9	C	-22.4956825											
10	D	607.215766											
11	E	0.00940441											
12													
13													
14		Month	Production	Cost	Unit Cost	Avg. Model	Linear Model	Error^2	Quadratic Model	Error^2			
15		Jun-93	0.5	3284.04	6291.26437	252.126	2362.50726	849222.593	310.846321	8839880.65			
16		Dec-92	3.0	2268.3	747.626895	1465.422	2578.51284	96232.0062	1635.22577	400782.979			
17		Feb-93	3.2	3020.83	936.110939	1558.641	2595.10881	181238.531	1725.23524	1678565.78			
18		Jan-93	3.6	2644.565	727.328108	1756.188	2630.27851	204.103828	1910.44185	538936.801			
19		Mar-93	4.2	1787.9	422.471645	2044.056	2681.52824	798571.433	2166.85281	143605.234			
20		Nov-92	5.5	3833.11	699.85576	2645.391	2788.58515	1091032.17	2650.91527	1397584.39			
21		Apr-93	5.7	2164.3	380.369069	2748.27	2806.90091	412935.926	2726.74465	316343.981			
22		May-93	9.5	1690	177.260331	4604.922	3137.44448	2095095.52	3744.41096	4220604.38			
23		Aug-92	15.2	3290.56	216.712329	7333.872	3623.28506	110705.965	4033.50726	551970.628			
24		Sep-92	15.5	4609.26	297.46757	7484.085	3650.02779	920126.436	4007.71625	361854.879			
25		Oct-92	18.1	4138.87	228.150047	8762.103	3877.55596	68285.0274	3612.27417	277303.184			
26		Average	7.7	2975.6	483.0		SSE	6623649.71	SSE	18727432.9			
27		Std.Dev.	5.99960742	963.597949	1769.90122								
28		UB	18.1	4609.3	6291.3								
29		M+SD	13.7	3939.2	2252.9								
30		Mean	7.7	2975.6	483.0								
31		M-SD	1.7	2012.0	-1286.9								
32		LB	0.5	1690.0	177.3								
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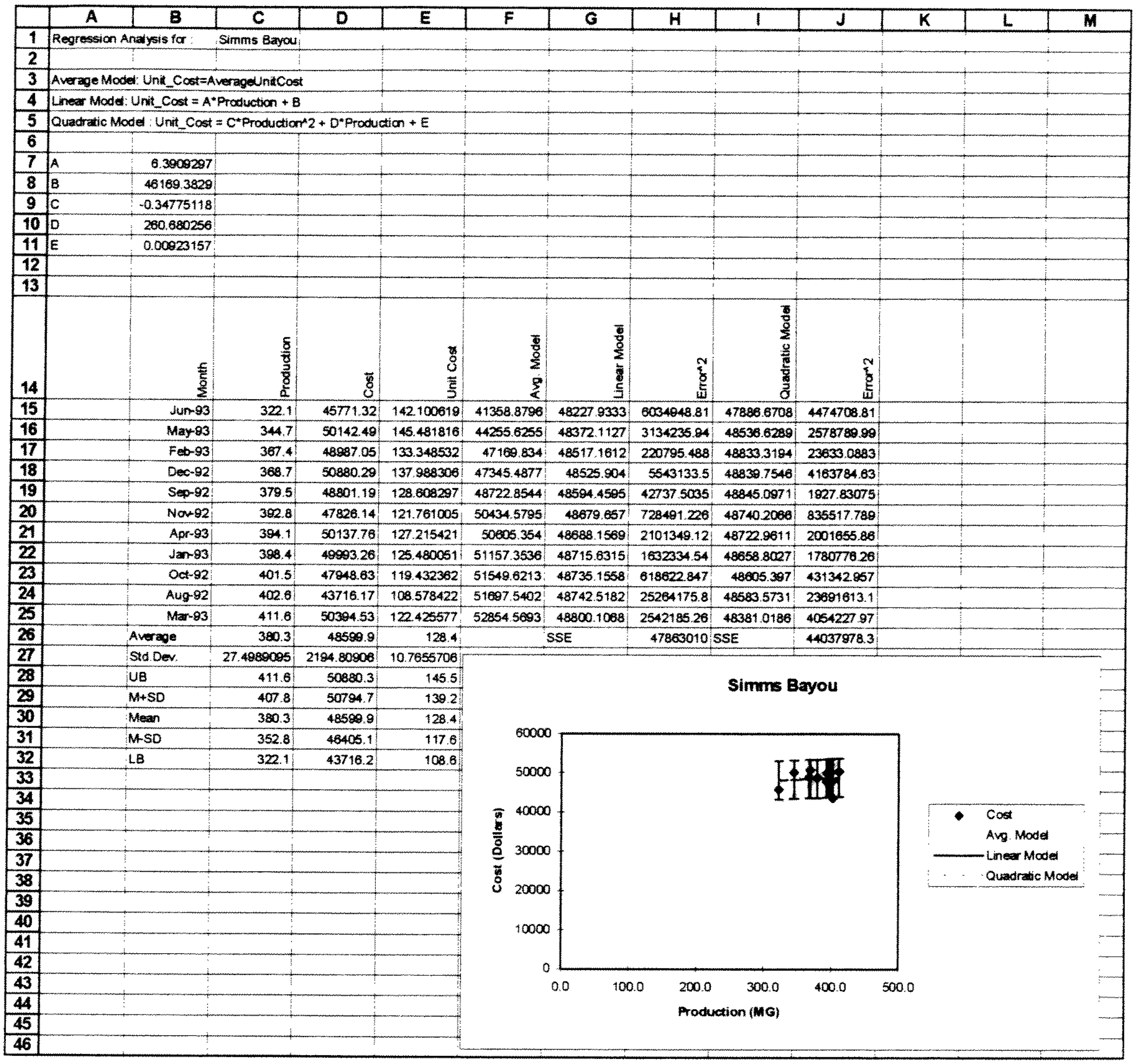
Figure 2.30 Rosewood 2 Production Cost Analysis

The figure for Rosewood 2 shows that the linear cost model is a good approximation of the production-cost relationship for this plant. Nearly all of the historical data fall within the 20% variation range of the model. For this plant, the other two models are poor predictors of the cost-production relationship.



	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Regression Analysis for :		Simms Bayou										
2													
3	Average Model: Unit_Cost=AverageUnitCost												
4	Linear Model: Unit_Cost = A*Production + B												
5	Quadratic Model : Unit_Cost = C*Production^2 + D*Production + E												
6													
7	A	6.3909297											
8	B	46169.3829											
9	C	-0.34775118											
10	D	260.680256											
11	E	0.00923157											
12													
13													
14		Month	Production	Cost	Unit Cost	Avg. Model	Linear Model	Error^2	Quadratic Model	Error^2			
15		Jun-93	322.1	45771.32	142.100619	41358.8796	48227.9333	6034948.81	47886.6708	4474708.81			
16		May-93	344.7	50142.49	145.481816	44255.6255	48372.1127	3134235.94	48536.6289	2578789.99			
17		Feb-93	367.4	48987.05	133.348532	47169.834	48517.1612	220795.488	48833.3194	23633.0883			
18		Dec-92	368.7	50880.29	137.988306	47345.4877	48525.904	5543133.5	48839.7546	4163784.63			
19		Sep-92	379.5	48801.19	128.608297	48722.8544	48594.4595	42737.5035	48845.0971	1927.83075			
20		Nov-92	392.8	47826.14	121.761005	50434.5795	48679.657	728491.226	48740.2066	835517.789			
21		Apr-93	394.1	50137.76	127.215421	50605.354	48688.1569	2101349.12	48722.9611	2001655.86			
22		Jan-93	398.4	49993.26	125.480051	51157.3536	48715.6315	1632334.54	48658.8027	1780776.26			
23		Oct-92	401.5	47948.63	119.432362	51549.6213	48735.1558	618622.847	48605.397	431342.957			
24		Aug-92	402.6	43716.17	108.578422	51697.5402	48742.5182	25264175.8	48583.5731	23691613.1			
25		Mar-93	411.6	50394.53	122.425577	52854.5693	48800.1068	2542185.26	48381.0186	4054227.97			
26		Average	380.3	48599.9	128.4		SSE	47863010	SSE	44037978.3			
27		Std.Dev.	27.4989095	2194.80906	10.7655706								
28		UB	411.6	50880.3	145.5								
29		M+SD	407.8	50794.7	139.2								
30		Mean	380.3	48599.9	128.4								
31		M-SD	352.8	46405.1	117.6								
32		LB	322.1	43716.2	108.6								
33													
34													
35													
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46													

Figure 2.33 Simms Bayou Production Cost Analysis

The figure for Simms Bayou shows that all the linear cost and quadratic cost models are good predictors of the historical cost-production relationship. The average cost model is acceptable, underpredicting at the low end of historical production and overpredicting by about 20% at the high end.

Figure 2.40 compares the optimal allocation solutions to the historical production costs.

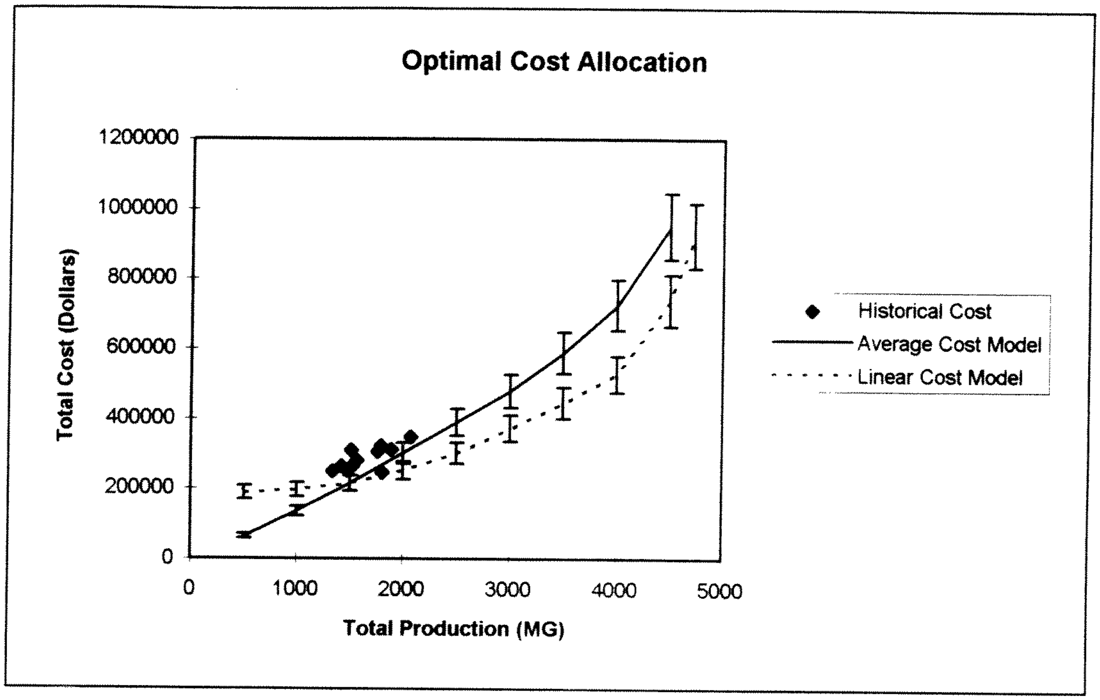

Figure 2.40 Comparison of Historical Cost-Production Relationship and Model Relationships

This figure illustrates several features of the cost analysis effort. First, the historical operation produced water at a higher cost than the model predicts was achieveable, suggesting some imporvement in allocations could save operational costs. The error bars on the figure represent 10% variation in the predicted optimal cost. Since the historical values lie above the upper error range, it is likely that the model indeed suggests some improvement can be made by optimal allocation strategies.

The second, and more important feature, suggested by the figure is that the historical operation was not too bad. The system was being operated somewhere near its optimal value (according to the model). Because the average cost model is reasonable for the historical production volumes we choose to make all subsequent calculations in this report are based on the average cost model. The error in using this approach rather than the linear cost model is that the average cost model will predict slightly higher production costs outside of the historical range of production values, and it will underpredict costs at low production volumes. However, the average cost model greatly simplifies the computations for minium cost calculations when system hyraulics is considered, and it is not expected to produce different allocations that the linear cost model for the ranges of interest.

In summary the cost analysis suggests that the average cost model is adequate for production volumes in the historical range.

The procedure to compute the cost of water at each plant is:

- Obtain the monthly well report, enter the production volume formula into a spreadsheet and compute the monthly production volume for each plant.
- Obtain the monthly electricity cost report, merge this spreadsheet with the production volume report to calculate the monthly unit cost of water produced at each plant.
- Use the SOLVER to determine the fitting parameters for the linear or quadratic model.

Research into Production Cost Reduction by Energy Management of Houston's Surface and Groundwater Systems

Final Report

Part III

Demand Estimation

by

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February 8, 1996

Prepared for

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1801 Main Street
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City of Houston Project # 33100
University of Houston Project # 1558893

Contents

General Approach

Demand determines (in a non-unique fashion) how much water one must supply to the network, and ultimately affects both costs and revenues. If we know how much water is demanded (and the network behavior and the aquifer behavior), we can adjust supply allocations to (1) satisfy the demand, and (2) minimize costs.

In this research actual demand is the actual amount of water demanded by customers. Actual demand is distinct from and different than estimated or projected demand. Address matching is the process of correlating a street address with a geographic location. Geographical Information System (GIS) is a database management program that couples location and other information, and graphically presents the information on a map.

An estimate of demand is required by the network simulation model to help determine if different supply allocations can satisfy demand and satisfy system pressure requirements. An estimate based on actual geographically distributed demand is considered in this research to be superior to estimates based on per-capita demand estimates. Demand is estimated using actual demand data from billing records obtained from water customer service, and is then assigned to the nodes in the network simulation model. The proceudre is summarized below.

First one must have a network simulation model such as depicted in Figure 3.1.

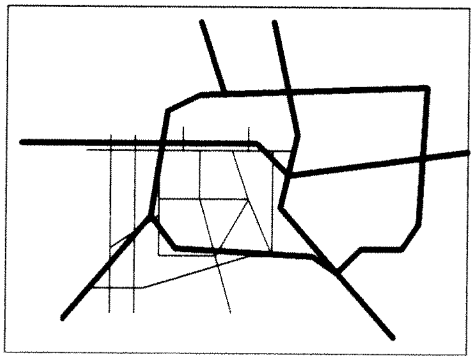


Figure 3.1. Network Model

The model will require a demand to be assigned to each node (or junction), as depicted in Figure3.2.

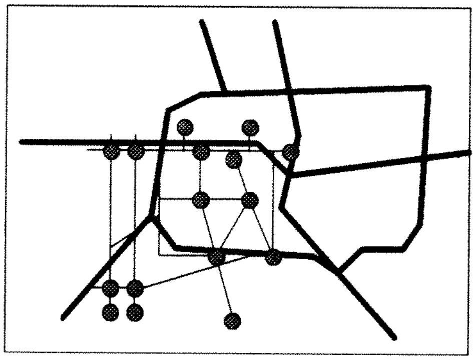


Figure 3.2. Demands Assigned to Each Model Node

Then a supply allocation will be assigned to the supply nodes as depicted in Figure 3.3.

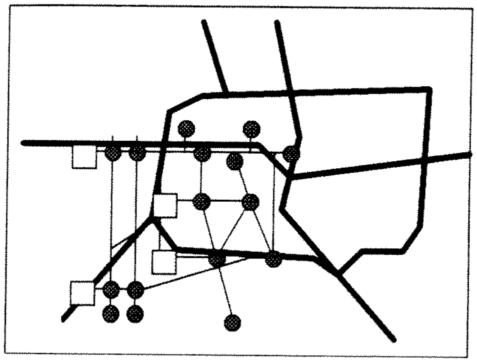


Figure 3.3. Supply Allocated to Supply Nodes.

Then the model will be run, and if the pressures are acceptable, the analyst has just identified a feasible supply allocation for the particular demand configuration.

The assignment of demand was determined by first obtaining billing data from Water Customer Service. Then ATLAS-GIS was used to match the billing addresses (meter addresses) to census tract (TIGER) files. The matching procedure assigns the latitude and longitide of a street address in the TIGER file to the same the street address on the billing record as depicted in Figure 14.

Raw Data

```
Name     Address          ZIP    Block#   Usage
-------  ---------------  -----  ----   --------
Clinton  20 Houston Ave   77001  444A   1100 g/mo.
Bush     12 Texas Street  77002  555B   2000 g/mo.
```

Processed Data

```
Address          LAT      LON      Usage
---------------  -------  -------  ---------
20 Houston Ave   29.9999  95.5555  1100 g/mo.
12 Texas Street  29.5555  94.4444  2000 g/mo.
```

Figure 3.4. Address Matching

Once this matching is completed, the GIS creates an ASCII file that overlays the demand locations onto a map of the network as depicted in Figures 3.5 and 3.6.

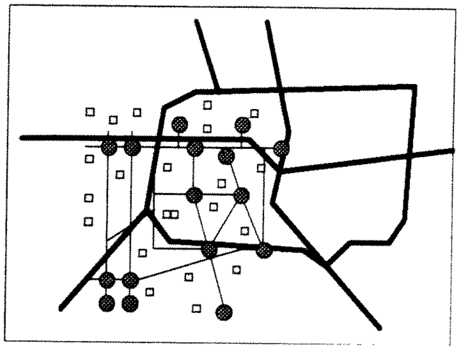


Figure 3.5. Matched Addresses Overlayed onto Network Map (General).

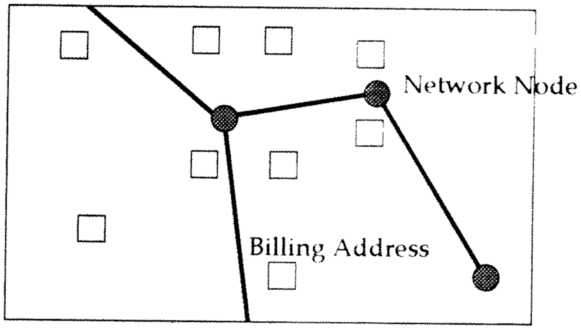


Figure 3.6. Matched Addresses Overlayed onto Network Map (Detail).

A WINDOWS based program custom written for this research takes this file and compares these locations to the locations of the nodes in the model and assigns the actual demands from the billing records to the nearest model node. This process is shown pictorally in Figures 3.7 and 3.8.

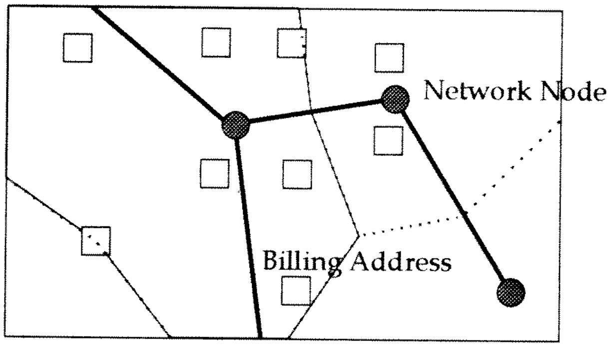


Figure 3.7. Nodal Demand Assignment (Detail)

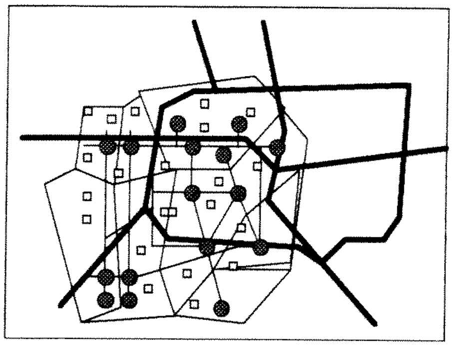


Figure 3.8. Nodal Demand Assignment (General)

Procedure for Estimating Water Demand from Billing Records using ATLAS-GIS Software

Getting Water Customer Service Billing Records into GIS for Demand Estimation

This set of instructions describes how to obtain and convert water billing records into Atlas GIS computer program. The instructions use a step-by-step example to show how to use the several computer software tools to do the work. Actual billing records and a simple network model are used in this tutorial. We choose Block map 490 as the target area for this tutorial. The number of the billing records in this area is 6479, which is not too large for relatively fast computer simulations in this workshop. A 9-node 13-pipe network model is used in this tutorial.

Here are contents of this instructions:
- Data transfer
- Basic Atlas GIS Skills
- Planning with Atlas GIS
- Data Import
- Address Matching
- Export Datapoint Files
- Demand Estimation

The softwares used in this instructions are:
- ARC.EXE : a backup utility
- TRANSFER.EXE : a custom-made program to transfer raw data to Atlas GIS readable data
- Atlas GIS : a geographic information system
- NEAR.EXE : a custom-made program to estimate demands of pipeline models

Data Transfer

(1) Contact Mr. Bob Hodge in Water Customer Service, Public Utilities at (713) 226-5653. He will download data from their mainframe computer into a local IBM-compatible PC.

(2) Use **ARJ.EXE** to copy/compress files from the local PC to floppy disks. Since the size of data files may be more than 20 megabytes, it is necessary to use computer backup utilities to transfer files into floppy disks. In this example, we choose **ARJ.EXE** as the backup utility. Under **DOS environment**, the command to use **ARJ.EXE** is

```
ARJ.EXE A -V1200 TEST.A01 FILE.TXT
```

where

ARJ.EXE	is the program's name.
A	stands for ADD.
-V1200	means to save files into 1.2 megabyte disks. (use -V1440 for 1.44 megabyte disks)
TEST.A01	is the filename of the first disk of the compressed archive. The second disk's name will be TEST.A02, and so on. ARJ.EXE will notify users to change disks.
FILE.TXT	is the name of files to be added into the archive.

Usually, a 20 megabytes text file can be stored/compressed into 4 to 5 disks (6 megabytes).

(3) Use **ARJ.EXE** to transfer/uncompress files from floppy disks to a computer which is designated for this work. The command is

```
ARJ.EXE E -V1200 TEST.A01
```

where

ARJ.EXE	is the program's name.
E	stands for EXPAND/EXTRACT.
-V1200	means to save files into 1.2 megabyte disks. (use -V1440 for 1.44 megabyte disks)
TEST.A01	is the filename of the first disk of the compressed archive. The second disk's name is TEST.A02, and so on. ARJ.EXE will notify users to change disks.

(4) Use **TRANSFER.EXE** to transfer files from raw data format into Atlas GIS readable format. The files obtained from Water Customer Service contain some unused information and may not be readable by GIS software. Use **TRANSFER.EXE** program to eliminate unused data and transfer files from raw data into GIS format. **TRANSFER.EXE** is a custom-made FORTRAN program.

Basic Atlas GIS Skills

(1) Under **<u>DOS environment</u>**, change the directory to AGIS. And type "**AGIS**" to open the ATLAS GIS program.

(2) Atlas GIS is a menu-driven-based GIS program. To process a task, a user chooses a series of commands from the menus.

(3) Atlas GIS has three basic file type:

Geographic files	store geographic information
Attribute files	database of geographic file
Datapoint files	database file with coordinates

(4) Open Houston area geographic file by choosing the following commands from the menus

File	to access File menu
Geographic	to access Geographic file menu
Use	to open a geographic file

and choose the file "**SBXTX201**", which is the map of Harris County.

(5) To open a datapoint file of southwest Houston pump stations, use the following commands,

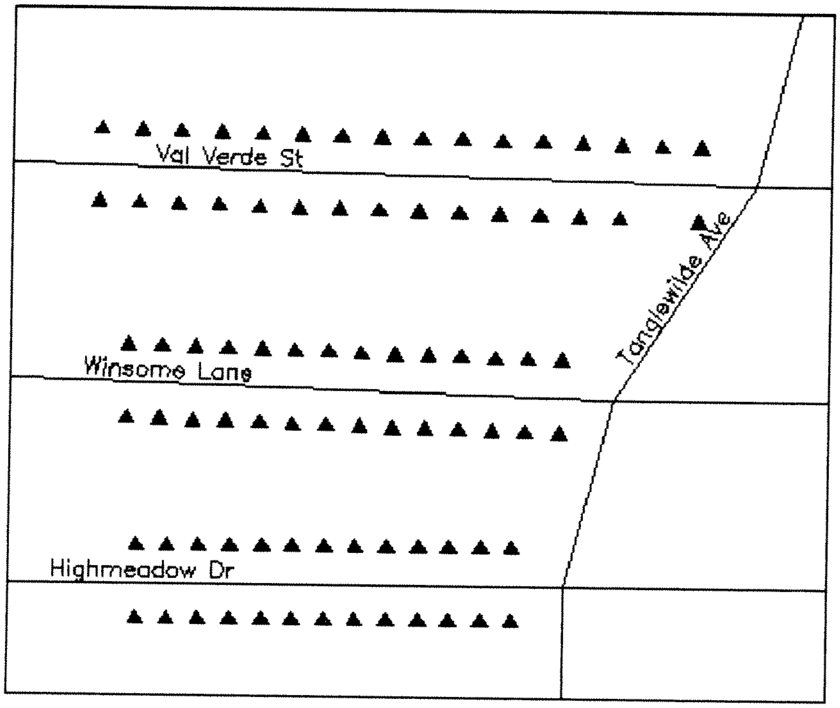
File	to access File menu
Datapoint	to access Datapoint file menu
Use	to open a datapoint file

and choose the file "**B490**", which is the datapoint file of the water usage of Block Map 490 area.

(6) To zoom-in to a small area, use the following commands,

View	to access View menu
Map	to access Map menu
In	zoom-in (choose **Out** to zoom-out, **Pan** to move around)

The following picture is an example,

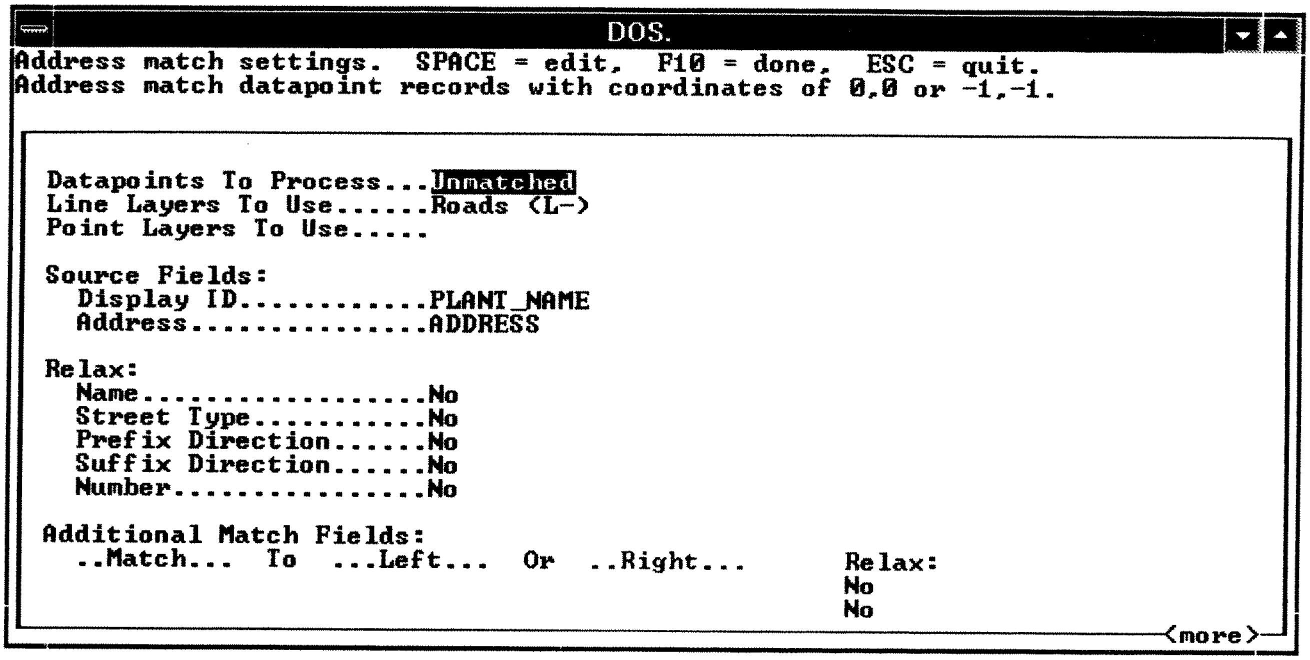


Planning with Atlas GIS

(1) To show the total water usage in a certain area (circle, box, or polygon), use the following commands (assuming a geographic file and a datapoint file have been opened) to select,

Select	access Select menu.
Draw	access Draw menu. (other available options are One, Many, ...)
Circle	draw a circle. All data points inside the circle will be selected. (other available options are Box and Polygon)

then use the following commands to view the information of the selected points,



```
Address match settings.  SPACE = edit,  F10 = done,  ESC = quit.
Address match datapoint records with coordinates of 0,0 or -1,-1.

 Datapoints To Process...Unmatched
 Line Layers To Use......Roads (L-)
 Point Layers To Use.....

 Source Fields:
   Display ID............PLANT_NAME
   Address...............ADDRESS

 Relax:
   Name..................No
   Street Type...........No
   Prefix Direction......No
   Suffix Direction......No
   Number................No

 Additional Match Fields:
   ..Match...  To   ...Left...  Or  ..Right...      Relax:
                                                    No
                                                    No
                                                               <more>
```

The options in the batch address matching is fairly straight forward.
"Datapoints To Process" should be "Unmatched".
"Line Layers To Use" should be always "Roads" in this project.
"Point Layers To Use" is not important in this project.
The options in "Relax" can be changed.

(2) Press the function key "**F10**" to do address matching.

(3) Address matching could be very time consuming.

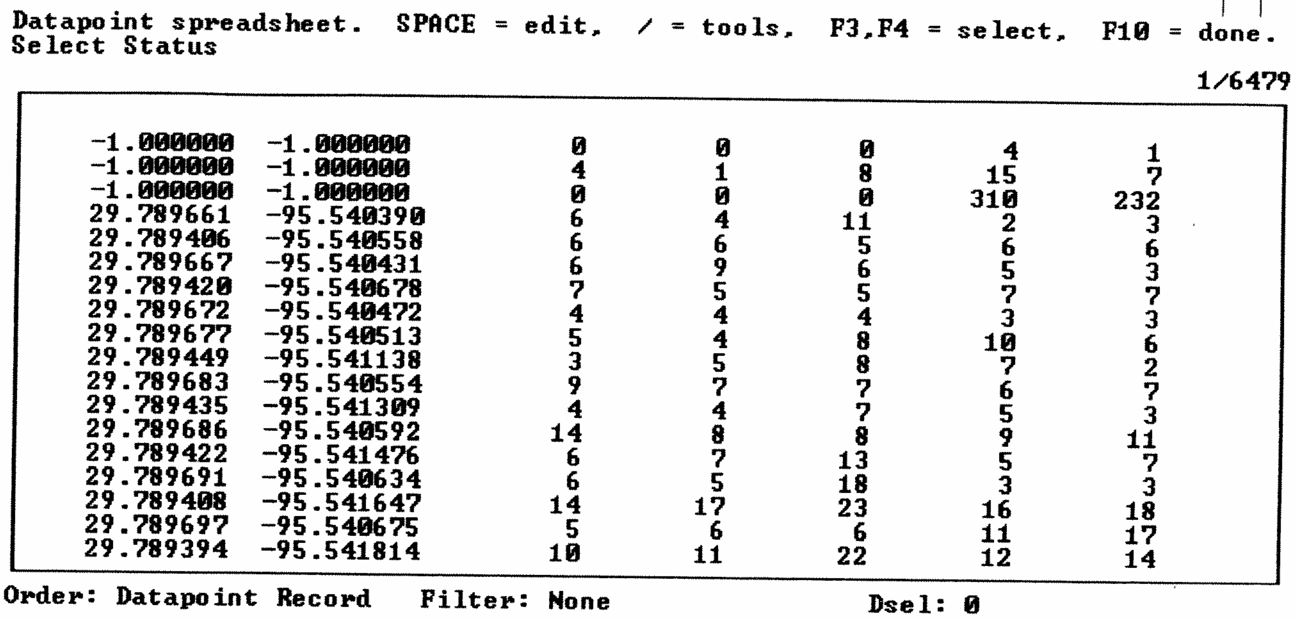
(4) Repeatedly batch address match process by changing "Relax" options could produce better matched percentage.

Export Datapoint Files

(1) Atlas GIS allows users to select certain fields/items of datapoint files to export. The command set is,

Edit	to access Edit menu
Datapoint	to access Datapoint file menu
Browse	browse the datapoint file

The following window should appear,



```
Datapoint spreadsheet.  SPACE = edit,  / = tools,  F3,F4 = select,  F10 = done.
Select Status
                                                                            1/6479

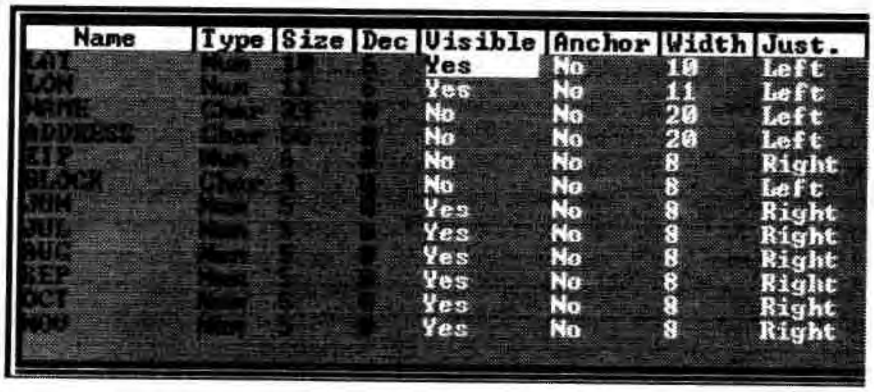
     -1.000000   -1.000000          0        0        0        4        1
     -1.000000   -1.000000          4        1        8       15        7
     -1.000000   -1.000000          0        0        0      310      232
     29.789661   -95.540390         6        4       11        2        3
     29.789406   -95.540558         6        6        5        6        6
     29.789667   -95.540431         6        9        6        5        3
     29.789420   -95.540678         7        5        5        7        7
     29.789672   -95.540472         4        4        4        3        3
     29.789677   -95.540513         5        4        8       10        6
     29.789449   -95.541138         3        5        8        7        2
     29.789683   -95.540554         9        7        7        6        7
     29.789435   -95.541309         4        4        7        5        3
     29.789686   -95.540592        14        8        8        9       11
     29.789422   -95.541476         6        7       13        5        7
     29.789691   -95.540634         6        5       18        3        3
     29.789408   -95.541647        14       17       23       16       18
     29.789697   -95.540675         5        6        6       11       17
     29.789394   -95.541814        10       11       22       12       14

Order: Datapoint Record   Filter: None                    Dsel: 0
```

(2) Use **tools** to set up fields/items. The command set is,

/	to access Tools menu
View	to access View menu
Settings	set parameters

The following window should appear,



Name	Type	Size	Dec	Visible	Anchor	Width	Just.
LAT	Num	[illegible]	[illegible]	Yes	No	10	Left
LON	Num	[illegible]	[illegible]	Yes	No	11	Left
NAME	Char	[illegible]	[illegible]	No	No	20	Left
ADDRESS	Char	[illegible]	[illegible]	No	No	20	Left
ZIP	Num	[illegible]	[illegible]	No	No	8	Right
BLOCK	Char	[illegible]	[illegible]	No	No	8	Left
NUM	[illegible]	[illegible]	[illegible]	Yes	No	8	Right
JUL	[illegible]	[illegible]	[illegible]	Yes	No	8	Right
AUG	[illegible]	[illegible]	[illegible]	Yes	No	8	Right
SEP	[illegible]	[illegible]	[illegible]	Yes	No	8	Right
OCT	[illegible]	[illegible]	[illegible]	Yes	No	8	Right
NOV	[illegible]	[illegible]	[illegible]	Yes	No	8	Right

(3) Change the settings in "**Visible**" field. In this project, the **Visibles** of **NAME**, **ADDRESS**, **ZIP**, & **BLOCK** should be set to "**No**", as shown in the picture.

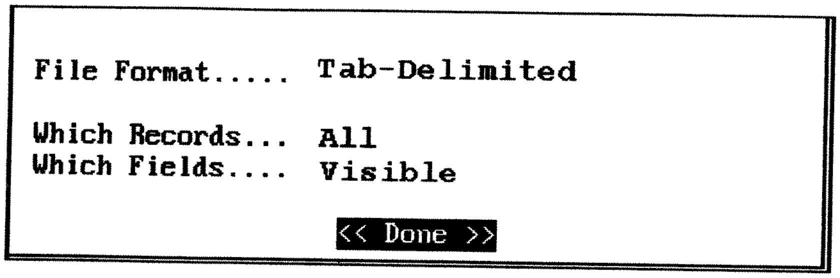
(4) Press function key "**F10**" several times to back to the main menu.

(5) Use the following commands to export datapoint files.

File	to access File menu
Datapoint	to access Datapoint file menu

Tools	to access Tools menu
Export	to choose Export file format

The following window should appear,


File Format..... Tab-Delimited

Which Records... All
Which Fields.... Visible

(6) The export file formats include "Fixed Length", "Comma-Delimited", and others. However, we choose "Tab-Delimited" format in this example. Change the settings as shown in the picture. The output filename in this example is "**AD490.TXT**".

Demand Estimation

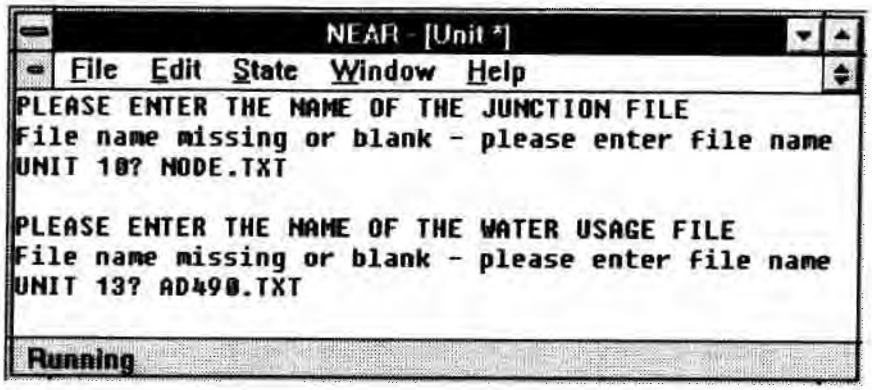
(0.1) Create a 9-node 13-pipe KYPIPE network model (details in another document).
(0.2) Locate LAT-LON coordinates for every junction node.
(0.3) Create a junction-node-coordinates file with the following format

9		[Total number of junction nodes]
-95.5444	29.7833	[Junction LON, Junction LAT]
-95.5236	29.7833	
-95.5028	29.7833	
-95.5444	29.7570	
-95.5236	29.7570	
-95.5028	29.7570	
-95.5444	29.7306	
-95.5236	29.7306	
-95.5028	29.7306	

The name of the file is "NODE.TXT" in this example.

(1) Use **NEAR.EXE** computer program to estimate demand. The program NEAR.EXE, which is a Microsoft Windows program, uses nearest distance method to distribute historical water usage data into junction nodes of the pipeline network model. The input files in this program are the junction-node-coordinates file (NODE.TXT) and the address matched file (AD490.TXT) from Atlas GIS. The output (OUTPUT.TXT) in this program is the estimated demand for each junction node.

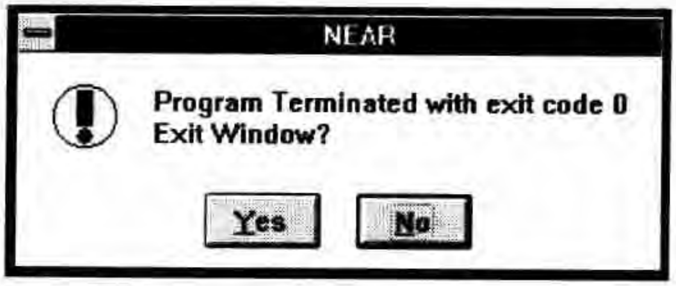
(2) To use NEAR.EXE, go to File Manager. Double click "**NEAR.EXE**". The following window should appear,



```
PLEASE ENTER THE NAME OF THE JUNCTION FILE
File name missing or blank - please enter file name
UNIT 10? NODE.TXT

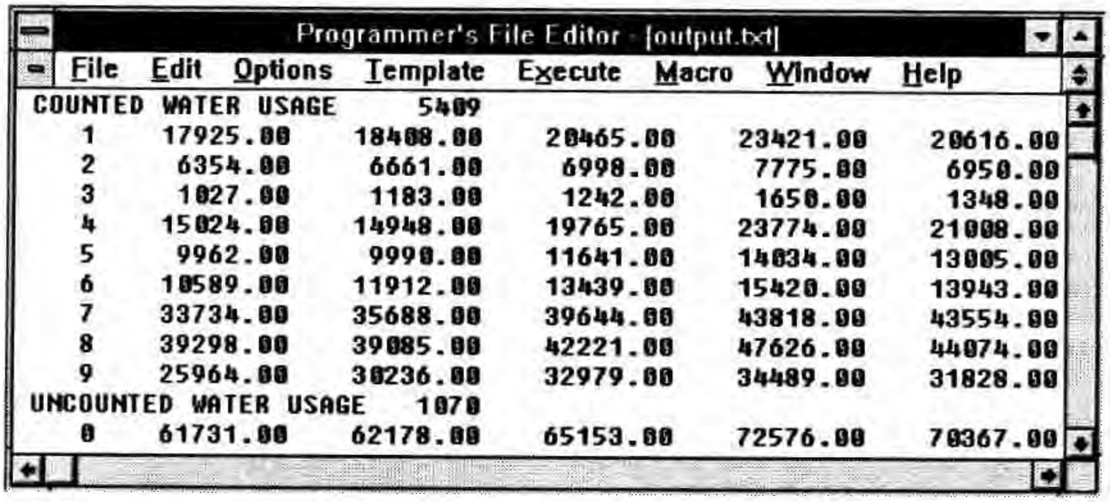
PLEASE ENTER THE NAME OF THE WATER USAGE FILE
File name missing or blank - please enter file name
UNIT 13? AD490.TXT
```

(3) Click "Yes" to terminate the program.



```
Program Terminated with exit code 0
Exit Window?
```

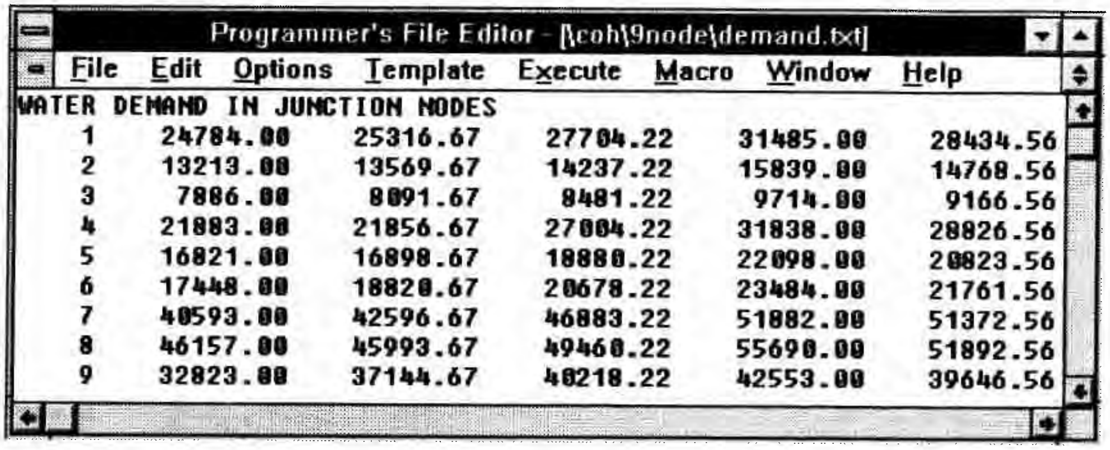
(4) The output of the file is shown in the follow picture,



```
COUNTED WATER USAGE      5409
     1     17925.00     18408.00     20465.00     23421.00     20616.00
     2      6354.00      6661.00      6998.00      7775.00      6950.00
     3      1027.00      1183.00      1242.00      1650.00      1348.00
     4     15024.00     14948.00     19765.00     23774.00     21008.00
     5      9962.00      9990.00     11641.00     14034.00     13005.00
     6     10589.00     11912.00     13439.00     15420.00     13943.00
     7     33734.00     35688.00     39644.00     43818.00     43554.00
     8     39298.00     39085.00     42221.00     47626.00     44074.00
     9     25964.00     30236.00     32979.00     34489.00     31828.00
UNCOUNTED WATER USAGE    1070
     0     61731.00     62178.00     65153.00     72576.00     70367.00
```

There are 6479 billing records in "AD490.TXT" file. The water usages of 5409 address matched records have been distributed into 9 junction nodes. The total water usages of 1070 address unmatched records are shown in the last line. The first column represents the junction node number. The second to sixth columns represent the water usages of the junctions from June 1993 to October 1993 in 1000 gallons/month.

(5) In this example, the unmatched water usages will be evenly distributed into nine junction nodes. So the final demand estimation looks like,



```
WATER DEMAND IN JUNCTION NODES
      1    24784.00     25316.67     27704.22     31485.00     28434.56
      2    13213.00     13569.67     14237.22     15839.00     14768.56
      3     7886.00      8091.67      8481.22      9714.00      9166.56
      4    21883.00     21856.67     27004.22     31838.00     28826.56
      5    16821.00     16898.67     18880.22     22098.00     20823.56
      6    17448.00     18820.67     20678.22     23484.00     21761.56
      7    40593.00     42596.67     46883.22     51882.00     51372.56
      8    46157.00     45993.67     49460.22     55690.00     51892.56
      9    32823.00     37144.67     40218.22     42553.00     39646.56
```

The unit of the water usage is "1000 Gal per Month". The water usage in "Million Gal per Day" will be,

Node No.	Jun.	Jul.	Sept.	Oct.	Nov.
1	0.83	0.84	0.92	1.05	0.95
2	0.44	0.45	0.47	0.53	0.49
3	0.26	0.27	0.28	0.32	0.31
4	0.73	0.73	0.90	1.06	0.96
5	0.56	0.56	0.63	0.74	0.69
6	0.58	0.63	0.69	0.78	0.73
7	1.35	1.42	1.56	1.73	1.71
8	1.54	1.53	1.65	1.86	1.73
9	1.09	1.24	1.34	1.42	1.32

In the pipeline network model, we will use the water demand estimation of October 1993.

Research into Production Cost Reduction by Energy Management of Houston's Surface and Groundwater Systems

Final Report

Part IV

System Hydraulic Modeling

by

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Final Report

Prepared for

Planning and Operations Support
Department of Public Works and Engineering
City of Houston
1801 Main Street
Houston, Texas

City of Houston Project # 33100
University of Houston Project # 1558893

Contents

Water System Hydraulics

The groundwater supply and surface water distribution system are conceptualized as shown in Figure 4.1 below. The aquifer system supplies water to the distribution system through well fields throughout the modeled area. A surface water supply source is also shown on the conceptual drawing. In our study area, the surface water supplies are assumed to enter at the eastern edge of the network model and represent water supplied from the surface water plants to the north and east for the study area. Additionaly, a surface water supply is assumed to be directly connected to the Southwest Pumping Plant.

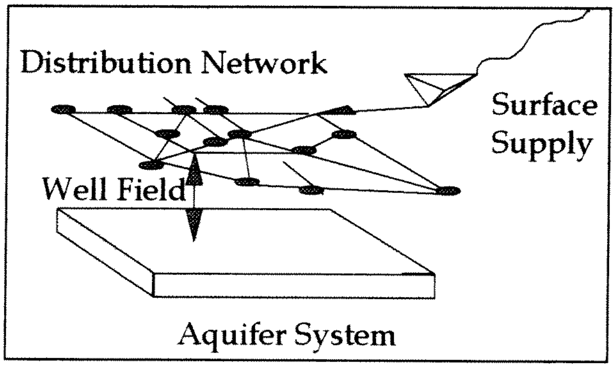


Figure 4.1. Conceptual Aquifer-Network Model

The distribution network supplies waters to customers (nodes) at specified flow rates (demand) and is subjected to a pressure constraint. That is, the system pressure must always be larger than some lower limit and smaller than some upper limit. We used the values of 10 psi for the lower limit and 110 psi for the upper limit.

The aquifer system is one source of water supply for the surface distribution system. The aquifer stores water, transmits water, and experiences drawdown as water is removed from storage and placed into the system. Generally, a higher rate of supply increases drawdown in a wellfield, which in-turn, will tend to lead to land subsidence.

The network modeling goals of the research were to simulate pressures in the network for different supply and demand configurations; then determine if these pressures are acceptable. The aquifer modeling goals of this research were to simulate drawdown at the wellfields in response to different supply allocations; then report the magnitude of these drawdowns. We did not attempt to simulate associated land subsidence caused by a particular drawdown. A useful estimation technique is suggested later to give a first-order estimate of the expected land subsidence.

The network hydraulics simulation model is based on steady-state pipe-flow principles as depicted in Figure 4.2.

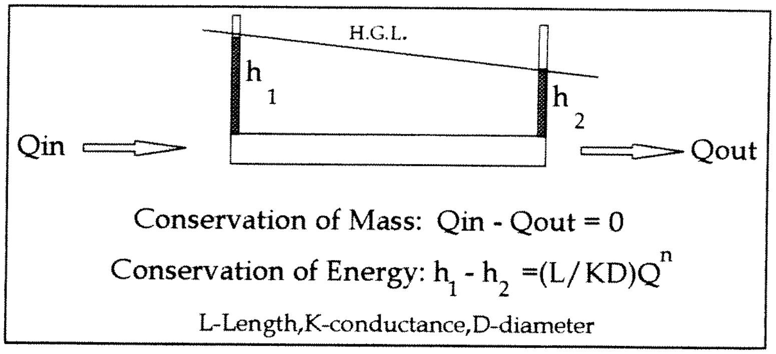


Figure 4.2. Schematic of Pipe-Flow Principles.

The flow principles are based on the conservation of mass within a pipeline and the conservation of energy along the flow line. The head-loss is this research was computed using the Hazen-Williams formula. In addition to flow balances within pipes, mass balances at each junction are also required. Figure 4.3 is a diagram of a junction node.

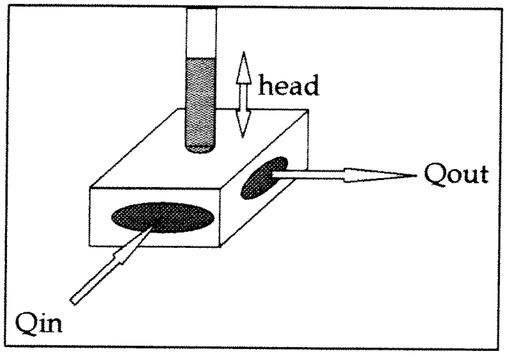


Figure 4.3. Schematic of a Junction Node.

In this research the junction nodes have the following properties: A node joins two or more pipes, a node is the only place where water is added or removed from the network (hence nodes represent wellfields, surface supply points, and customer demand points); A node produces no head-loss, A node is the computation location where system pressures are evaluated.

The nodes and pipes in the system are interconnected as shown in Figure 4.4. A mass balance equation is written for each node, a head loss equation is written for each closed pipe loop, and total flow is balanced. These equations are collected (assembled) into a system of simultaneous non-linear equations and are subsequently solved to produce a set of flows and pressures that satisfy the mass and energy balance requirements of the network model.

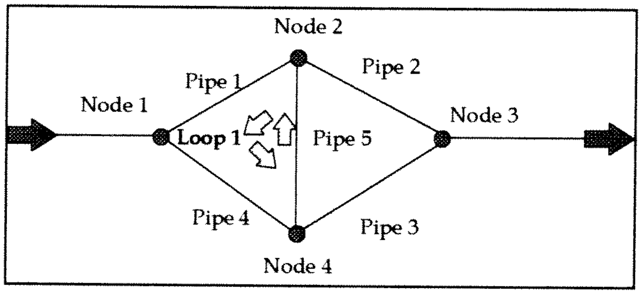


Figure 4.4. Schematic of an Interconnected System.

The creation of the equations, assembly, and solution is carried out using the KYPIPE2 hydraulic simulation model. To simulate any network we need to specify the geometry, pipe length and diameters, the loss coefficients, supply and demand flow rates. The model will calculate pressures and internal (pipe) flows.

The aquifer hydraulics principles are practically identical. The aquifer system is divided into blocks as shown in Figure 4.5.

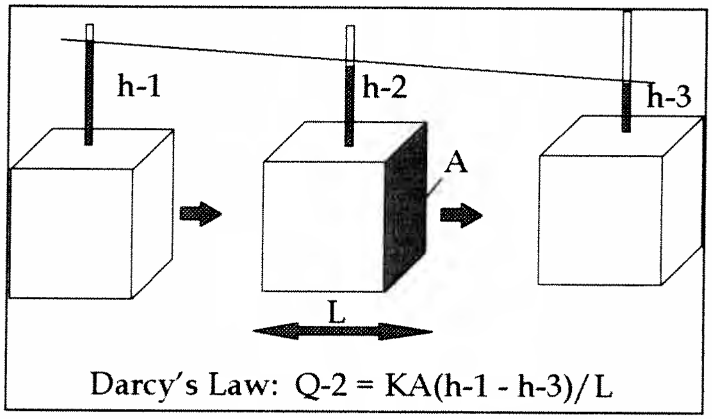


Figure 4.5. Schematic of Aquifer Blocks (pulled apart for details of flow)

The blocks represent the hydraulic properties of a portion of the aquifer system. Blocks transmit water to adjacent blocks when there is a difference in head between two blocks according to Darcy's law. In figure 23, Darcy's Law is shown for Block 2. The equation states that the flow through Block 2 is proportional to the hydraulic conductivity of the block, the cross sectional area (in the vertical) of the block, the difference in head (driving force) across the block, and inversely proportional to the length of the block. In the context of flow, aquifer blocks are analogous to pipes in the network model.

In contrast to the pipeline mode, the storage properties are also assigned to the blocks instead of the nodes (in the aquifer case these would be all the block interfaces and would be a surface instead of a single junction). Figure 4.6 is a schematic of the storage properties represented at a block.

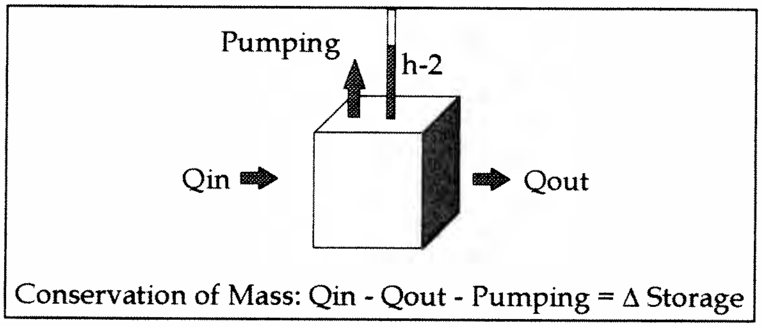


Figure 4.6. Schematic of Block Storage Principles

The figure shows a generic block. The storage properties are simply a statement of mass conservation across the block faces. The change in storage is expressed as the product of aquifer head, block plan view area, and the block storage coefficient. The storage coefficient relates the amount of water in storage at any instant to the head in the aquifer at any instant. Typical values range from near the aquifer's porosity, to values several orders of magnitude smaller depending on the dominant storage mechanism.

A balance equation for each block is written that relates head differences in adjacent blocks, storage properties, pumpage and recharge, to the rate of change of head in the block of interest. These equations are then "assembled" (shown pictorially in Figure 4.7), into a set of simultaneous linear equations, which are then solved to produce a set of heads that satisfy the flow and storage requirements of the aquifer.

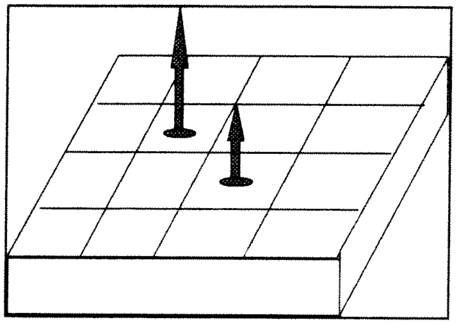


Figure 4.7. Aquifer Block Assembly

The creation of the equations, assembly, and solution is carried out using the MODFLOW aquifer simulation model. To simulate any aquifer we need to specify the geometry, transmission and storage properties, pumpage and recharge conditions. The model will produce the required heads to satisfy these conditions in the aquifer (or the drawdowns).

Hydraulic Network Setting for This Research

Figure 4.8 and 4.9 below shows the study area pipeline network and the pumping stations (well field) locations that were used in this research. These maps and subsequent maps in this section are all printed at the same scale and are intended to serve as overlays. The envelope in the back of this report contains the overlays printed on clear acetate.

The pipelines shown on the figures represent a conceptualization of pipelines in the study area of one foot diameter and greater. The pumping stations are treated as supply nomed in the computer model. Two eastern edge nodes are identified as surface water supplies and are treated as fixed grade nodes and water is allowed to enter the model to satisfy the conservation balance equations. One extreme node in the southwestern corner of the model is also a fixed grade node used to force non-zero system pressures in the simulation model.

The hydraulic requirements of each pumping station were determined from historical and reported maximum capacities for each station from the monthly well report. Figure 4.10 shows the plant capacities in millions of gallons per day that could be produced by each plant.

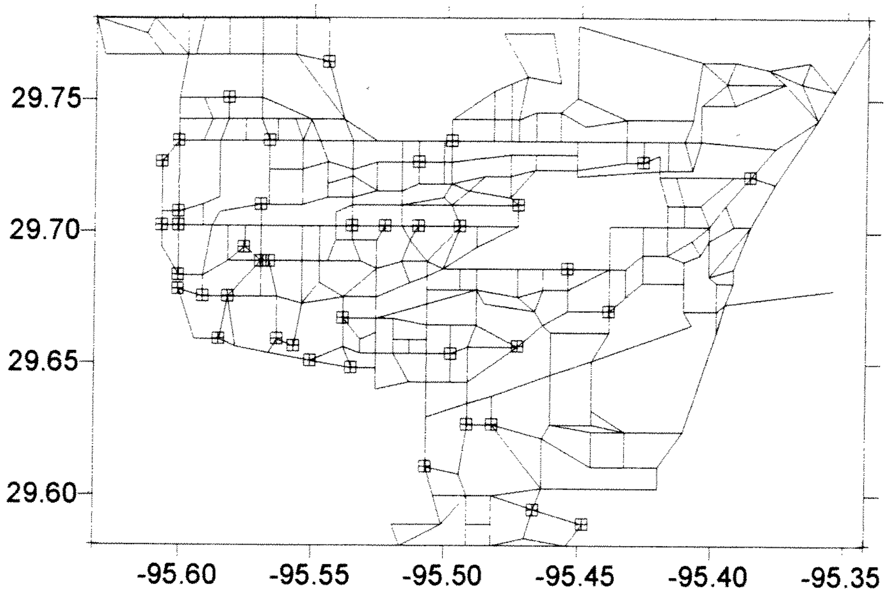


Figure 4.7. Distribution Network System Showing Pipelines and the Locations of Pumping Plants (Wellfields).

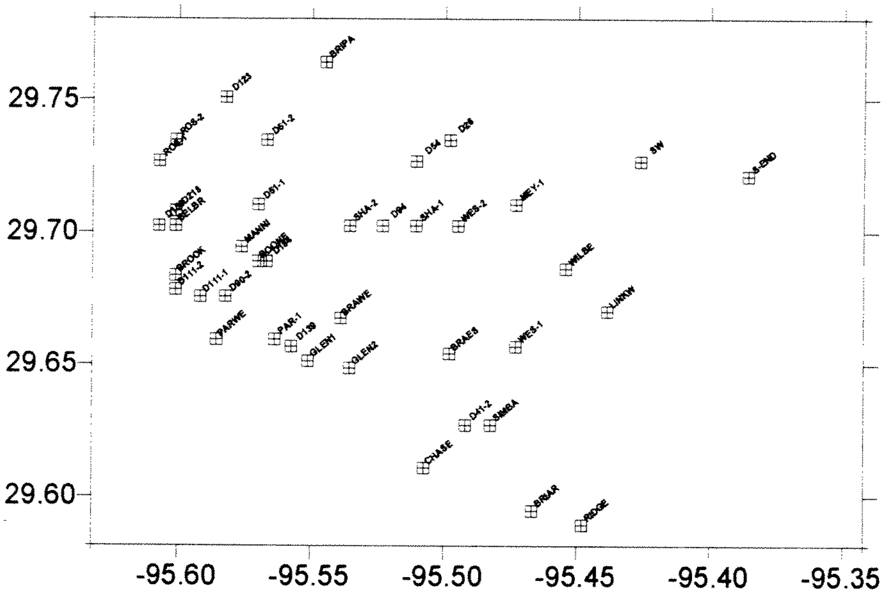


Figure 4.8 Locations of Pumping (Supply) Stations in Model

Southwest Houston Service Area																
Unit Water Cost																
			Plant Capacity in Million Gallons/31.25 days (i.e. MG/Month)													
	Serv.		Date													
Node#	Units	Plant Name	Aug-92	Sep-92	Oct-92	Nov-92	Dec-92	Jan-93	Feb-93	Mar-93	Apr-93	May-93	Jun-93	Count	Sum	Average
	1	BellaireBraes	406	406	406	406	406	406	406	406	406	406	406	11.00	4465	406
	1	BooneRoad	26	26	26	26	26	26	26	26	26	26	26	11.00	287	26
	2	Braeswood	95	95	95	95	95	95	95	95	95	95	95	11.00	1040	95
	1	BriargrovePark	45	45	45	45	45	45	45	45	45	45	45	11.00	495	45
	1	Briarwick	63	63	63	63	63	63	63	63	63	63	63	11.00	693	63
	1	Brookfield	35	35	35	35	35	35	35	35	35	35	35	11.00	386	35
	3	Chasewood	185	185	185	185	185	185	185	185	185	185	185	11.00	2039	185
	1	D_111_1	50	50	50	50	50	50	50	50	50	50	50	11.00	545	50
	1	D_111_2	57	57	57	57	57	57	57	57	57	57	57	11.00	629	57
	2	D_123	124	124	124	124	124	124	124	124	124	124	124	11.00	1361	124
	1	D_139	30	30	30	30	30	30	30	30	30	30	30	11.00	334	30
	3	D_158	85	85	85	85	85	85	85	85	85	85	85	11.00	936	85
	1	D_184	89	89	89	89	89	89	89	89	89	89	89	11.00	978	89
	2	D_218	144	144	144	144	144	144	144	144	144	144	144	11.00	1584	144
		D_41	109	109	109	109	109	109	109	109	109	109	109	11.00	1200	109
	1	D_51_1	57	57	57	57	57	57	57	57	57	57	57	11.00	631	57
	1	D_51_2	72	72	72	72	72	72	72	72	72	72	72	11.00	790	72
	2	D_54	176	176	176	176	176	176	176	176	176	176	176	11.00	1931	176
	1	D_90_2	45	45	45	45	45	45	45	45	45	45	45	11.00	500	45
	1	D_94	93	93	93	93	93	93	93	93	93	93	93	11.00	1025	93
	1	FairdaleD_26	155	155	155	155	155	155	155	155	155	155	155	11.00	1705	155
	1	Glenshire_1	43	43	43	43	43	43	43	43	43	43	43	11.00	478	43
	1	Glenshire_2	38	38	38	38	38	38	38	38	38	38	38	11.00	413	38
		Houston_3														
	1	Manning	47	47	47	47	47	47	47	47	47	47	47	11.00	512	47
	1	Meyerland_1	50	50	50	50	50	50	50	50	50	50	50	11.00	545	50
		Meyerland_2														
	1	MUD_98	54	54	54	54	54	54	54	54	54	54	54	11.00	594	54
	1	ParkglenWest	43	43	43	43	43	43	43	43	43	43	43	11.00	470	43
	1	Parkglen_1	34	34	34	34	34	34	34	34	34	34	34	11.00	371	34
	1	Ridgemont	48	48	48	48	48	48	48	48	48	48	48	11.00	525	48
	1	Rosewood_1	140	140	140	140	140	140	140	140	140	140	140	11.00	1535	140
	1	Rosewood_2	37	37	37	37	37	37	37	37	37	37	37	11.00	406	37
	1	Sharpstown_1	140	140	140	140	140	140	140	140	140	140	140	11.00	1542	140
	1	Sharpstown_2	101	101	101	101	101	101	101	101	101	101	101	11.00	1109	101
	1	SimsBayou	484	484	484	484	484	484	484	484	484	484	484	11.00	5321	484
	4	SouthEnd	306	306	306	306	306	306	306	306	306	306	306	11.00	3364	306
		Southwest	931	931	931	931	931	931	931	931	931	931	931	11.00	10237	931
	1	Westbury_1	71	71	71	71	71	71	71	71	71	71	71	11.00	782	71
	1	Westbury_2	93	93	93	93	93	93	93	93	93	93	93	11.00	1020	93
	1	Willowbend	21	21	21	21	21	21	21	21	21	21	21	11.00	233	21
	2	Linkwood	53	53	53	53	53	53	53	53	53	53	53	11.00	585	53
	1	BraeburnWest	40	40	40	40	40	40	40	40	40	40	40	11.00	441	40

Figure 4.11. Plant Capacity Table (Based on Historical/Nominal Capacity from Monthly Well Reports)

Hydrologic Setting for This Research

Southwest Houston groundwater wells were considered to be connected with Evangeline Aquifer and this aquifer was referred as Southwest Houston Study Area Aquifer. In order to simplify this simulation problem, Southwest Houston aquifer was set up as a 2,000 ft thick confined aquifer which was 105,700 ft long and 26,530 ft wide. No-flow boundaries were employed in this modeling and external recharge was applied along the boundaries by means of recharge wells. The model's purpose is to simulate drawdowns near wellfields due to groundwater pumping. Figure 4.12 is a schematic of the Conceptual Model of the Southwest Houston Study Area Aquifer.

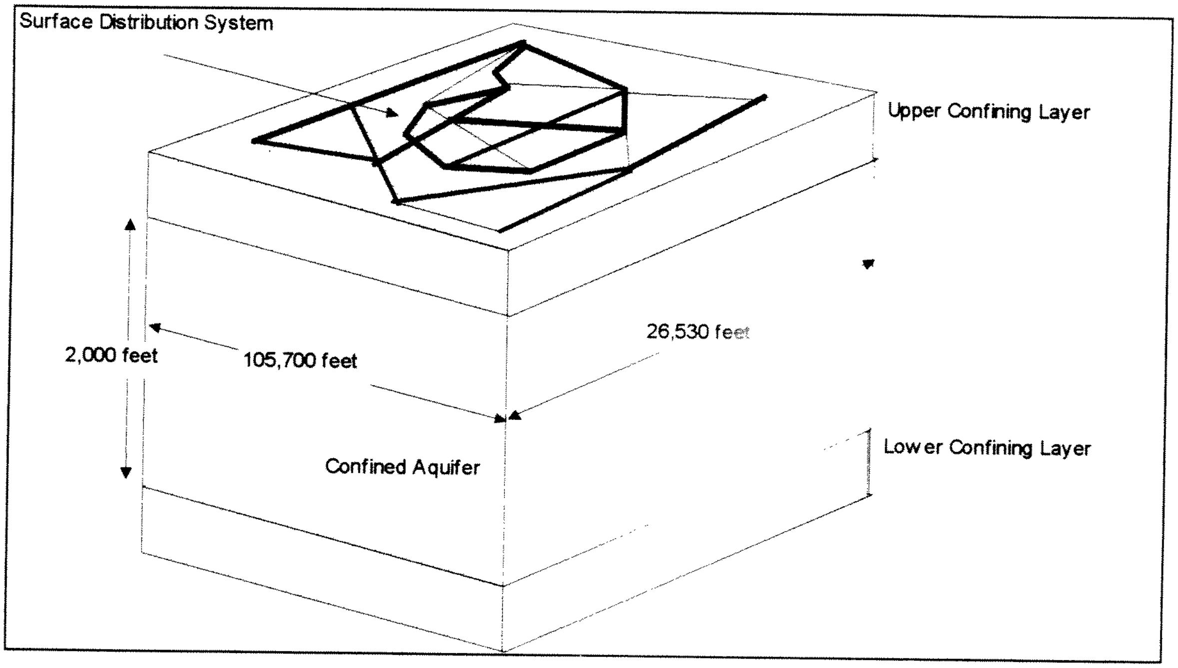


Figure 4.12. Conceptual Model of the Southwest Houston Study Area Aquifer.

The Southwest Houston Study Area Aquifer was discritized as 2,000 blocks (50 columns and 40 rows). Each of the 16 cells occupying 4 corners of the aquifer had a 4,000 ft by 4,000 ft area and the remaining cells have a 1,950 ft by 1,950 ft area. Figure 4.13 is a diagram of the model grid system.

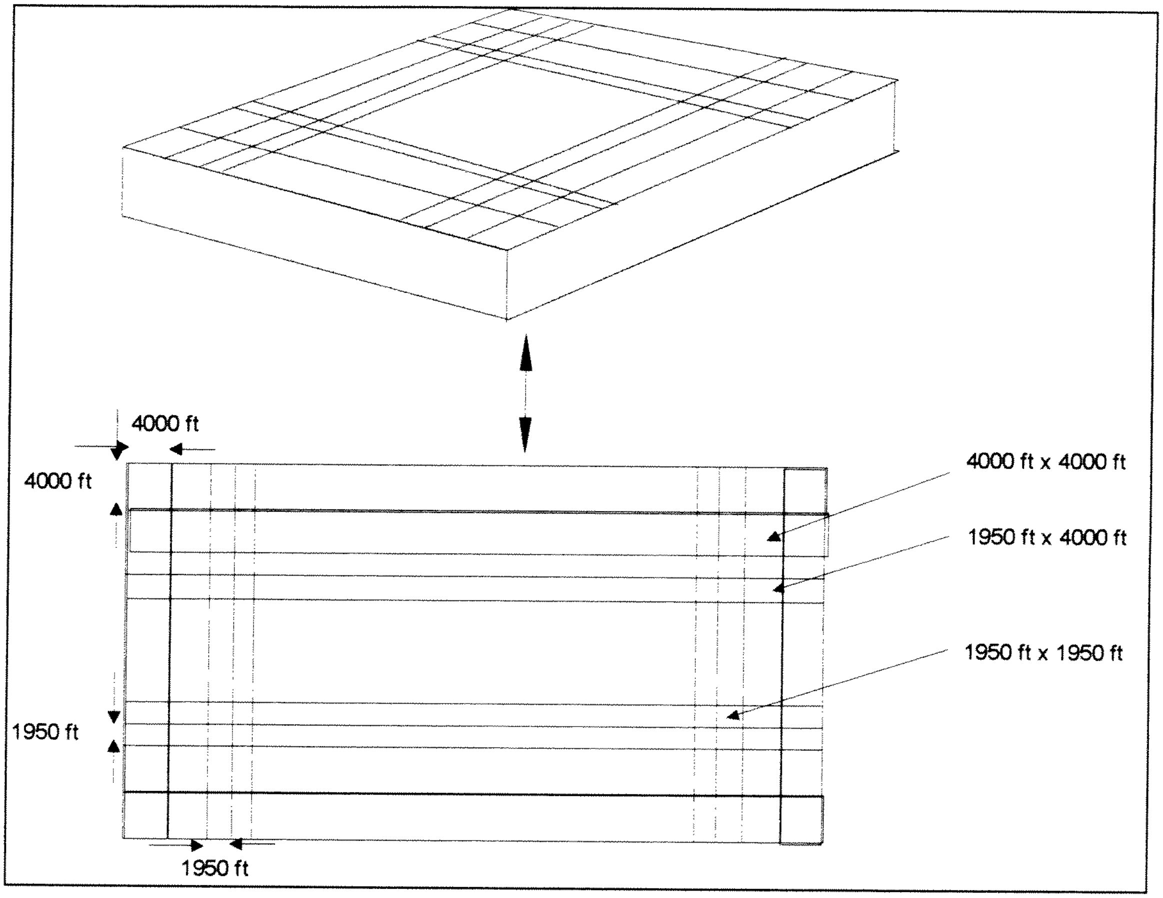


Figure 4.13. Model Grid System

The aquifer blocks are assumed to behave as confined aquifers and groundwater flow is governed by Darcy's law. The aquifer was heterogeneous in terms of transmissivity which varied (after trail-and-error calibration) in a range of 10 to $9.99\text{x}10^6$ ft^2/day. These transmissivities are values that predict drawdowns due to groundwater pumping. The simulated drawdowns are averages for an entire cell and will not be exactly the same as those in individual wells.

Calibration Procedure

The MODFLOW Basic Package, Block-Centered Flow Package, Well package, and Strongly Implicit Package were employed in the following fashion:

- The grid and hydrology incorporating the conceptualizations were coded into MODFLOW files.
- An initial head of 1 foot was arbitrarily used to simulate drawdowns of groundwater pumping in the Basic Package file because the initial head was dies not affect the values of drawdown. The stress period length was one month.
- Transmissivity values were placed in the Block-Centered Flow package. A storage coefficient of 0.008 was used based on data in "Texas Water Development Board Report 190". A uniform transmissivity of 1,000 ft^2/day was considered as the initial model, with this value were changing by trial and error to match the historical drawdowns (from monthtly well reports).

- The pumping rates of August 1992 were used as the calibration period, and were incorporated into Well Package.

- Once these packages were loaded, the first simulation was conducted. The values of drawdown obtained from the first simulation were compared with the real values of August 1992 and they did not match well with each other. The transmissivities were then changed and the simulation repeated until an acceptable match was achieved.

The results of the calibration simulation (using August 1992 pumping data) are shown in Figure 4.14 below.

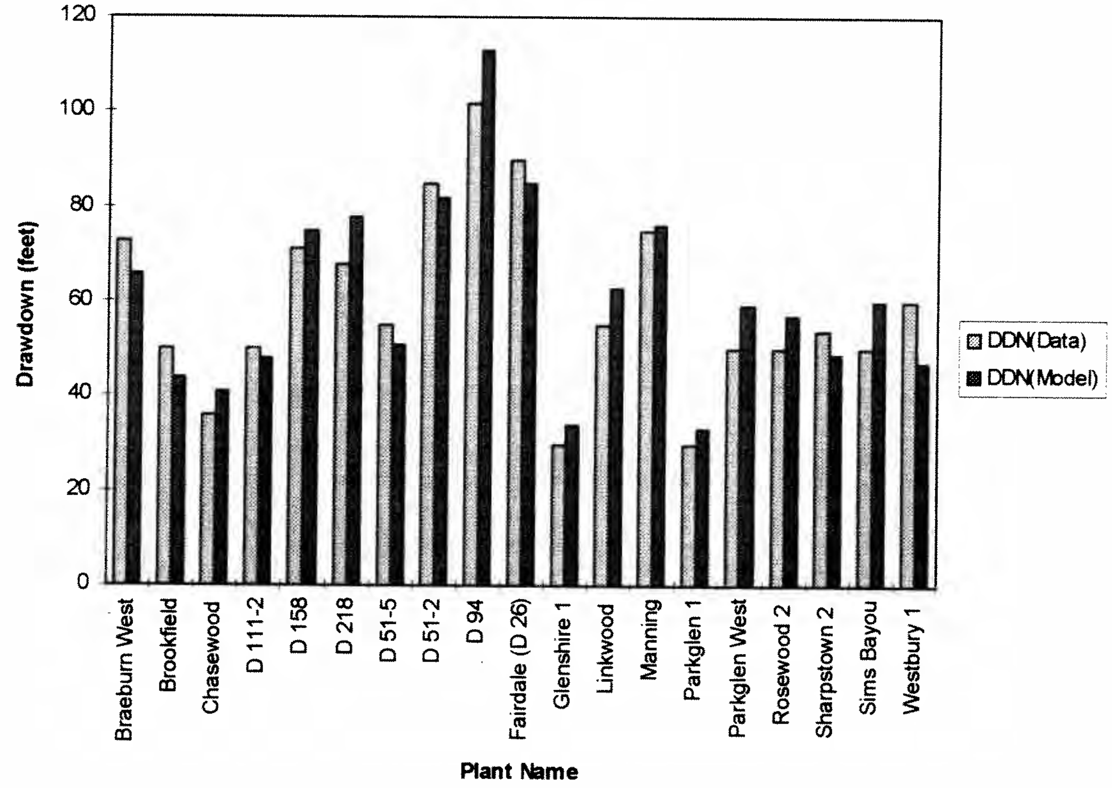


Figure 4.14. Simulated and Historical Drawdowns for August 1992

The simulated drawdowns in this case are slightly greater than the historical drawdowns.

The same input data were then used to simulate the next month with only the pumping rates (September 1992 pumping data) changed. The results of this simulation are shown in Figure 4.15 below.

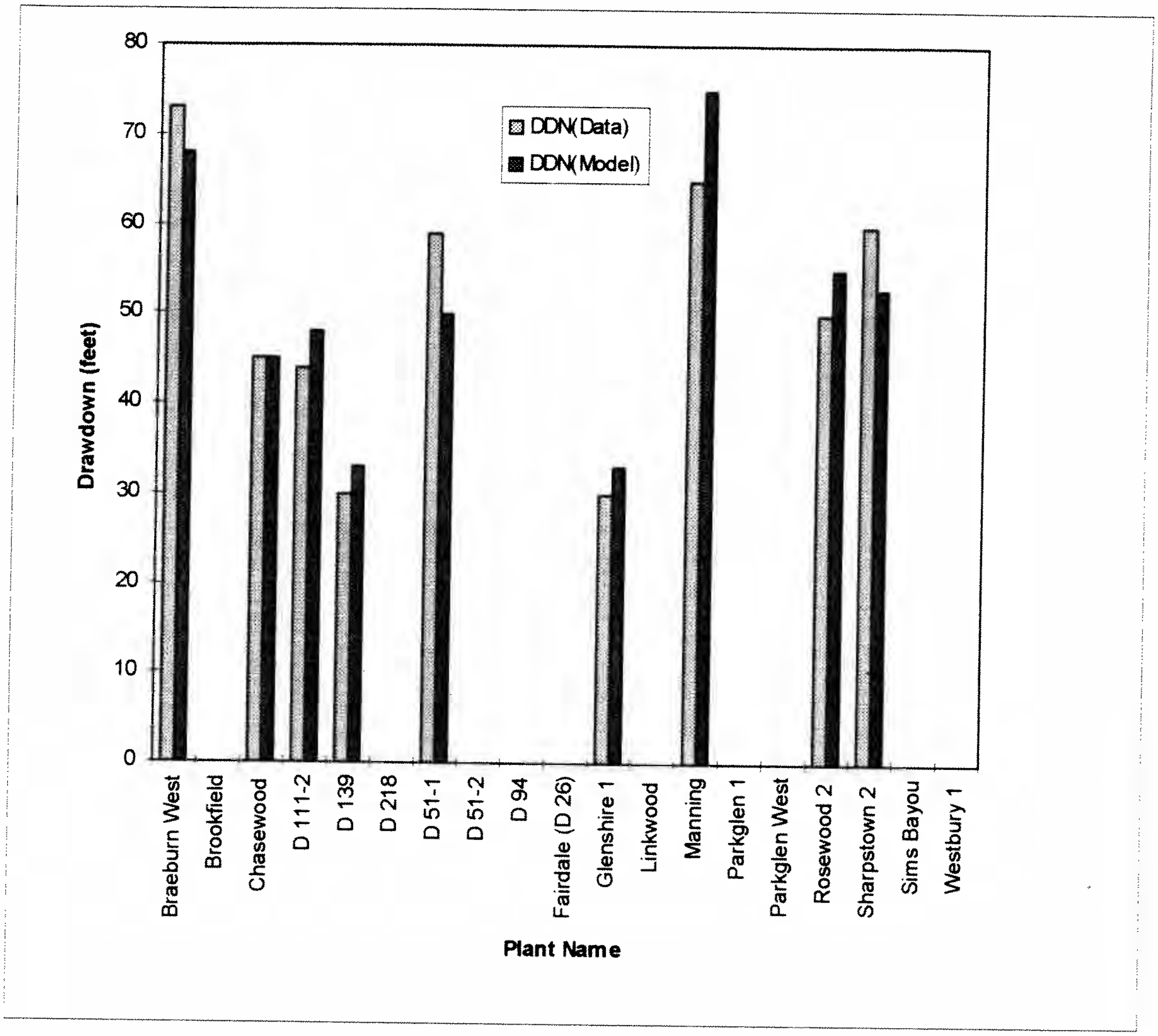


Figure 4.15. Simulated and Historical Drawdowns for September 1992

The simulated drawdowns in this case are slightly greater at some contorl points, and smaller at others. The maximum error in both cases is about 20%, which we consider accurate enough for identifying important performance trends in the simulation-optimization cases, and the predictions are in the same order of magnitude as the real drawdowns.

To summarize the groundwater modeling component of this research:

- A conceptual groundwater aquifer model has been set up for the southwest Houston area: the domain of this aquifer has a 105,700 ft x 26,530 ft area and this aquifer is a confined aquifer which has thickness of 2,000 ft.

- A range of transmissivity for modeling purpose has been achieved which is 10 to 9.99×10^6 ft^2/day and the storage coefficient chosen as 0.008.

- The model can predict drawdowns of groundwater pumping in a reasonable accuracy: the error is in a range of 4-20%, most time about 10%.
- The model is intended only to predict drawdown at the selected plants and should not be used for regional aquifer simulation without further testing and calibration.

Once the drawdowns are computed, a rough estimate of land subsidence can be obtained from the following equation based on analysis of an extensive confined aquifer by Bear and Corapcioglu (1981).

$$\delta(block) = \frac{S}{2} s(block) \tag{4.1}$$

where δ is the average block subsidence, S is the storage coefficient of the block, and s is the computed (average) block drawdown. Equation 1 is a very rough estimate, based on a model that is not designed to explain behavior in aquifers with variable formation properties, however it does give useful estimates.

For example, the storage coefficient in the Baytown area is on the order of 0.008 (Cleveland, et al., 1992). The drawdown in Baytown on 12/3/77 from one month earlier was roughly 27 feet. Using the formula one would predict a land subsidence value of 1.3 inches. The measured land subsidence was on the order of 0.6 inches. In this example the formula overpredicts by a factor of about two; which is a reasonable order of magnitude estimate.

KYPIPE2 Simplified User Instructions

Building a Pipeline Network Model using KYPIPE program

This set of instructions describes how to construct a KYPIPE pipeline network model for use in determining the effects of water distributions on the pipeline network.

The instructions use a step-by-step example to show how to use the KYPIPE file builder programs (the KYPIPE built-in editor and one preprocessor program) to build the correct input files required by the KYPIPE model. Also a step-by-step example to show how to use the KYPIPE built-in tools to view and analyze the output of the KYPIPE program.

Before Building the Model

The KYPIPE model requires many different items of data that are generally inconvenient to collect during the actual file-building process. Before building the files organize your data (on paper) into the following groups:

Model geometry
You should have a pipeline network map.

Node Properties
You need to know the number of pipes and nodes.
You need to know the elevation of the nodes.
You need to know the demand and recharge of the nodes.

Pipe Properties
You need to know the diameters of the pipes.
You need to know the friction coefficients of the pipes.
You need to know the head losses of the pipes.

Others
You need to know the locations of the reservoirs (if there're reservoirs).
You need to know the locations of the values (if there're values).

The most-used KYPIPE built-in tools are:

PIPEDATA - Data Entry / Editing
KYPIPE - Network Analysis
VIEW - View Files on Screen
PIPEVIEW - Screen Graphic Displays
PRINT - Print Results Using Printer
HELP - Review KYPIPE Help Information

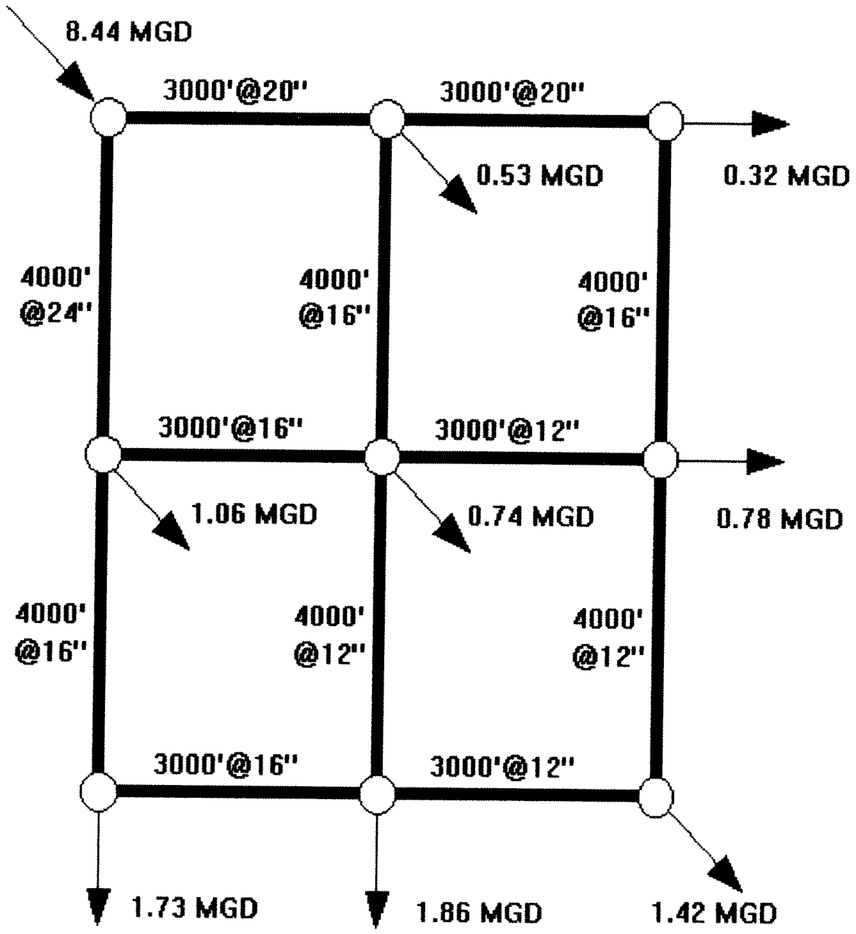
Additionally a user-friendly graphical preprocessor for arranging pumpage of selected 41 pump stations is included in this report. We built this preprocessor to help you do the water management task without using the not-so-friendly KYPIPE built-in tools.

Now for the example:

KYPIPE INPUT Example

KYPIPE built-in editor, PIPEDATA, is used to generate input data files for KYPIPE. KYPIPE is a DOS application. KYPIPE2 can be run under either DOS or MS Windows 3.1. We strongly recommend running KYPIPE2 under DOS, because it will run much faster under DOS environment.

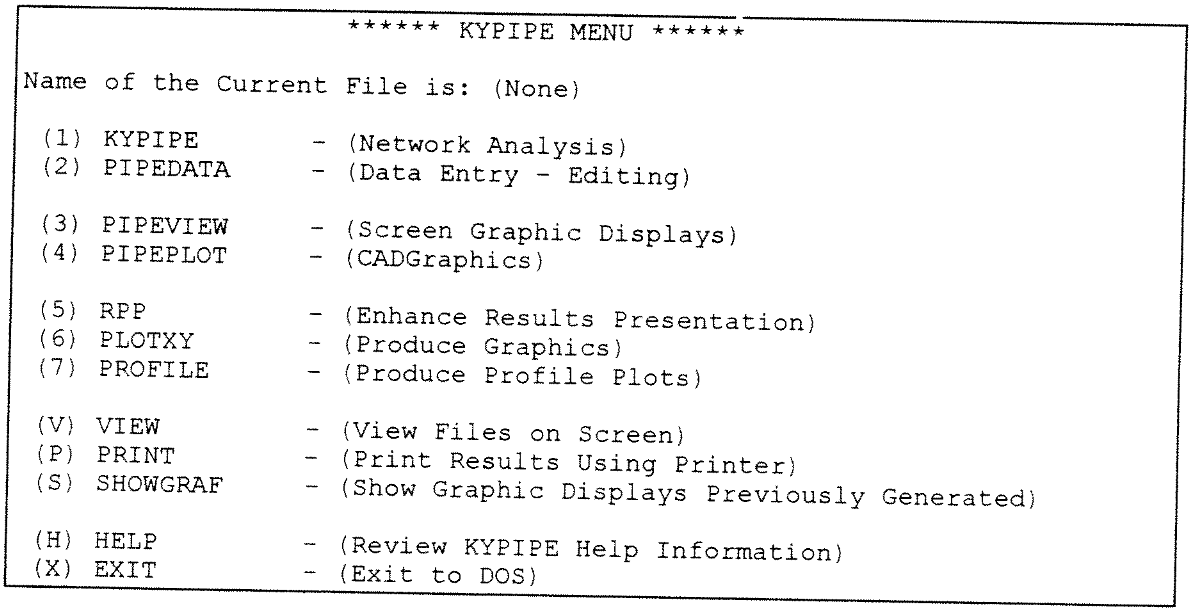
The example shown in here is a 12 pipes, 9 nodes pipeline network. The water inflow and outflow in this example is based on the demand estimation data of Oct. 1993 of Blockmap 490.


8.44 MGD
3000'@20"
3000'@20"
0.53 MGD
0.32 MGD
4000'
@24"
4000'
@16"
4000'
@16"
3000'@16"
3000'@12"
1.06 MGD
0.74 MGD
0.78 MGD
4000'
@16"
4000'
@12"
4000'
@12"
3000'@16"
3000'@12"
1.73 MGD
1.86 MGD
1.42 MGD

Starting KYPIPE2 program

Step 1: change the current directory into KYPIPE2 directory

Step 2: key-in the following command "KY2" to start the program. A menu, KYPIPE MENU should appear similar to the figure shown below:



```
                    ****** KYPIPE MENU ******

Name of the Current File is: (None)

 (1) KYPIPE       - (Network Analysis)
 (2) PIPEDATA     - (Data Entry - Editing)

 (3) PIPEVIEW     - (Screen Graphic Displays)
 (4) PIPEPLOT     - (CADGraphics)

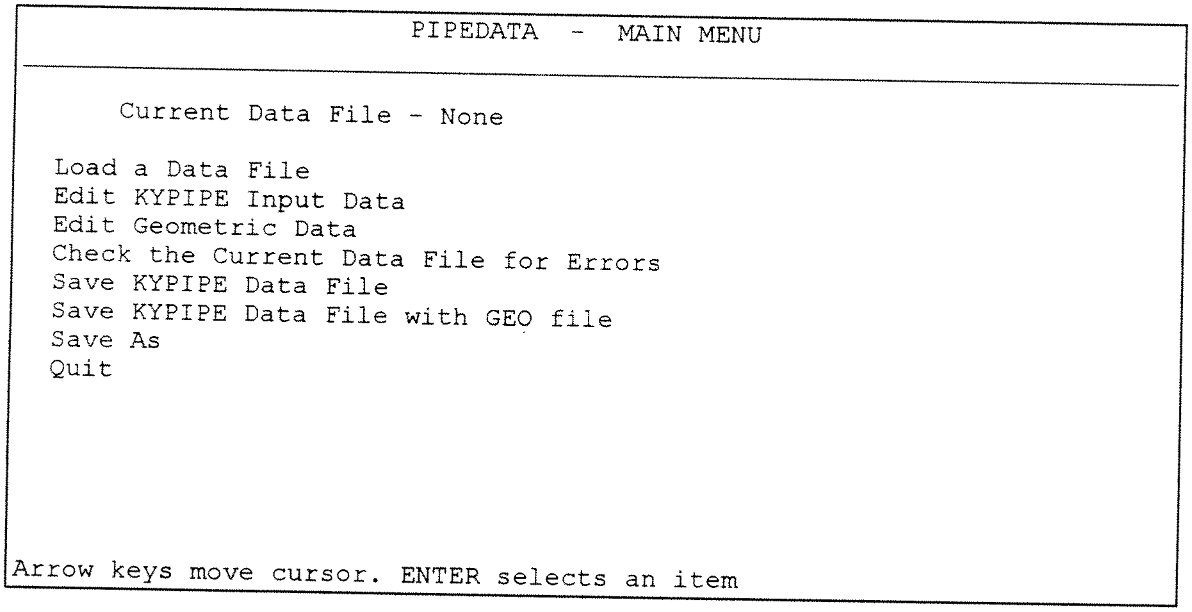
 (5) RPP          - (Enhance Results Presentation)
 (6) PLOTXY       - (Produce Graphics)
 (7) PROFILE      - (Produce Profile Plots)

 (V) VIEW         - (View Files on Screen)
 (P) PRINT        - (Print Results Using Printer)
 (S) SHOWGRAF     - (Show Graphic Displays Previously Generated)

 (H) HELP         - (Review KYPIPE Help Information)
 (X) EXIT         - (Exit to DOS)
```

Starting PIPEDATA module

Step 1: key-in "2" to choose PIPEDATA from KYPIPE MENU. A PIPEDATA MAIN MENU should appear as shown below:



```
                        PIPEDATA  -  MAIN MENU
______________________________________________________________________

     Current Data File - None

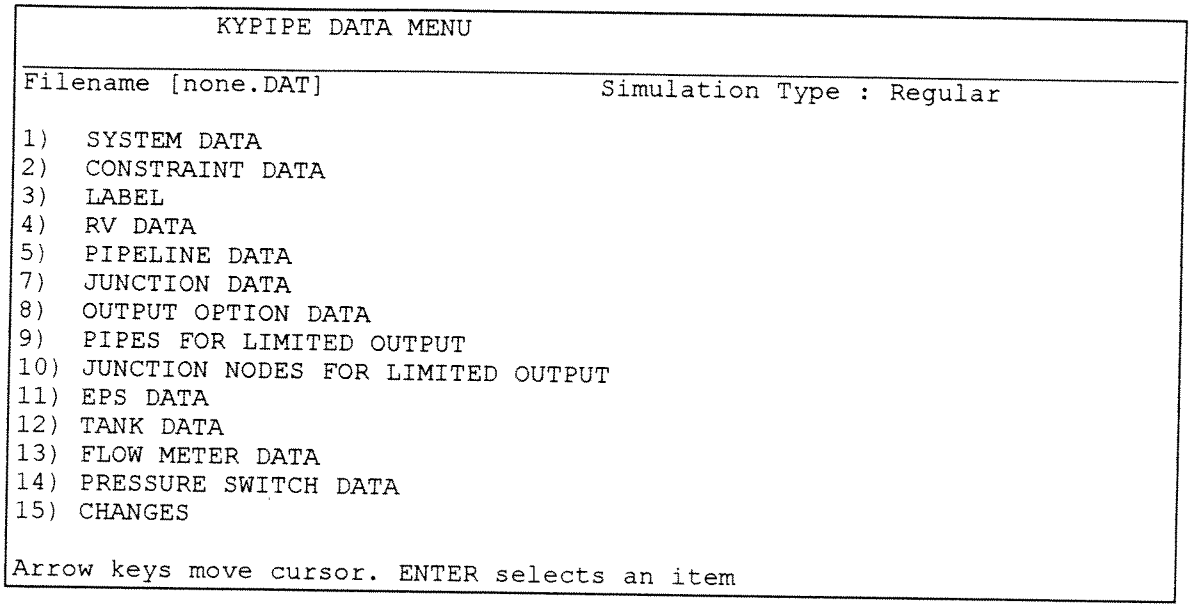
 Load a Data File
 Edit KYPIPE Input Data
 Edit Geometric Data
 Check the Current Data File for Errors
 Save KYPIPE Data File
 Save KYPIPE Data File with GEO file
 Save As
 Quit





Arrow keys move cursor. ENTER selects an item
```

Step 2: Select "Edit KYPIPE Input Data" to create a new file. The following menu should appear:

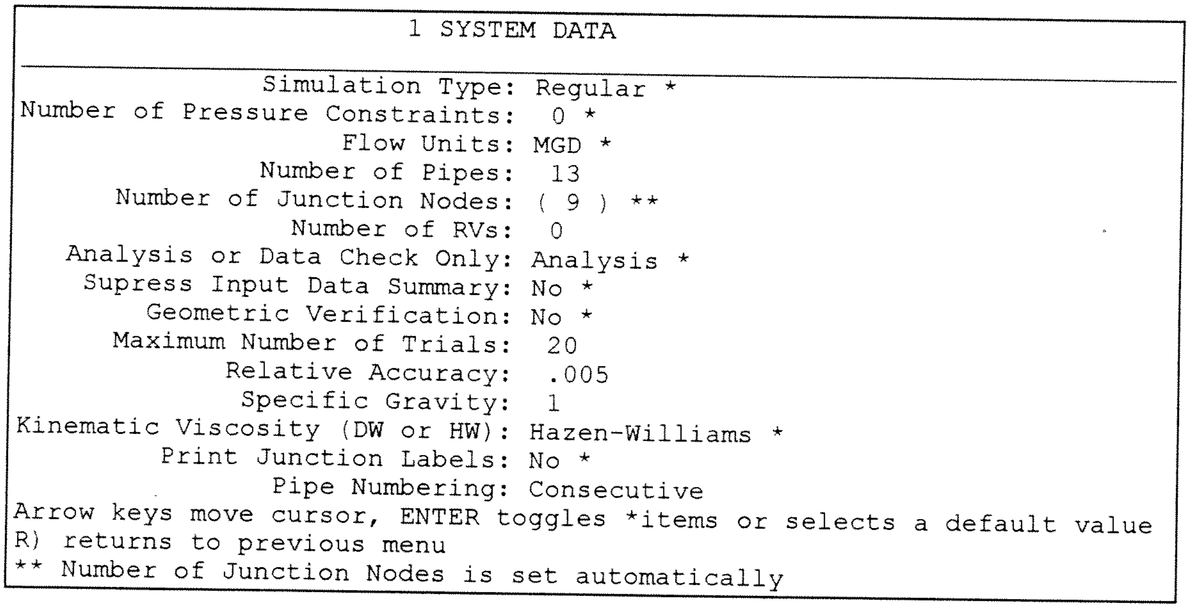


```
              KYPIPE DATA MENU
---------------------------------------------------------------------
Filename [none.DAT]                 Simulation Type : Regular

1)  SYSTEM DATA
2)  CONSTRAINT DATA
3)  LABEL
4)  RV DATA
5)  PIPELINE DATA
7)  JUNCTION DATA
8)  OUTPUT OPTION DATA
9)  PIPES FOR LIMITED OUTPUT
10) JUNCTION NODES FOR LIMITED OUTPUT
11) EPS DATA
12) TANK DATA
13) FLOW METER DATA
14) PRESSURE SWITCH DATA
15) CHANGES

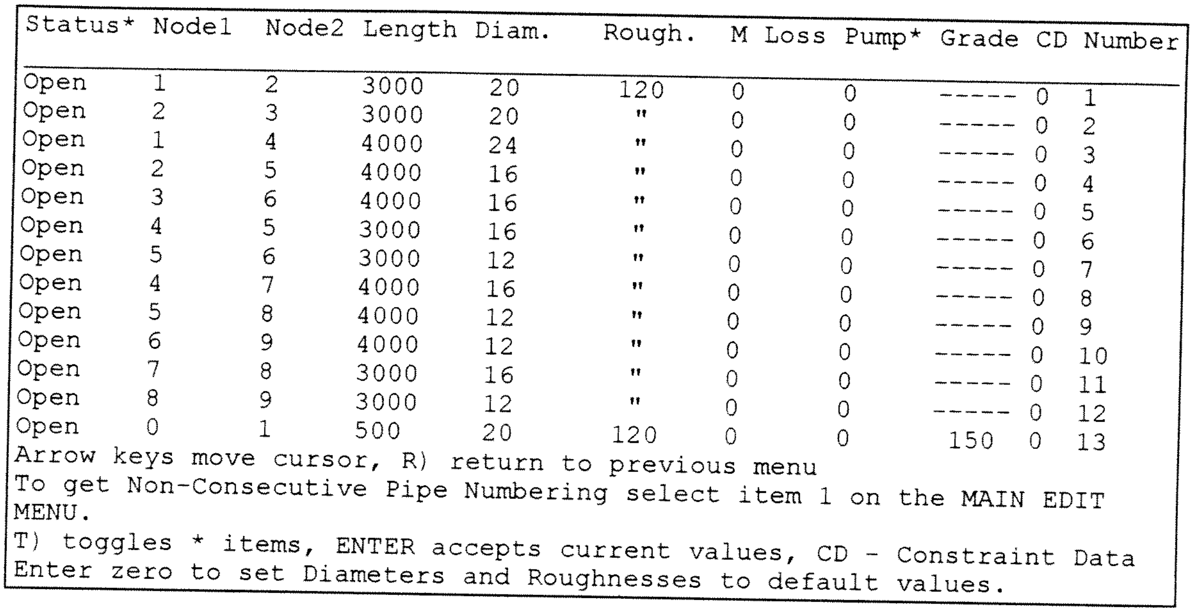
Arrow keys move cursor. ENTER selects an item
```

Step 3: Select "SYSTEM DATA" to edit the basic system data. The following menu appears: (entering the correct number into the menu)



```
                        1 SYSTEM DATA
---------------------------------------------------------------------
               Simulation Type: Regular *
Number of Pressure Constraints:  0 *
                    Flow Units: MGD *
               Number of Pipes:  13
      Number of Junction Nodes: ( 9 ) **
                Number of RVs:  0
   Analysis or Data Check Only: Analysis *
    Supress Input Data Summary: No *
        Geometric Verification: No *
      Maximum Number of Trials:  20
             Relative Accuracy:  .005
              Specific Gravity:  1
Kinematic Viscosity (DW or HW): Hazen-Williams *
         Print Junction Labels: No *
               Pipe Numbering: Consecutive
Arrow keys move cursor, ENTER toggles *items or selects a default value
R) returns to previous menu
** Number of Junction Nodes is set automatically
```

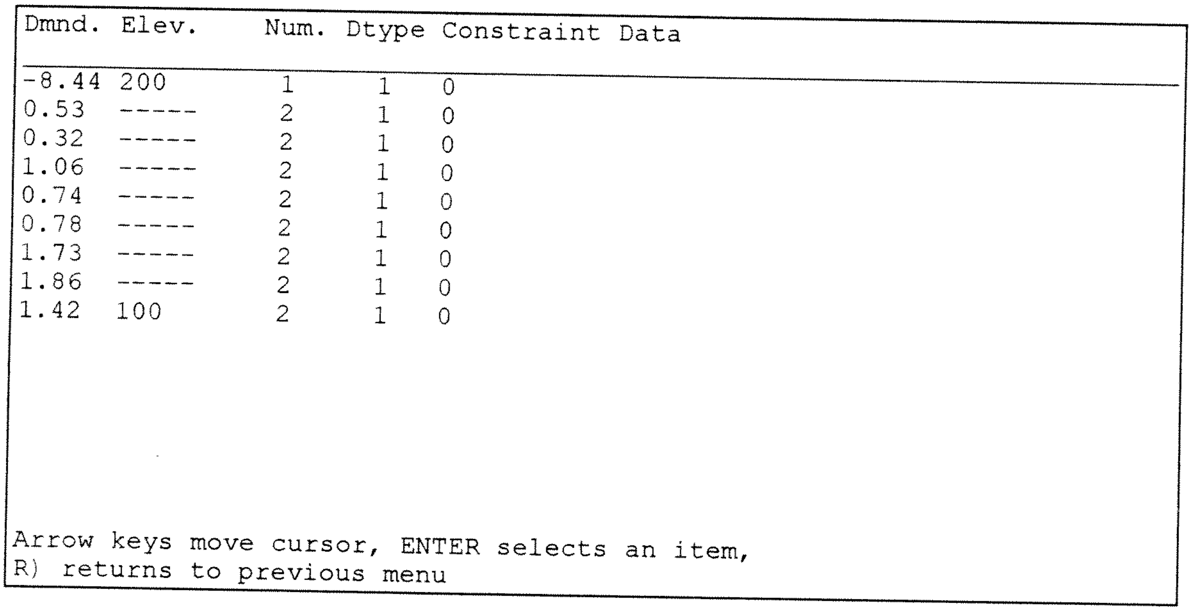
Step 4: After entering the correspond number, press "R" to return to the previous menu. Then choose "PIPELINE DATA" to edit pipelines.



```
Status* Node1  Node2 Length Diam.    Rough.  M Loss  Pump* Grade CD Number

Open     1      2     3000    20      120     0       0    -----  0  1
Open     2      3     3000    20       "      0       0    -----  0  2
Open     1      4     4000    24       "      0       0    -----  0  3
Open     2      5     4000    16       "      0       0    -----  0  4
Open     3      6     4000    16       "      0       0    -----  0  5
Open     4      5     3000    16       "      0       0    -----  0  6
Open     5      6     3000    12       "      0       0    -----  0  7
Open     4      7     4000    16       "      0       0    -----  0  8
Open     5      8     4000    12       "      0       0    -----  0  9
Open     6      9     4000    12       "      0       0    -----  0  10
Open     7      8     3000    16       "      0       0    -----  0  11
Open     8      9     3000    12       "      0       0    -----  0  12
Open     0      1     500     20      120     0       0     150   0  13
Arrow keys move cursor, R) return to previous menu
To get Non-Consecutive Pipe Numbering select item 1 on the MAIN EDIT
MENU.
T) toggles * items, ENTER accepts current values, CD - Constraint Data
Enter zero to set Diameters and Roughnesses to default values.
```

Step 5: Press "R" to return to the previous menu. Then choose "JUNCTION DATA" to edit junctions' data. The following screen should appear:



```
Dmnd.  Elev.     Num.  Dtype Constraint Data

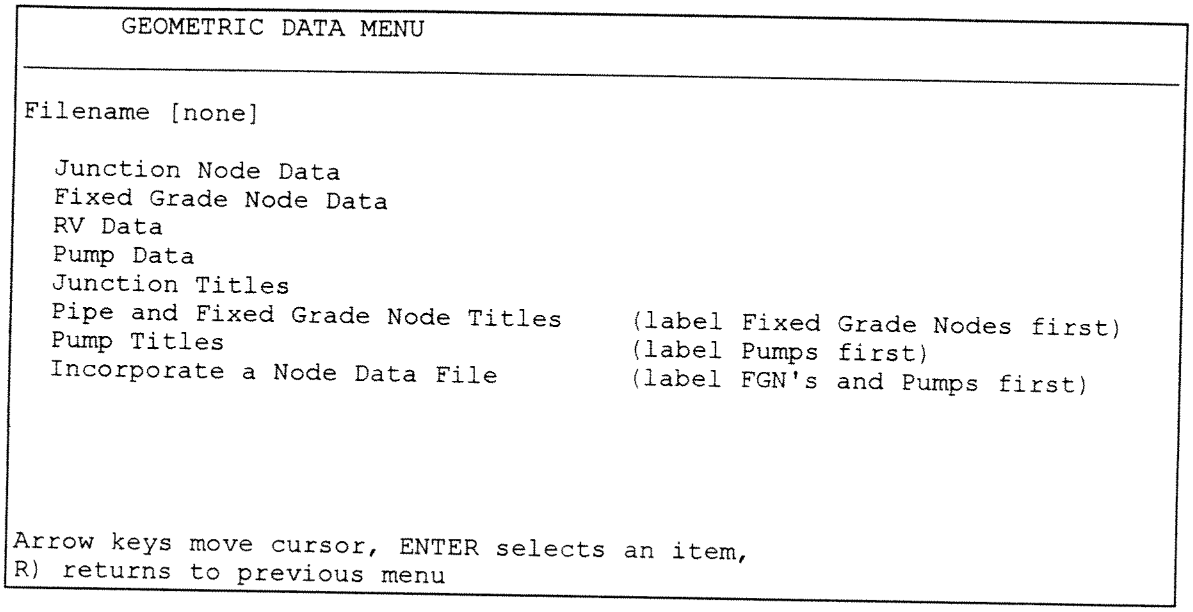
-8.44  200        1      1     0
0.53   -----      2      1     0
0.32   -----      2      1     0
1.06   -----      2      1     0
0.74   -----      2      1     0
0.78   -----      2      1     0
1.73   -----      2      1     0
1.86   -----      2      1     0
1.42   100        2      1     0






Arrow keys move cursor, ENTER selects an item,
R) returns to previous menu
```

Step 6: Press "R" to return to the previous menu. Then choose "Edit Geometric Data" to add geometrical information into KYPIPE. The following screen should appear:



```
      GEOMETRIC DATA MENU
___________________________________________________________________________

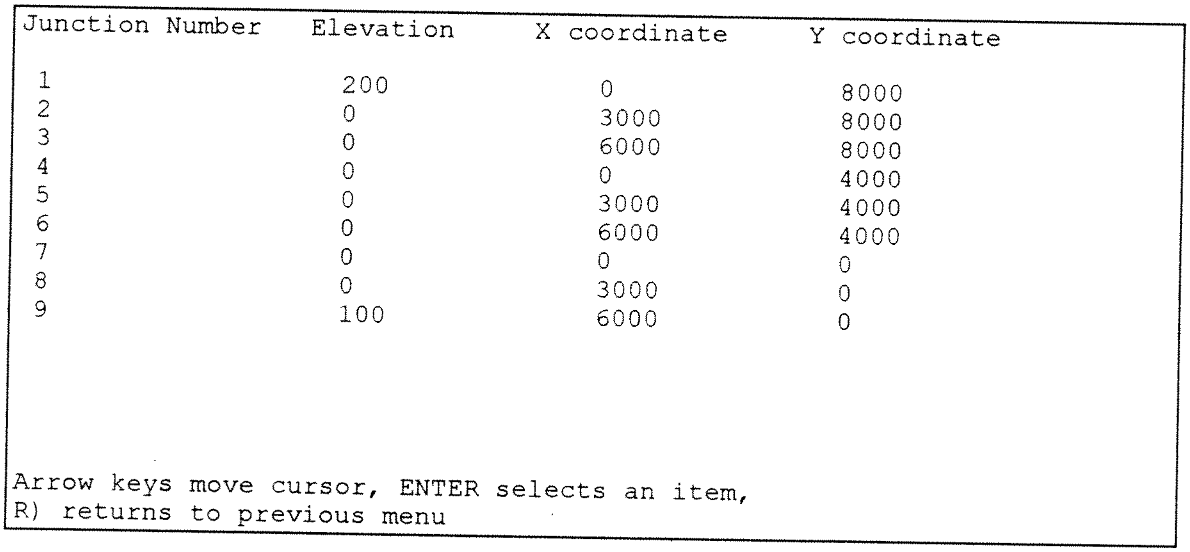
Filename [none]

  Junction Node Data
  Fixed Grade Node Data
  RV Data
  Pump Data
  Junction Titles
  Pipe and Fixed Grade Node Titles       (label Fixed Grade Nodes first)
  Pump Titles                            (label Pumps first)
  Incorporate a Node Data File           (label FGN's and Pumps first)




Arrow keys move cursor, ENTER selects an item,
R) returns to previous menu
```

Step 7: Choose "Junction Node Data" to add geometrical information of junctions. The following screen should appear:



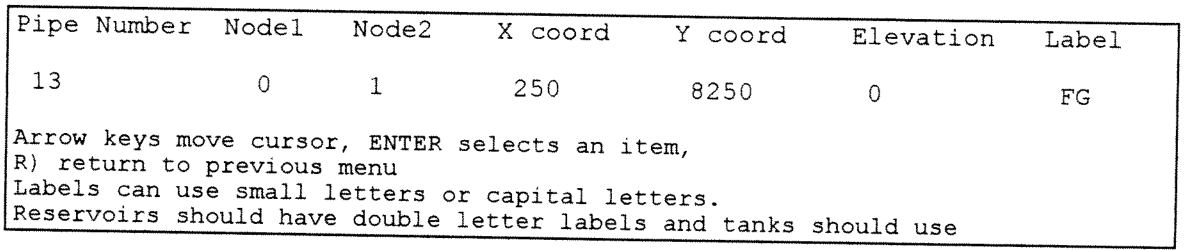
```
Junction Number   Elevation     X coordinate     Y coordinate

 1                  200            0                8000
 2                  0              3000             8000
 3                  0              6000             8000
 4                  0              0                4000
 5                  0              3000             4000
 6                  0              6000             4000
 7                  0              0                0
 8                  0              3000             0
 9                  100            6000             0




Arrow keys move cursor, ENTER selects an item,
R) returns to previous menu
```

Step 8: Press "R" to return to the previous menu. Choose "Fixed Grade Node Data" to edit fixed grade node data. The following screen should appear:



```
Pipe Number  Node1   Node2    X coord    Y coord    Elevation   Label

 13            0       1        250        8250       0           FG

Arrow keys move cursor, ENTER selects an item,
R) return to previous menu
Labels can use small letters or capital letters.
Reservoirs should have double letter labels and tanks should use
```

single letters.

Step 9: Press "R" twice to return to the previous menu. Choose "Save KYPIPE Data File with GEO file" to save both KYPIPE Data file and KYPIPE Geometric file. In this example, we save files as "example1.dat" and "example1.geo".

Step 10: Choose "Quit" to leave PIPEVIEW.

Running KYPIPE Analysis Program

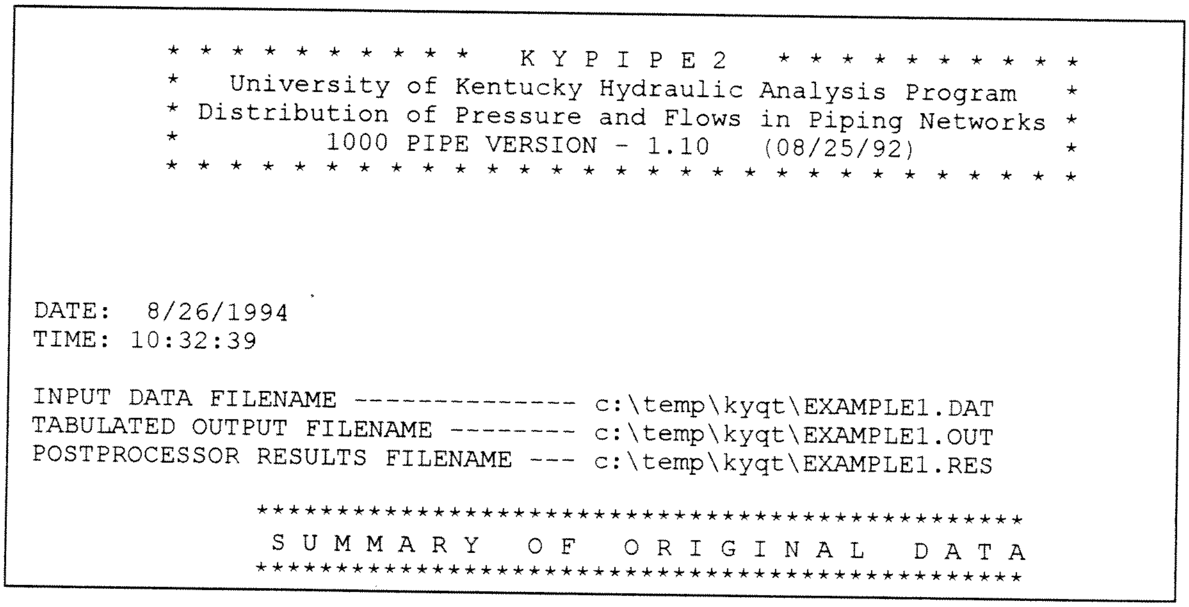
Step: Choose "KYPIPE" from the KYPIPE MENU to run the program.

Printing Result Using PRINT module

Step: Choose "PRINT" from the KYPIPE MENU to send the result file to a printer.

Using VIEW Module to See Results

Step 1: Choose "VIEW" from the KYPIPE MENU. The following screen should appear:



```
         * * * * * * * * * *   K Y P I P E 2   * * * * * * * * * *
         *   University of Kentucky Hydraulic Analysis Program   *
         * Distribution of Pressure and Flows in Piping Networks *
         *        1000 PIPE VERSION - 1.10   (08/25/92)          *
         * * * * * * * * * * * * * * * * * * * * * * * * * * * * *




DATE:  8/26/1994
TIME: 10:32:39

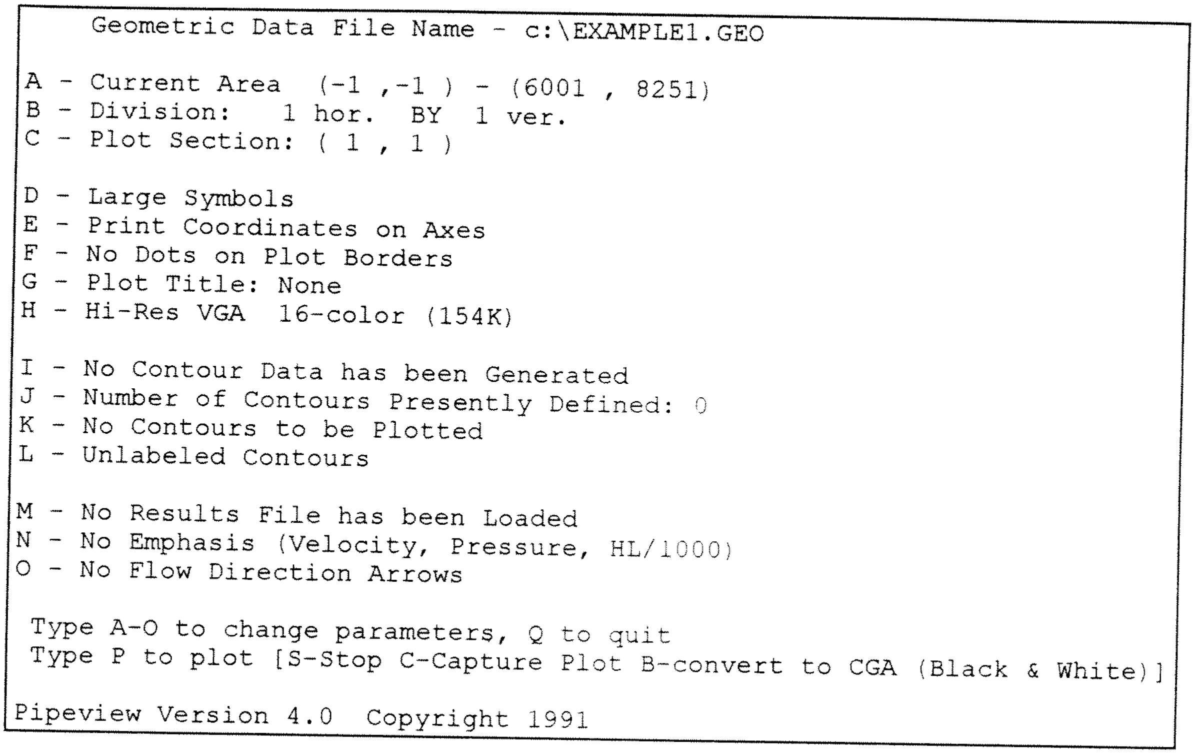
INPUT DATA FILENAME -------------- c:\temp\kyqt\EXAMPLE1.DAT
TABULATED OUTPUT FILENAME -------- c:\temp\kyqt\EXAMPLE1.OUT
POSTPROCESSOR RESULTS FILENAME --- c:\temp\kyqt\EXAMPLE1.RES

              ***********************************************
               S U M M A R Y   O F   O R I G I N A L   D A T A
              ***********************************************
```

Step2: Use arrow keys to view the whole file. Use "Esc" or "Q" to quit VIEW module.

Viewing Screen Graphic Displays Using PIPEVIEW Module

Step 1: Choose "PIPEVIEW" from the KYPIPE MENU. The following screen should appear:



```
    Geometric Data File Name - c:\EXAMPLE1.GEO

A - Current Area  (-1 ,-1 ) - (6001 , 8251)
B - Division:   1 hor.  BY  1 ver.
C - Plot Section: ( 1 , 1 )

D - Large Symbols
E - Print Coordinates on Axes
F - No Dots on Plot Borders
G - Plot Title: None
H - Hi-Res VGA  16-color (154K)

I - No Contour Data has been Generated
J - Number of Contours Presently Defined: 0
K - No Contours to be Plotted
L - Unlabeled Contours

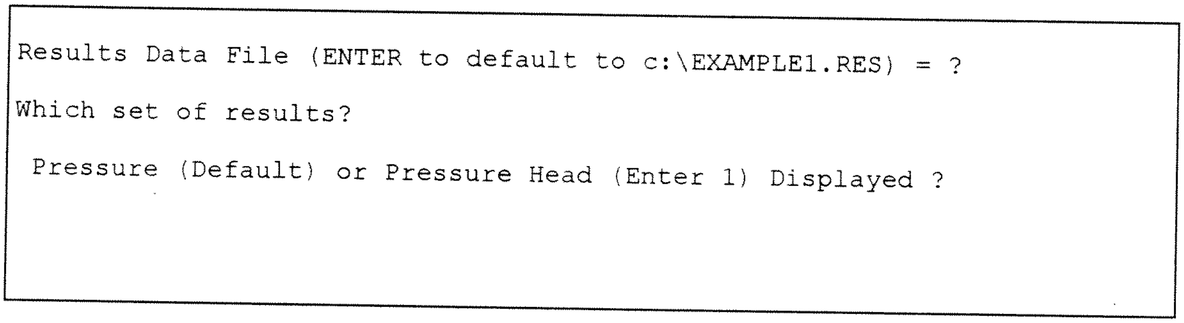
M - No Results File has been Loaded
N - No Emphasis (Velocity, Pressure, HL/1000)
O - No Flow Direction Arrows

 Type A-O to change parameters, Q to quit
 Type P to plot [S-Stop C-Capture Plot B-convert to CGA (Black & White)]

Pipeview Version 4.0  Copyright 1991
```

Step 2: To view the network plot, press "P" to see the plot. Press "S" to leave the plot screen.

Step 3: To view pressure contours in the plot, press "M" to load a result file. The following screen appears: Press "ENTER" to use default settings. After three "ENTER", the PIPEVIEW MENU should reappear.



```
Results Data File (ENTER to default to c:\EXAMPLE1.RES) = ?

Which set of results?

 Pressure (Default) or Pressure Head (Enter 1) Displayed ?
```

Step 4: Under the PIPEVIEW MENU screen. press "I" to generate contour data. In this example. choose "L" for the large contour type and "P" for a pressure contour plot.

```
Generate which type of contour data, (L)arge, (M)edium, or (S)mall?

Which type of contour (E)levation, (P)ressure or (H)ydralic grade line?
```

Step 5: Under the PIPEVIEW MENU screen, press "J" to define the number of contours. Enter "10" to create 10 contours. Press "Y" to have evenly spaced contours. Input "0, 100" to define the minimum value and the maximum value of the contours.

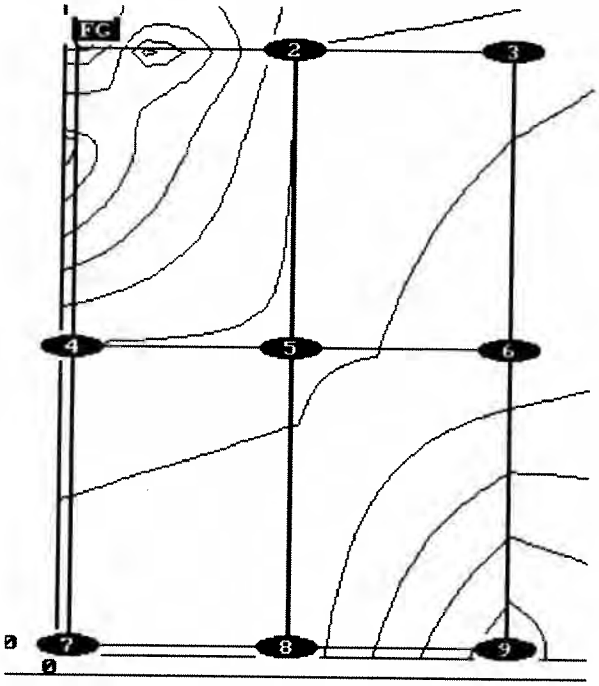
```
How many contours do you want to plot ? 10

Do you want evenly spaced contours? Y

Input first and last contours ?  0 , 100
```

Step 6: Under the PIPEVIEW MENU screen, press "K" to add contours into the pipeline network plot.

Step 7: Under the PIPEVIEW MENU screen, press "P" to view the result plot. The following plot should appear: (Use "S" to back to the PIPEVIEW MENU screen)



Step 8: To exit PIPEVIEW, press "Q".

Example1.DAT

```
00  2   13    9    0     0     0     0     0  0.000000  0.000000 0.0000000    0     0
KYPIPE Example1.DAT
12 Pipes
9 Nodes
0   1    2  3000.000     20.000    120.000      0.000      0.000      0.000    0     1
0   2    3  3000.000     20.000      0.000      0.000      0.000      0.000    0     2
0   1    4  4000.000     24.000      0.000      0.000      0.000      0.000    0     3
0   2    5  4000.000     16.000      0.000      0.000      0.000      0.000    0     4
0   3    6  4000.000     16.000      0.000      0.000      0.000      0.000    0     5
0   4    5  3000.000     16.000      0.000      0.000      0.000      0.000    0     6
0   5    6  3000.000     12.000      0.000      0.000      0.000      0.000    0     7
0   4    7  4000.000     16.000      0.000      0.000      0.000      0.000    0     8
0   5    8  4000.000     12.000      0.000      0.000      0.000      0.000    0     9
0   6    9  4000.000     12.000      0.000      0.000      0.000      0.000    0    10
0   7    8  3000.000     16.000      0.000      0.000      0.000      0.000    0    11
0   8    9  3000.000     12.000      0.000      0.000      0.000      0.000    0    12
0   0    1   500.000     20.000    120.000      0.000      0.000    150.000    0    13
      -8.44      200.000    11    1     9     0     0     0     0     0     0     0     0
       0.53      200.000    20    1     2    10     0     0     0     0     0     0     0
       0.32      200.000    30    2     3     0     0     0     0     0     0     0     0
       1.06      200.000    40    3     4    12     0     0     0     0     0     0     0
       0.74      200.000    50    4     5    10    11     0     0     0     0     0     0
       0.78      200.000    60    5     6     9     0     0     0     0     0     0     0
       1.73      200.000    70    6     7     0     0     0     0     0     0     0     0
       1.86      200.000    80    7     8    11     0     0     0     0     0     0     0
       1.42      200.000    90    8    12     0     0     0     0     0     0     0     0
0
    0     0     0     0     0     0     0     0
  -2.
```

Example1.GEO

```
9
 1 , 0 , 8000 , 200 ,
 2 , 3000 , 8000 , 0 ,
 3 , 6000 , 8000 , 0 ,
 4 , 0 , 4000 , 0 ,
 5 , 3000 , 4000 , 0 ,
 6 , 6000 , 4000 , 0 ,
 7 , 0 , 0 , 0 ,
 8 , 3000 , 0 , 0 ,
 9 , 6000 , 0 , 100 ,
 1
FG, 250 , 9250 , 0 ,
 0
 13
 1 ,1,2, 20 , 120 , 3000 ,
 2 ,2,3, 20 , 120 , 3000 ,
 3 ,1,4, 24 , 120 , 4000 ,
 4 ,2,5, 16 , 120 , 4000 ,
 5 ,3,6, 16 , 120 , 4000 ,
 6 ,4,5, 16 , 120 , 3000 ,
 7 ,5,6, 12 , 120 , 3000 ,
 8 ,4,7, 16 , 120 , 4000 ,
 9 ,5,8, 12 , 120 , 4000 ,
 10 ,6,9, 12 , 120 , 4000 ,
 11 ,7,8, 16 , 120 , 3000 ,
 12 ,8,9, 12 , 120 , 3000 ,
 13 ,FG,1, 20 , 120 , 500
```

```
          * * * * * * * * * *   K Y P I P E 2   * * * * * * * * * *
          *   University of Kentucky Hydraulic Analysis Program   *
          * Distribution of Pressure and Flows in Piping Networks *
          *         980 PIPE VERSION - 1.11    (02/20/93)          *
          * * * * * * * * * * * * * * * * * * * * * * * * * * * * *


 DATE :  5/11/1995
 TIME : 14:12:18
 INPUT DATA FILENAME -------------- COHSWKY.INP
 TABULATED OUTPUT FILENAME -------- COHSWKY.OUT
 POSTPROCESSOR RESULTS FILENAME --- RESFILE.RES


                 ************************************************
                  S U M M A R Y   O F   O R I G I N A L   D A T A
                 ************************************************



U N I T S   S P E C I F I E D

   FLOWRATE ............ = million gallons/day
   HEAD (HGL) .......... = feet
   PRESSURE ............ = psig


P I P E L I N E   D A T A

STATUS CODE:   XX -CLOSED PIPE    FG -FIXED GRADE NODE    PU -PUMP LINE
               CV -CHECK VALVE    RV -REGULATING VALVE

  PIPE        NODE NOS.      LENGTH    DIAMETER    ROUGHNESS    MINOR LOSS    FGN-HGL
 NUMBER       #1    #2        (ft)       (in)        COEFF.       COEFF.        (ft)
-------------------------------------------------------------------------------------
    1          1     2       3000.0      20.0        120.00         .00
    2          2     3       3000.0      20.0        120.00         .00
    3          1     4       4000.0      24.0        120.00         .00
    4          2     5       4000.0      16.0        120.00         .00
    5          3     6       4000.0      16.0        120.00         .00
    6          4     5       3000.0      16.0        120.00         .00
    7          5     6       3000.0      12.0        120.00         .00
    8          4     7       4000.0      16.0        120.00         .00
    9          5     8       4000.0      12.0        120.00         .00
   10          6     9       4000.0      12.0        120.00         .00
   11          7     8       3000.0      16.0        120.00         .00
   12          8     9       3000.0      12.0        120.00         .00
   13-FB       0     1        500.0      20.0        120.00         .00        300.00


J U N C T I O N   N O D E   D A T A


  JUNCTION     JUNCTION       EXTERNAL     JUNCTION
   NUMBER       TITLE          DEMAND      ELEVATION   CONNECTING PIPES
                               (mgd)         (ft)
------------------------------------------------------------------------------
     1                         -8.44        200.00      1    3   13
     2                           .53        200.00      1    2    4
     3                           .32        200.00      2    5
     4                          1.06        200.00      3    6    8
     5                           .74        200.00      4    6    7    9
     6                           .78        200.00      5    7   10
     7                          1.73        200.00      8   11
     8                          1.86        200.00      9   11   12
     9                          1.42        200.00     10   12
```

```
O U T P U T   O P T I O N   D A T A

OUTPUT SELECTION:  ALL RESULTS ARE INCLUDED IN THE TABULATED OUTPUT


S Y S T E M   C O N F I G U R A T I O N

    NUMBER OF PIPES ..................(p) =   13
    NUMBER OF JUNCTION NODES ..........(j) =    9
    NUMBER OF PRIMARY LOOPS ...........(l) =    4
    NUMBER OF FIXED GRADE NODES .......(f) =    1
    NUMBER OF SUPPLY ZONES ............(z) =    1


                  ************************************
                   S I M U L A T I O N   R E S U L T S
                  ************************************

THE RESULTS ARE OBTAINED AFTER  3 TRIALS WITH AN ACCURACY =  .00100


S I M U L A T I O N   D E S C R I P T I O N   (L A B E L)

Test Problem for City of Houston Energy Management Example
Twelve Pipe -- Single Supply Source Example to Illustrate
Data Entry and Output Interpretation


P I P E L I N E   R E S U L T S

STATUS CODE:   XX -CLOSED PIPE     FG -FIXED GRADE NODE    PU -PUMP LINE
               CV -CHECK VALVE     RV -REGULATING VALVE    TK -STORAGE TANK

  PIPE          NODE NOS.       FLOWRATE     HEAD     PUMP   MINOR     LINE     HL/
 NUMBER        #1      #2                    LOSS     HEAD    LOSS     VELO.   1000
                                  (mgd)      (ft)     (ft)    (ft)    (ft/s)  (ft/ft)
-------------------------------------------------------------------------------------
    1           1       2          3.43      3.65      .00     .00     2.43     1.22
    2           2       3          1.68       .98      .00     .00     1.19      .33
    3           1       4          5.01      4.06      .00     .00     2.47     1.01
    4           2       5          1.22      2.12      .00     .00     1.35      .53
    5           3       6          1.36      2.61      .00     .00     1.51      .65
    6           4       5          1.07      1.73      .00     .00     1.41      .58
    7           5       6           .55      1.46      .00     .00     1.07      .49
    8           4       7          2.68      9.16      .00     .00     2.97     2.29
    9           5       8          1.20      8.44      .00     .00     2.37     2.11
   10           6       9          1.13      7.45      .00     .00     2.22     1.86
   11           7       8           .95      1.01      .00     .00     1.06      .34
   12           8       9           .29       .47      .00     .00      .58      .16
   13-FG        0       1           .00       .00      .00     .00      .00      .00


J U N C T I O N   N O D E   R E S U L T S

JUNCTION   JUNCTION    EXTERNAL    HYDRAULIC    JUNCTION    PRESSURE    JUNCTION
 NUMBER     TITLE       DEMAND       GRADE     ELEVATION      HEAD      PRESSURE
                        (mgd)        (ft)        (ft)         (ft)        (psi)
----------------------------------------------------------------------------------
   1                    -8.44       300.00      200.00       100.00       43.33
   2                      .53       296.35      200.00        96.35       41.75
   3                      .32       295.37      200.00        95.37       41.33
   4                     1.06       295.95      200.00        95.95       41.58
   5                      .74       294.22      200.00        94.22       40.83
   6                      .78       292.76      200.00        92.76       40.20
   7                     1.73       286.79      200.00        86.79       37.61
   8                     1.86       285.78      200.00        85.78       37.17
```

```
     9                    1.42      285.31      200.00      85.31      36.97

SUMMARY OF INFLOWS AND OUTFLOWS

(+) INFLOWS INTO THE SYSTEM FROM FIXED GRADE NODES
(-) OUTFLOWS FROM THE SYSTEM INTO FIXED GRADE NODES

            PIPE        FLOWRATE
           NUMBER         (mgd)
           --------------------
             13            .00

NET SYSTEM INFLOW  =       .00
NET SYSTEM OUTFLOW =       .00
NET SYSTEM DEMAND  =       .00


**** KYPIPE SIMULATION COMPLETED ****
DATE :  5/11/1995
TIME : 14:12:20
```

Simplified User Instructions for USGS MODFLOW

Building a MODFLOW model

This set of instructions describes how to construct a MODFLOW groundwater flow model for use in determining the effects of different groundwater pumping schemes on the aquifer system. For the energy management problem, we have generally assumed that the producers goal is to minimize drawdown, either to reduce the lift distance (energy limits) or to reduce the potential subsidence (administrative limits).

The instructions use a step-by-step example to show how to use the MODFLOW file builder programs (called preprocessor programs) to build the correct input files required by the MODFLOW model.

Before Building a Model

The MODFLOW model requires many different items of data that are generally inconvienent to collect during the actual file-building process. Before building the files organize your data (on paper) into the following groups:

Model geometry
You should have a grid overlaying your model region.
You need to know the number of layers, rows, and columns.
You need to know which cells are no-flow, variable, and fixed-head.
You need to know what your initial heads are in the model.

Aquifer characteristics
You need to know the transmissivity for each cell in the grid.
You need to know the storativity for each cell in the grid.

Recharge characteristics
You need to know the recharge rate for the top layer in the model.

Well characteristics
You need to know the locations (cells) of wells and their pumping rates.

The six preprocessor modules that are often used are:

BASE (always) - sets up geometry
BCF (always) - sets up aquifer characteristics
WELL - sets up well files
DRAIN - sets up drain files (drains are like wells, except head instead of flow rate is specified)
RIVER - sets up river-aquifer interactions
RECH - sets up recharge files

Additionally a solver is required, a very robust solver is the SIP (Strongly Implicit Procedure) solver built into MODFLOW. Its use is set in the BASE module.

Now for the example:

MODFLOW INPUT Preprocessor Input Example

Six preprocessor programs (BASEPRE.EXE, BCFPRE.EXE, WELLPRE.EXE, DRAINPRE.EXE, RIVERPRE.EXE, and RECHPRE.EXE) are used to generate input data files for MODFLOW. All programs have to be run under MS Windows 3.1. A MS Windows version of MODFLOW (WINMOD.EXE) is included in the disk.

The example shown in here is a one layer, ten column by ten row, unconfined aquifer with one inject well and one pumping well. Base module, BCF module, Well module, and SIP module will be used to solve the problem. Preprocessors BASEPRE.EXE, BCFPRE.EXE, and WELLPRE.EXE are used to edit the input data files.

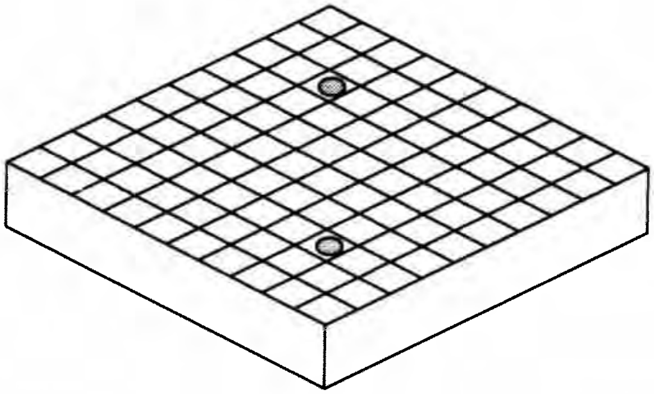
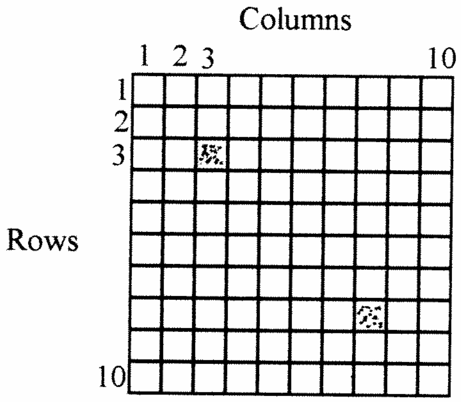


Figure 1. An example ground water aquifer

The aquifer has a hydraulic conductivity of 10.0 ft/day, and the bottom elevation is set at 0.01 feet. the injection well is located at cell 3,3 and the recharge well is located at cell 8,8. The aquifers geometry and grid is depicted below in Figure 2.



Aquifer Plan View - Pumping Well and Injection Well Cells are Shaded

Figure 2. Plan View of Grid System.

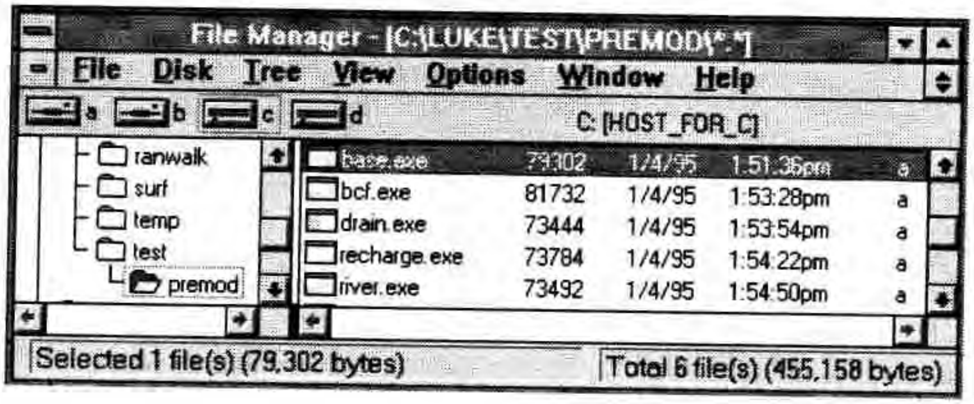
The BASE module will require information on layering, row, and column geometry. The BASE module requires us to also specify the number of stress periods; a stress period is a length of time when all stresses (pumping and injection) are at constant rate. Additionally it will require us to specify which additional modules are required. We will always require BCF and SIP. For this example we also will include

WELLS; the module that lest us simulate pumping and injection. Lastly we must supply information on starting heads and boundary types.

To start the BASE module, select the BASEPRE.exe file in the Windows File Manager. Double-click to launch the application. A window should appear with a command-line type of interface. Answer the questions asked by the preprocessor and when you finish the program it will create the correct basic input file for running MODFLOW. Once this basic file is created then you can run the next preprocessor to create the auxiliary files required by MODFLOW.

Running BASEPRE

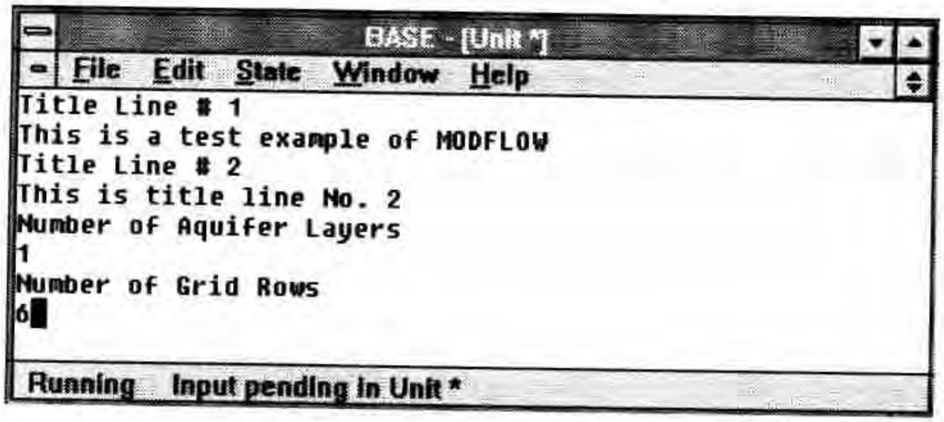
Step 1: Locate the BASEPRE module in the File Manager as depicted below:



```
base.exe       79302   1/4/95   1:51:36pm   a
bcf.exe        81732   1/4/95   1:53:28pm   a
drain.exe      73444   1/4/95   1:53:54pm   a
recharge.exe   73784   1/4/95   1:54:22pm   a
river.exe      73492   1/4/95   1:54:50pm   a
```

Selected 1 file(s) (79,302 bytes)   Total 6 file(s) (455,158 bytes)

Step 2: Double-click on the application to start the progam. A window should appear similar to the window shown below:

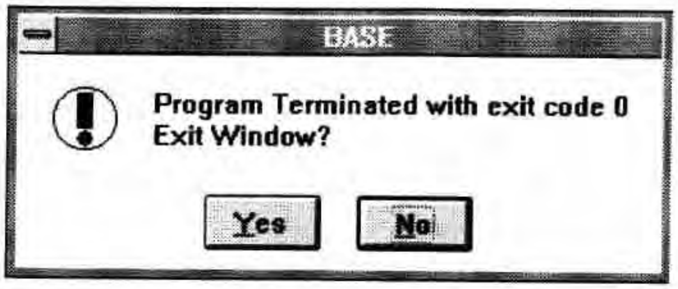


```
Title Line # 1
This is a test example of MODFLOW
Title Line # 2
This is title line No. 2
Number of Aquifer Layers
1
Number of Grid Rows
6
```

Running   Input pending in Unit *

Observe that several questions have already been answered by the user. A complete listing of the interaction is listed below Step 3: Bold face items are user entered values, the other items are prompts from the program.

Step 3: When the program is complete, the computer will generate a message similar to the message below. If the exit code is 0, then the program ran correctly. Clicking "Yes" will end the program and return you to the file manager. Clicking "No" will leave the program window active. You cannot do very much with the window, however you can scroll back through your data to be sure you entered it correctly. Unfortunately, to correct any errors you must run the program from the beginning again.



Program Terminated with exit code 0
Exit Window?

Observe that the program has terminated with an exit code of 0. This termination condition is the normal condition. It means the program ran correctly.

`Listing of complete session with BASEPRE for this example:`

```
Title Line # 1
>This is an example of using MODFLOW
Title Line # 2
>One layer with 10 by 10 grid aquifer system
Number of Aquifer Layers
>1
Number of Grid Rows
>10
Number of Grid Columns
>10
Number of Stress Periods
>1
Simulation Time Unit
 0  - undefined
 1  - seconds
 2  - minutes
 3  - hours
 4  - days
 5  - years
>4
Simulation Module Input File Unit Numbers
Enter 1 to include module, 0 otherwise

Block Centered Flow
>1
Block Centered Flow will be read from FOR011

Wells
>1
Wells will be read from FOR012

Drains
>0
Drains Module Not Included

Rivers
>0
Rivers Module Not Included

Evapo-Transpiration Module
>0
Evapo-Transpiration Module Not Included

General Head Boundary Module
>0
General Head Boundary Module Not Included

Recharge Module
>0
Recharge Module Not Included

Strongly Implicit Procedure
>1
Strongly Implicit will be read from FOR019

Slice Successive Over Relaxation
>0
SSOR Module Not Included
```

```
Output Control Module
>0
Output Control Module Not Included

Interbed Storage Module
>0
Interbed Storage Module Not Included

Memory Sharing Option  0=yes 1=no
>0

Save Starting Heads (i.e. Compute Drawdown?
  0=no  1=yes
>0
Layer           1 Boundary Array
  Are all values the same? 0=yes 1=no
>0
  Value? :
>1
 1  1  1  1  1  1  1  1  1  1
 1  1  1  1  1  1  1  1  1  1
 1  1  1  1  1  1  1  1  1  1
 1  1  1  1  1  1  1  1  1  1
 1  1  1  1  1  1  1  1  1  1
 1  1  1  1  1  1  1  1  1  1
 1  1  1  1  1  1  1  1  1  1
 1  1  1  1  1  1  1  1  1  1
 1  1  1  1  1  1  1  1  1  1
 1  1  1  1  1  1  1  1  1  1

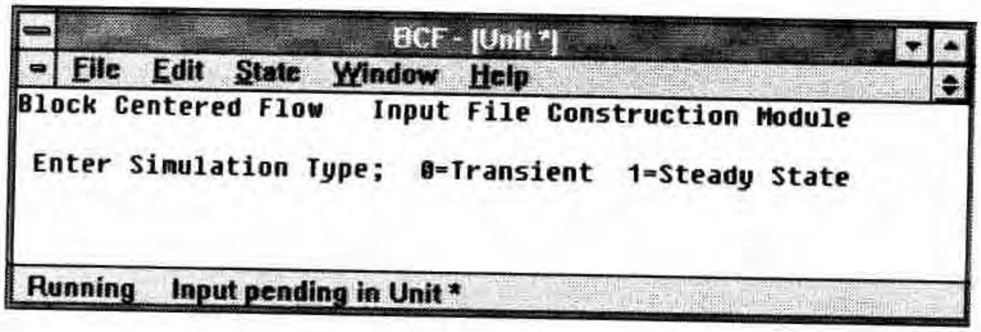
Head at No Flow Cells (usually use 999)
>999

Layer           1 Starting Head Array
  Are all values the same? 0=yes 1=no
>0
  Value? :
>100
 100.      100.      100.      100.      100.      100.      100.      100.      100.      100.
 100.      100.      100.      100.      100.      100.      100.      100.      100.      100.
 100.      100.      100.      100.      100.      100.      100.      100.      100.      100.
 100.      100.      100.      100.      100.      100.      100.      100.      100.      100.
 100.      100.      100.      100.      100.      100.      100.      100.      100.      100.
 100.      100.      100.      100.      100.      100.      100.      100.      100.      100.
 100.      100.      100.      100.      100.      100.      100.      100.      100.      100.
 100.      100.      100.      100.      100.      100.      100.      100.      100.      100.
 100.      100.      100.      100.      100.      100.      100.      100.      100.      100.
 100.      100.      100.      100.      100.      100.      100.      100.      100.      100.
 Stress Period          1   Length
> 1
 Stress Period          1 Computation Steps
> 1
 Stress Period          1 Time Step Multiplier
> 1
```

Running BCF:

Step 1: Locate the BCF (or BCFPRE) module in the File Manager:

Step 2: Double-click on the application to start the progam. A window should appear similar to the window shown below:



```
Block Centered Flow   Input File Construction Module

 Enter Simulation Type;  0=Transient  1=Steady State
```

Observe that several questions have already been answered by the user. A complete listing of the interaction is listed below Step 3: Bold face items are user entered values, the other items are prompts from the program.

Step 3: Same as Step 3 of BASEPRE.

Listing of complete session with BCF for this example:

```
Block Centered Flow   Input File Construction Module

 Enter Simulation Type;  0=Transient  1=Steady State
>1

 Enter Discharge Output Type
  -nn = Constant head flow terms printed to unit# nn
    0 = Cell by cell flow terms not printed
   nn = Cell by cell flow terms printed to unit# nn
>0
 Number of model layers (same as in BASEPREPRO)
                                          Max = 79
>1

 Number of model rows (same as in BASEPREPRO)
>10

 Number of model columns (same as in BASEPREPRO)
>10

Layer             Itype code :
   0 = confined
   1 = unconfined
   2 = confined unconfined constant T
   3 = confined/unconfined variable T
>1

Layer             1 Column/Row Anisotropy Factor
  Anisotropy Factor =  Tcol/Trow
>1

Cell width (delta-x) along rows
  Are all values the same? 0=yes 1=no
>0

  Value? :
>1000
 Cell width (delta-y) along columns
  Are all values the same? 0=yes 1=no
>0
  Value? :
```

```
>1000

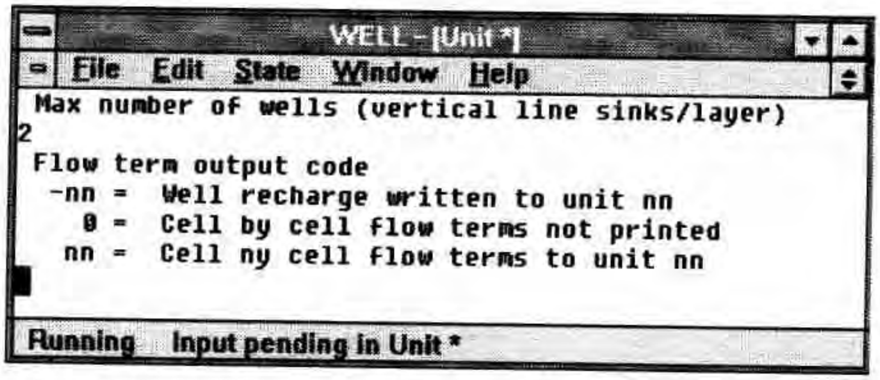
 Hydraulic Conductivtiy
Layer           1 Hydraulic Conductivtiy Array
  Are all values the same? 0=yes 1=no
>0
  Value? :
>10
 10.0      10.0      10.0      10.0      10.0      10.0      10.0      10.0      10.0      10.0
 10.0      10.0      10.0      10.0      10.0      10.0      10.0      10.0      10.0      10.0
 10.0      10.0      10.0      10.0      10.0      10.0      10.0      10.0      10.0      10.0
 10.0      10.0      10.0      10.0      10.0      10.0      10.0      10.0      10.0      10.0
 10.0      10.0      10.0      10.0      10.0      10.0      10.0      10.0      10.0      10.0
 10.0      10.0      10.0      10.0      10.0      10.0      10.0      10.0      10.0      10.0
 10.0      10.0      10.0      10.0      10.0      10.0      10.0      10.0      10.0      10.0
 10.0      10.0      10.0      10.0      10.0      10.0      10.0      10.0      10.0      10.0
 10.0      10.0      10.0      10.0      10.0      10.0      10.0      10.0      10.0      10.0
 10.0      10.0      10.0      10.0      10.0      10.0      10.0      10.0      10.0      10.0
 Bottom Elevation

Layer           1 Bottom Elevation Array
  Are all values the same? 0=yes 1=no
>0
  Value? :
>0.1
 .100      .100      .100      .100      .100      .100      .100      .100      .100      .100
 .100      .100      .100      .100      .100      .100      .100      .100      .100      .100
 .100      .100      .100      .100      .100      .100      .100      .100      .100      .100
 .100      .100      .100      .100      .100      .100      .100      .100      .100      .100
 .100      .100      .100      .100      .100      .100      .100      .100      .100      .100
 .100      .100      .100      .100      .100      .100      .100      .100      .100      .100
 .100      .100      .100      .100      .100      .100      .100      .100      .100      .100
 .100      .100      .100      .100      .100      .100      .100      .100      .100      .100
 .100      .100      .100      .100      .100      .100      .100      .100      .100      .100
 .100      .100      .100      .100      .100      .100      .100      .100      .100      .100
```

Running WELL:

Step 1: Locate the WELL (orWELLPRE) module in the File Manager.

Step 2: Double-click on the application to start the progam. A window should appear similar to the window shown below:



```
Max number of wells (vertical line sinks/layer)
2
Flow term output code
 -nn =  Well recharge written to unit nn
   0 =  Cell by cell flow terms not printed
  nn =  Cell ny cell flow terms to unit nn
```

Observe that several questions have already been answered by the user. A complete listing of the interaction is listed below Step 3: Bold face items are user entered values, the other items are prompts from the program.

Step 3: When the program is complete, the computer will generate a message. If the exit code is 0, then the program ran correctly. Clicking "Yes" will end the program and return you to the file manager.

Listing of complete session with WELLPRE for this example:

```
 Max number of wells (vertical line sinks/layer)
>2
 Flow term output code
  -nn =  Well recharge written to unit nn
    0 =  Cell by cell flow terms not printed
   nn =  Cell ny cell flow terms to unit nn
>0

 Number of Stress Periods (same as in BASEPREPRO)
>1

 Well data use code
 -1 = use well data from previous stress period
 nn = #wells active current stress period
>2

 For stress period           1 Active well :          1
 Layer :  (z axis)
>1
 Row   :  (y axis)
>3
Column :  (x axis)
>3
Pumping (-); Injection (+) Rate :
>-100

 For stress period           1 Active well :          2
 Layer :  (z axis)
>1
 Row   :  (y axis)
>8
Column :  (x axis)
>8
Pumping (-); Injection (+) Rate :
>+100
```

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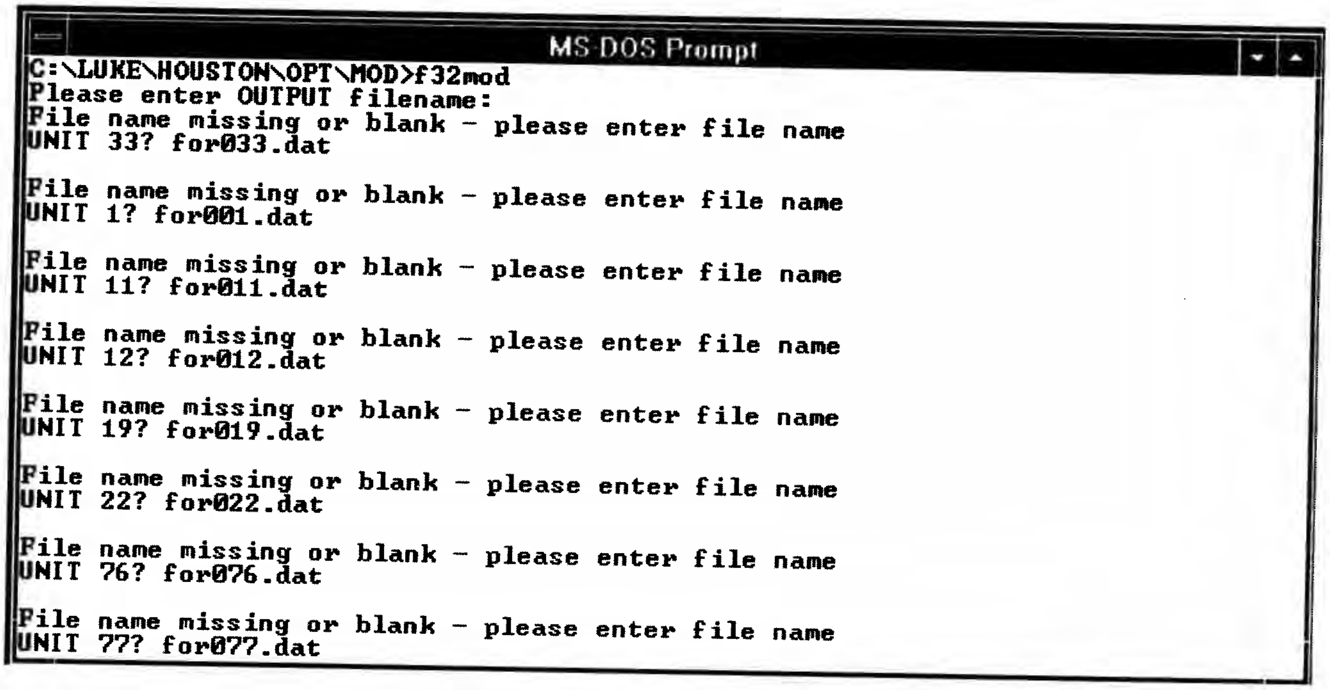
Running F32MOD (32-bit MODFLOW)

Program F32MOD was created by using Microsoft FORTRAN Powerstation Version 1.0, which is a 32-bit FORTRAN compiler. F32MOD runs faster and provides less floating truncate error than 16-bit MODFLOW compiled by Microsoft FORTRAN Version 5.1.

Step 1: Open a DOS Window under MS Windows environment. Change to the program directory.

Step 2: Key in the name of the program (F32MOD). A DOS window should appear similar to the window shown below:



```
C:\LUKE\HOUSTON\OPT\MOD>f32mod
Please enter OUTPUT filename:
File name missing or blank - please enter file name
UNIT 33? for033.dat

File name missing or blank - please enter file name
UNIT 1? for001.dat

File name missing or blank - please enter file name
UNIT 11? for011.dat

File name missing or blank - please enter file name
UNIT 12? for012.dat

File name missing or blank - please enter file name
UNIT 19? for019.dat

File name missing or blank - please enter file name
UNIT 22? for022.dat

File name missing or blank - please enter file name
UNIT 76? for076.dat

File name missing or blank - please enter file name
UNIT 77? for077.dat
```

Observe that the MODFLOW program asks the user for the names of several files. The first file (UNIT 33) can be any valid DOS filename. The remaining files must be in the from " FOR " "XXX" ".DAT" where "XXX" is a three digit number that corresponds to the unit number. For instance, UNIT 1 will read from file "FOR001.XXX". The preprocessors create these files using these exact file names, so it should not pose a problem. This peculiar input format is used so that the advanced FORTRAN user can supply named files particular to a specific problem.

Step 3: When the program is complete, the computer will generate a message "Stop - Program terminated". Enter "Exit" to close the DOS window.

When you have completed the MODFLOW program , the simulation results will be placed in the ASCII file that you named at the beginning of the program (in this case `exampl1.doc`). This file can be viewed using a word processor or a file editor. When viewed, its contents can be cut-and-pasted into a spreadsheet such as Lotus 1-2-3 for further analysis. The interpretation section will illustrate how to take the contents of the MODFLOW output file and paste them into the spreadsheet. Its contents are reproduced below for this problem.

exampl1.doc:

```
1                    U.S. GEOLOGICAL SURVEY MODULAR FINITE-DIFFERENCE GROUND-WATER MODEL
01
    1 LAYERS         5 ROWS         5 COLUMNS                                          2
   1 STRESS PERIOD(S) IN SIMULATION
 MODEL TIME UNIT IS DAYS
0I/O UNITS:
 ELEMENT OF IUNIT:  1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
         I/O UNIT: 11 12  0  0  0  0  0  0 19  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
0BAS1 -- BASIC MODEL PACKAGE, VERSION 1, 12/08/83 INPUT READ FROM UNIT  1
 ARRAYS RHS AND BUFF WILL SHARE MEMORY.
 START HEAD WILL NOT BE SAVED -- DRAWDOWN CANNOT BE CALCULATED
    214 ELEMENTS IN X ARRAY ARE USED BY BAS
    214 ELEMENTS OF X ARRAY USED OUT OF  85000
0BCF1 -- BLOCK-CENTERED FLOW PACKAGE, VERSION 1, 04/24/85 INPUT READ FROM UNIT 11
 STEADY-STATE SIMULATION
      LAYER  AQUIFER TYPE
      -------------------
        1         1
     51 ELEMENTS IN X ARRAY ARE USED BY BCF
    265 ELEMENTS OF X ARRAY USED OUT OF  85000
0WEL1 -- WELL PACKAGE, VERSION 1, 04/24/85 INPUT READ FROM 12
 MAXIMUM OF     1 WELLS
      4 ELEMENTS IN X ARRAY ARE USED FOR WELLS
    269 ELEMENTS OF X ARRAY USED OUT OF  85000
0SIP1 -- STRONGLY IMPLICIT PROCEDURE SOLUTION PACKAGE, VERSION 1, 04/24/85 INPUT READ FROM UNIT 19
 MAXIMUM OF  90 ITERATIONS ALLOWED FOR CLOSURE
  5 ITERATION PARAMETERS
    465 ELEMENTS IN X ARRAY ARE USED BY SIP
    734 ELEMENTS OF X ARRAY USED OUT OF  85000
11
0                                                                                      1


                                      BOUNDARY ARRAY FOR LAYER  1 WILL BE READ ON UNIT  1 USING FORMAT:
(20I3)
                         ----------------------------------------------------------------------------
---------------------


         1   2   3   4   5
 ...........................
0  1     0   0   0   0   0
0  2     1   1   1   1   1
0  3     1   1   1   1   1
0  4     1   1   1   1   1
0  5    -1  -1  -1  -1  -1
0AQUIFER HEAD WILL BE SET TO  999.00     AT ALL NO-FLOW NODES (IBOUND=0).
0


                                      INITIAL HEAD FOR LAYER  1 WILL BE READ ON UNIT  1 USING FORMAT:
(10G10.3)
                         ----------------------------------------------------------------------------
---------------------


              1            2            3            4            5
 ..................................................................
0  1     100.0        100.0        100.0        100.0        100.0
0  2     120.0        120.0        120.0        120.0        120.0
0  3     130.0        130.0        130.0        130.0        130.0
0  4     110.0        110.0        110.0        110.0        110.0
0  5     100.0        100.0        100.0        100.0        100.0
0DEFAULT OUTPUT CONTROL -- THE FOLLOWING OUTPUT COMES AT THE END OF EACH STRESS PERIOD:
 TOTAL VOLUMETRIC BUDGET
          HEAD
0


                         COLUMN TO ROW ANISOTROPY WILL BE READ ON UNIT 11 USING FORMAT: (10G10.3)
                         ----------------------------------------------------------------------------
----

   1.0000
0


                                      DELR WILL BE READ ON UNIT 11 USING FORMAT: (10G10.3)
                         ----------------------------------------------------------------------------
----
```

```
    1000.0        1000.0        1000.0        1000.0        1000.0
0

                                                 DELC WILL BE READ ON UNIT 11 USING FORMAT: (10g10.3)
                                 ------------------------------------------------------------------------
----

    1000.0        1000.0        1000.0        1000.0        1000.0
0

                                          HYD. COND. ALONG ROWS WILL BE READ ON UNIT 11 USING FORMAT: (10G10.3)
                                 ------------------------------------------------------------------------
--------

               1           2           3           4           5
 ............................................................
0  1     300.0       300.0       300.0       300.0       300.0
0  2     300.0       300.0       300.0       300.0       300.0
0  3     300.0       300.0       300.0       300.0       300.0
0  4     300.0       300.0       300.0       300.0       300.0
0  5     300.0       300.0       300.0       300.0       300.0
0

                                                 BOTTOM WILL BE READ ON UNIT 11 USING FORMAT: (10G10.3)
                                 ------------------------------------------------------------------------
--------

               1           2           3           4           5
 ............................................................
0  1     .1000       .1000       .1000       .1000       .1000
0  2     .1000       .1000       .1000       .1000       .1000
0  3     .1000       .1000       .1000       .1000       .1000
0  4     .1000       .1000       .1000       .1000       .1000
0  5     .1000       .1000       .1000       .1000       .1000
0

                                                          SOLUTION BY THE STRONGLY IMPLICIT PROCEDURE
                                                          -------------------------------------------
0
                                                   MAXIMUM ITERATIONS ALLOWED FOR CLOSURE =       90
                                                                  ACCELERATION PARAMETER =     1.0000
                                                       HEAD CHANGE CRITERION FOR CLOSURE =     .10000E-04
                                                       SIP HEAD CHANGE PRINTOUT INTERVAL =        1
0
   5 ITERATION PARAMETERS CALCULATED FROM SPECIFIED WSEED =  .00100000 :

         .0000000E+00   .8221720E+00   .9683772E+00   .9943766E+00   .9990000E+00
1
                                                      STRESS PERIOD NO.   1, LENGTH =   100.0000
                                                      ----------------------------------------------

                                                      NUMBER OF TIME STEPS =     1

                                                       MULTIPLIER FOR DELT =     1.000

                                                    INITIAL TIME STEP SIZE =   100.0000
0           1 WELLS
                                                   LAYER    ROW    COL    STRESS RATE   WELL NO.
                                                   --------------------------------------------
0                                                    1       2      3     -10.000           1
    12 ITERATIONS FOR TIME STEP   1 IN STRESS PERIOD  1
0MAXIMUM HEAD CHANGE FOR EACH ITERATION:
0 HEAD CHANGE LAYER,ROW,COL HEAD CHANGE LAYER,ROW,COL HEAD CHANGE LAYER,ROW,COL HEAD CHANGE LAYER,ROW,COL
HEAD CHANGE LAYER,ROW,COL
 ----------------------------------------------------------------------------------------------------------
----------------------------
    -15.58      (  1,   3,   1)  -15.79      (  1,   2,   5)  -4.468      (  1,   2,   4)  -.6649      (  1,   2,   1)
-.1213E-01 (  1,   2,   2)
     .6632E-02 (  1,   2,   3)   .3246E-02 (  1,   2,   4)   .1326E-02 (  1,   2,   2)   .1095E-03 (  1,   2,   3)
-.5164E-04 (  1,   2,   4)
    -.1526E-04 (  1,   3,   5)  -.7962E-05 (  1,   2,   5)
0
1
                         HEAD IN LAYER  1 AT END OF TIME STEP  1 IN STRESS PERIOD  1
              -----------------------------------------------------------------------

               1           2           3           4           5
 ............................................................
0  1     999.0       999.0       999.0       999.0       999.0
```

```
0  2    100.0        100.0        100.0        100.0        100.0
0  3    100.0        100.0        100.0        100.0        100.0
0  4    100.0        100.0        100.0        100.0        100.0
0  5    100.0        100.0        100.0        100.0        100.0
0


                                         VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP  1 IN STRESS PERIOD
1
                                         ---------------------------------------------------------------------------
--
0                                CUMULATIVE VOLUMES      L**3
STEP       L**3/T                                                                                RATES FOR THIS TIME
                                 ------------------
----                                                                                             --------------------


                                      IN:
                                      ---                                                                        IN:
                                         STORAGE =     .00000                                                    ---
STORAGE =     .00000
                                  CONSTANT HEAD =     984.83
HEAD =     9.8483 ·                                                                                          CONSTANT
                                           WELLS =     .00000
WELLS =     .00000
0                                       TOTAL IN =     984.83
IN =     9.8483                                                                                                  TOTAL
0                                    OUT:
                                     ----                                                                       OUT:
                                         STORAGE =     .00000                                                   ----
STORAGE =     .00000
                                  CONSTANT HEAD =     .00000
HEAD =     .00000                                                                                           CONSTANT
                                           WELLS =     1000.0
WELLS =     10.000
0                                      TOTAL OUT =     1000.0
OUT =     10.000                                                                                                TOTAL
0                                       IN - OUT =    -15.174
OUT =    -.15174                                                                                                IN -
0                              PERCENT DISCREPANCY =                     -1.53
DISCREPANCY =                                -1.53                                                        PERCENT



0


                   TIME SUMMARY AT END OF TIME STEP  1 IN STRESS PERIOD  1
                                        SECONDS       MINUTES         HOURS           DAYS            YEARS
                                     -----------------------------------------------------------------------------
           TIME STEP LENGTH           .864000E+07    144000.         2400.00         100.000          .273785
        STRESS PERIOD TIME            .864000E+07    144000.         2400.00         100.000          .273785
   TOTAL SIMULATION TIME              .864000E+07    144000.         2400.00         100.000          .273785
1
```

KYPIPE/MODFLOW Input File Generator Interface for Strategic Production Planning

KYPIPE & MODFLOW Shell (PKYMOD.EXE)

PKYMOD.EXE is an integrated shell which allows users to launch KYPIPE program, KYPIPE pre- and post-processors, MODFLOW program, and MODFLOW pre- and post-processors.

Prerequirement of Using PKYMOD.EXE

Hardwares & Softwares
(1) IBM compatible PC with 80486 or better CPU.
(2) 4 MB RAM.
(3) MS-DOS 5.0 or later and MS Windows 3.1.
(4) 5 MB free hard disk space.
(5) Need to have VBRUN300.DLL in either WINDOWS directory or the current directory.

Modifications to SYSTEM.INI and Installation of F32 files
(1) Modifies the SYSTEM.INI file in your Windows directory. Adds the following information in the [386ENH] section:

```
device=c:\windows\dosxnt.386
device=c:\windows\mmd.386
```

(2) copy "DOSXNT.386" and "MMD.386" to the directory "Windows".
(3) Turn 32-bit File Access off.
(4) Open a DOS Window under MS Windows.
(5) Enter program's name (for example, F32OPTCT.EXE) in the DOS Window, and press "Enter" key.
(6) Users can interupt the program anytime by press "Ctrl-C" keys.

Data files
(1) A standard KYPIPE input file named "KY_INP.DAT" (details read KYPIPE 2 user's manual)
(2) A set of standard MODFLOW input files named "FOR001.DAT", "FOR011.DAT", and so on. The number of MODFLOW files is depended on the number of packages used. (details read MODFLOW user's manual)
(3) A data file called "PUMPNAME.TXT". The format of the file is shown below:

There are 40 records in this file. Each record includes five items:
- node number
- maximum capacity
- unit cost
- node internal water demand
- name of the pump station

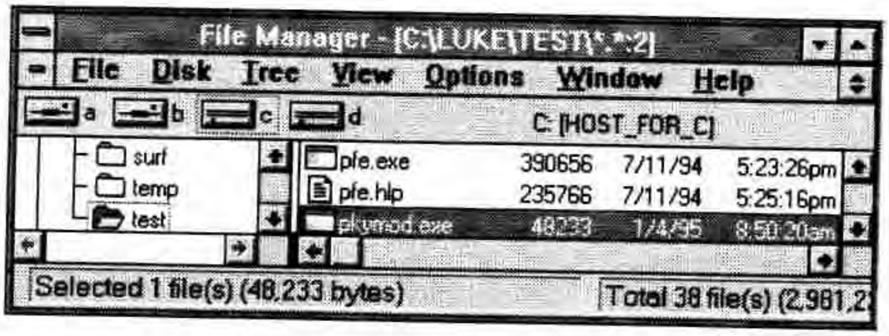
Again, the total number of records must be 40.

In this example, there is only one pump station. The file looks like,

```
10, 11, 12, 13, Pump No. 1     ┐
0, 0, 0, 0, None               |
......                         | 40 records
......                         |
0, 0, 0, 0, None               ┘
```

Using PKYMOD.EXE

Step 1: Locate the PKYMOD.EXE in the File Manager as depicted below:

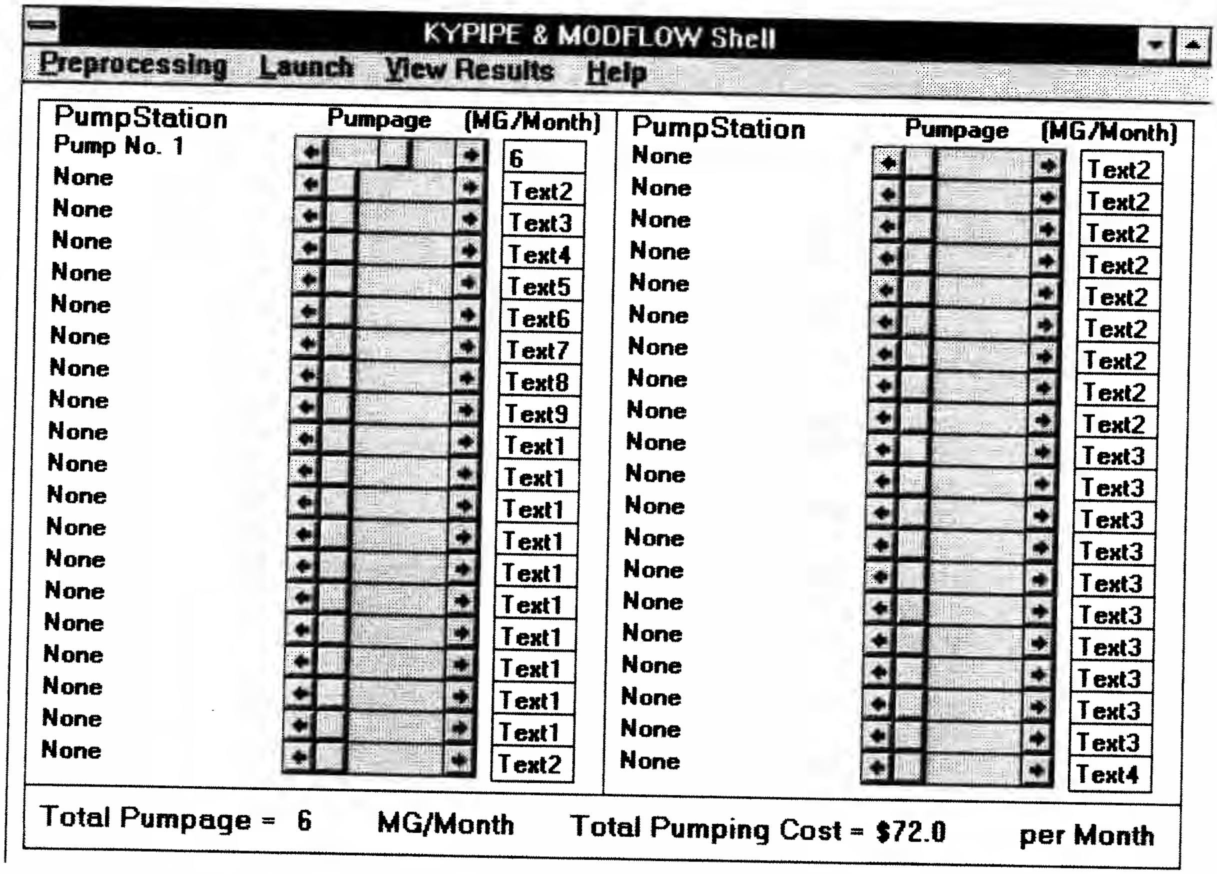


pfe.exe	390656	7/11/94	5:23:26pm
pfe.hlp	235766	7/11/94	5:25:16pm
pkymod.exe	48233	1/4/95	8:50:20am

Selected 1 file(s) (48,233 bytes)

Total 38 file(s) (2,981,2

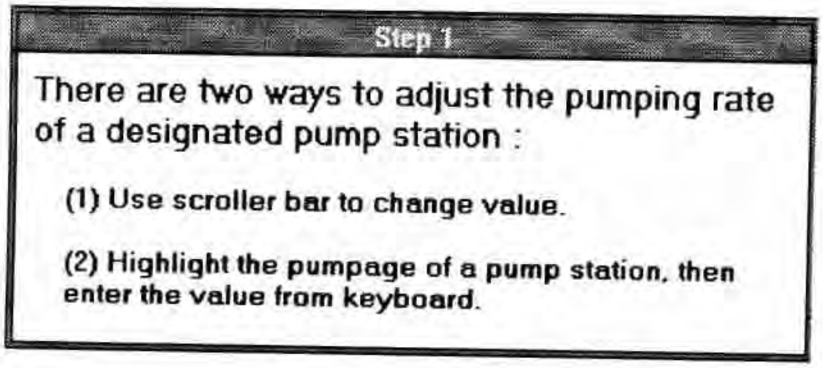
Step 2: Double-click on the application to start the program. A window should appear similar to the window shown below:



PumpStation	Pumpage (MG/Month)	PumpStation	Pumpage (MG/Month)
Pump No. 1	6	None	Text2
None	Text2	None	Text2
None	Text3	None	Text2
None	Text4	None	Text2
None	Text5	None	Text2
None	Text6	None	Text2
None	Text7	None	Text2
None	Text8	None	Text2
None	Text9	None	Text2
None	Text1	None	Text3
None	Text1	None	Text3
None	Text1	None	Text3
None	Text1	None	Text3
None	Text1	None	Text3
None	Text1	None	Text3
None	Text1	None	Text3
None	Text1	None	Text3
None	Text1	None	Text3
None	Text1	None	Text3
None	Text2	None	Text4

Total Pumpage = 6 MG/Month Total Pumping Cost = $72.0 per Month

Step 3: Click "Step 1" command from the menu bar item "Preprocessing". The following window should appear. Users can adjust the desired pumpage of pumping stations using either scroll bars or keyboard.

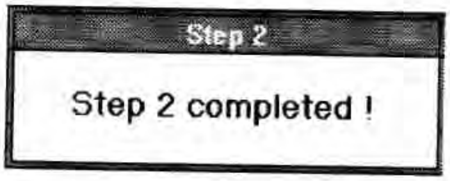


There are two ways to adjust the pumping rate of a designated pump station :

(1) Use scroller bar to change value.

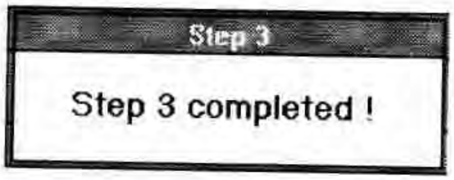
(2) Highlight the pumpage of a pump station, then enter the value from keyboard.

Step 4: Click "Step 2" command from the menu bar item "Preprocessing" to produce a temperate pumpage file. A "Step 2" window should appear as soon as the process is done. Click any location other than the "Step 2" window to close the window.



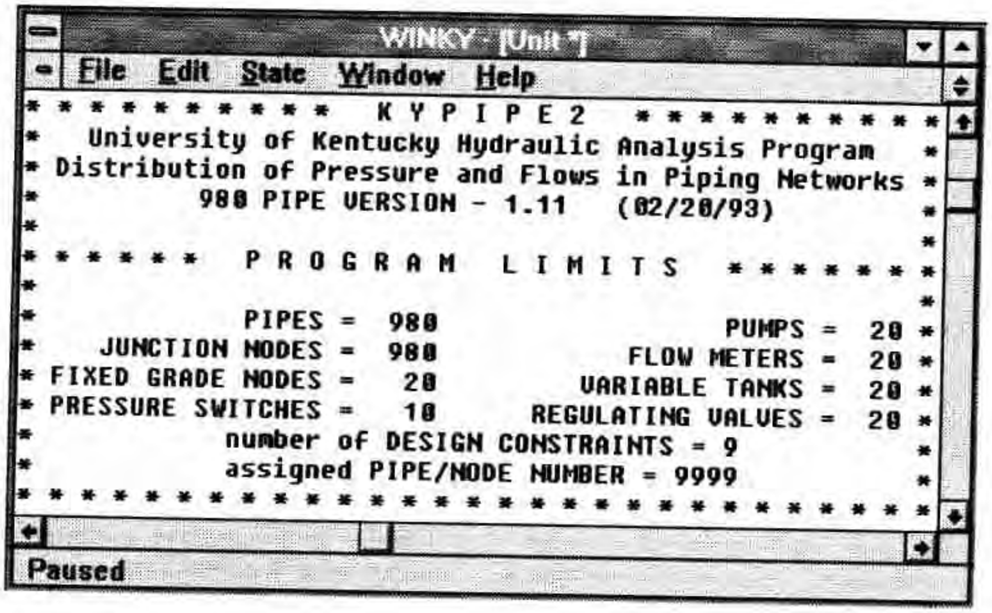
Step 2 completed !

Step 5: Click "Step 3" command from the menu bar item "Preprocessing" to create a new KYPIPE input file and a new MODFLOW well input file. A "Step 3" window should appear as soon as the process is done. Click any location other than the "Step 3" window to close the window.



Step 3 completed !

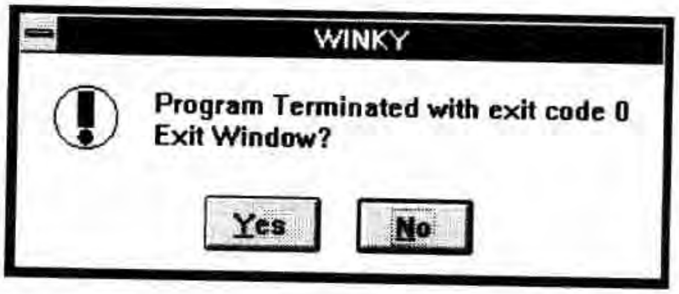
Step 6: Click "Run KYPIPE" command from the menu bar item "Launch" to launch KYPIPE program. A window should appear similar to the window shown below:



```
* * * * * * * * * *   K Y P I P E 2   * * * * * * * * * *
*   University of Kentucky Hydraulic Analysis Program   *
* Distribution of Pressure and Flows in Piping Networks *
*          980 PIPE VERSION - 1.11   (02/20/93)          *
*                                                        *
* * * * * *   P R O G R A M   L I M I T S   * * * * * * *
*                                                        *
*             PIPES =  980                  PUMPS =  20 *
*    JUNCTION NODES =  980            FLOW METERS =  20 *
* FIXED GRADE NODES =   20        VARIABLE TANKS =  20 *
* PRESSURE SWITCHES =   10      REGULATING VALVES =  20 *
*            number of DESIGN CONSTRAINTS = 9            *
*            assigned PIPE/NODE NUMBER = 9999            *
* * * * * * * * * * * * * * * * * * * * * * * * * * * * *
```

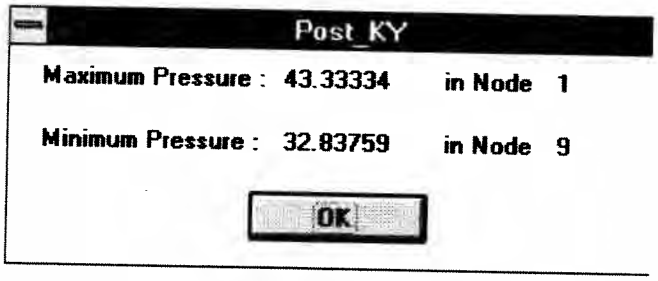
Paused

A window should appear as soon as the process is done. Click "Yes" button to close the window.



Program Terminated with exit code 0
Exit Window?

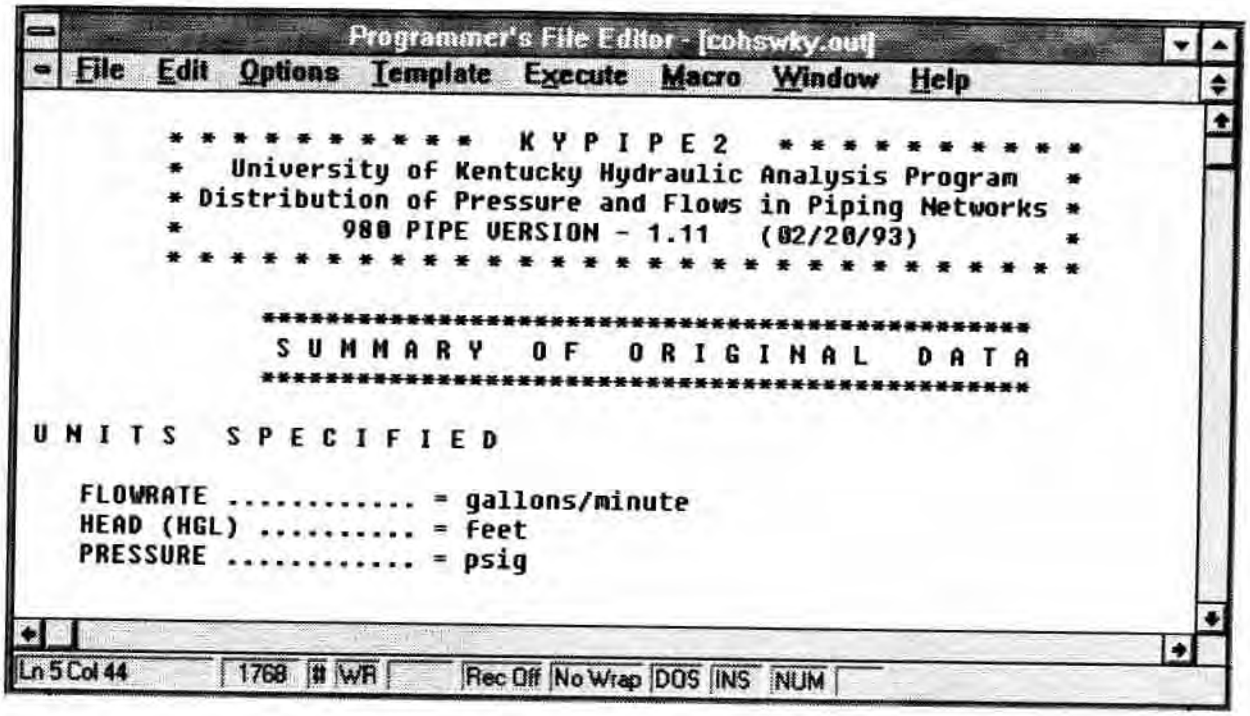
Step 7: To view the result of the maximum and minimum pressures, click "Max & Min Pressure" command from the menu bar item "View Results". Click "OK" button to close the window.



Maximum Pressure : 43.33334 in Node 1

Minimum Pressure : 32.83759 in Node 9

Step 8: To view the result of KYPIPE output file, click "KYPIPE" command from the menu bar item "View Results". This will launch a text editor called "Programmer's File Editor" as shown in the picture below:



```
     * * * * * * * * * *   K Y P I P E 2   * * * * * * * * * *
     *   University of Kentucky Hydraulic Analysis Program   *
     * Distribution of Pressure and Flows in Piping Networks *
     *          980 PIPE VERSION - 1.11   (02/20/93)          *
     * * * * * * * * * * * * * * * * * * * * * * * * * * * * *

        ************************************************
         S U M M A R Y   O F   O R I G I N A L   D A T A
        ************************************************

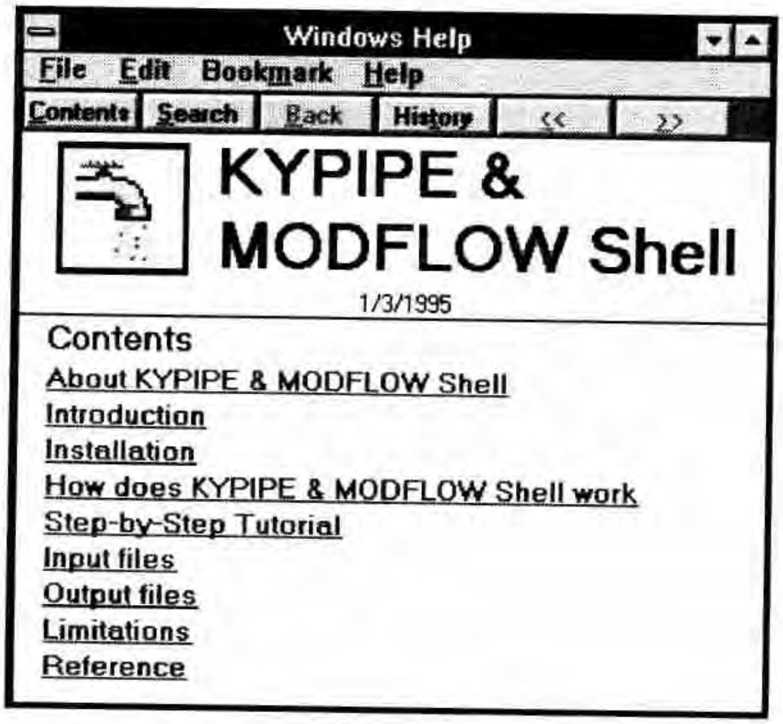
U N I T S   S P E C I F I E D

   FLOWRATE ............ = gallons/minute
   HEAD (HGL) .......... = feet
   PRESSURE ............ = psig
```

Choose "Open" command from the menu bar item "File" of the text editor, and open a file named "COHSWKY.OUT" to view the KYPIPE results.

Choose "Exit" command from the menu bar item "File" of the text editor to close the editor.

Step 9: To view the help file, click any commands from the menu bar item "Help".



KYPIPE & MODFLOW Shell

1/3/1995

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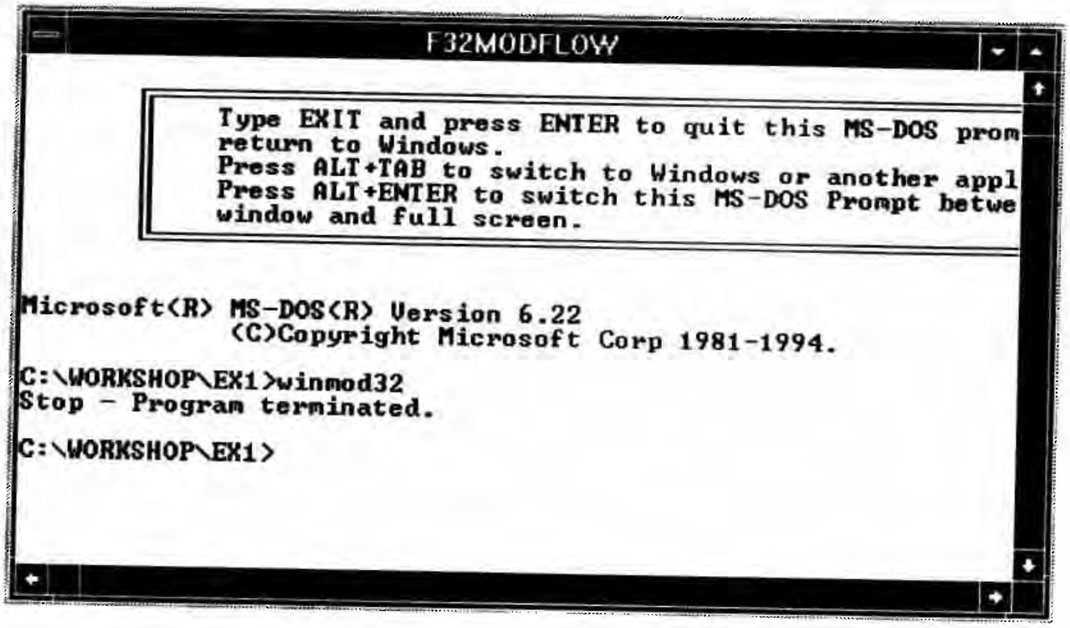
About KYPIPE & MODFLOW Shell
Introduction
Installation
How does KYPIPE & MODFLOW Shell work
Step-by-Step Tutorial
Input files
Output files
Limitations
Reference

Step 10: To run MODFLOW, follow the similar steps for KYPIPE (from Step 6 to Step 8). Click "Run MODFLOW" command from the menu bar item "Launch" to launch MODFLOW program. A DOS window should appear similar to the window shown below:



```
Type EXIT and press ENTER to quit this MS-DOS prom
return to Windows.
Press ALT+TAB to switch to Windows or another appl
Press ALT+ENTER to switch this MS-DOS Prompt betwe
window and full screen.

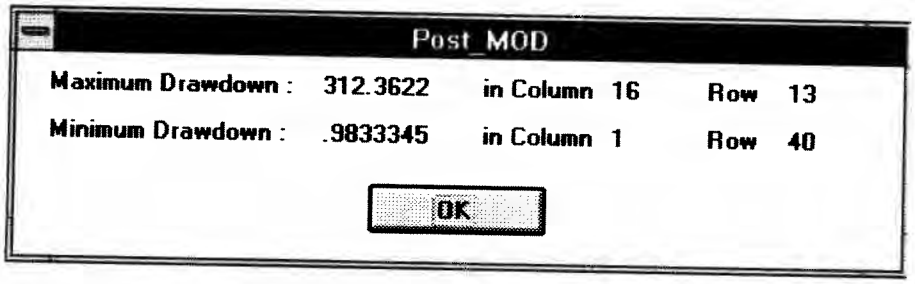
Microsoft(R) MS-DOS(R) Version 6.22
             (C)Copyright Microsoft Corp 1981-1994.

C:\WORKSHOP\EX1>winmod32
Stop - Program terminated.

C:\WORKSHOP\EX1>
```

Users can enter "EXIT" to close the DOS window.

Step 11: To view the result of the maximum and minimum drawdown, click "Max & Min Drawdown" command from the menu bar item "View Results". Click "OK" button to close the window.



Maximum Drawdown : 312.3622 in Column 16 Row 13

Minimum Drawdown : .9833345 in Column 1 Row 40

Step 12: To view the result of MODFLOW output file, click "MODFLOW" command from the menu bar item "View Results". This will launch a text editor called "Programmer's File Editor". Choose "Open" command from the menu bar item "File" of the text editor, and open a file named "FOR033.DAT" to view the MODFLOW results. Choose "Exit" command from the menu bar item "File" of the text editor to close the editor.

Research into Production Cost Reduction by Energy Management of Houston's Surface and Groundwater Systems

Final Report

Part V

Simulation-Optimization Modeling and Results

by

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University of Houston Project # 1558893

Table of Contents

Simulation-Optimization Model

The integrated simulation model was coupled to the GRG-2 non-linear optimization code (Warren and Lasdon, 1989) to delineate optimal strategies for water supply under two different overall oblectives. The first objective is to minimize the cost to deliver a prescribed amount of water while maintaining prescribed system pressures and prescribed maximum drawdowns. The second objective is to minimize the maximum drawdown to deliver a prescribed amount of water while maintaining prescribed system pressures and prescribed maximum cost.

The GRG-2 model repeatedly runs the simulation model with different input values to locate solutions to these optimization problems. These solutions typically required 16 to 24 hours of computation time on an Intel 486-66 machine. Faster times can be expected with faster machines.

Southwest Houston Service Area																
Unit Water Cost																
			Plant Capacity in Million Gallons/31.25 days (i.e. MG/Month)													
	Serv.		Date													
Node#	Units	Plant Name	Aug-92	Sep-92	Oct-92	Nov-92	Dec-92	Jan-93	Feb-93	Mar-93	Apr-93	May-93	Jun-93	Count	Sum	Average
	1	BellaireBraes	406	406	406	406	406	406	406	406	406	406	406	11.00	4465	406
	1	BooneRoad	26	26	26	26	26	26	26	26	26	26	26	11.00	287	26
	2	Braeswood	95	95	95	95	95	95	95	95	95	95	95	11.00	1040	95
	1	BriargrovePark	45	45	45	45	45	45	45	45	45	45	45	11.00	495	45
	1	Briarwick	63	63	63	63	63	63	63	63	63	63	63	11.00	693	63
	1	Brookfield	35	35	35	35	35	35	35	35	35	35	35	11.00	386	35
	3	Chasewood	185	185	185	185	185	185	185	185	185	185	185	11.00	2039	185
	1	D_111_1	50	50	50	50	50	50	50	50	50	50	50	11.00	545	50
	1	D_111_2	57	57	57	57	57	57	57	57	57	57	57	11.00	629	57
	2	D_123	124	124	124	124	124	124	124	124	124	124	124	11.00	1361	124
	1	D_139	30	30	30	30	30	30	30	30	30	30	30	11.00	334	30
	3	D_158	85	85	85	85	85	85	85	85	85	85	85	11.00	936	85
	1	D_184	89	89	89	89	89	89	89	89	89	89	89	11.00	978	89
	2	D_218	144	144	144	144	144	144	144	144	144	144	144	11.00	1584	144
		D_41	109	109	109	109	109	109	109	109	109	109	109	11.00	1200	109
	1	D_51_1	57	57	57	57	57	57	57	57	57	57	57	11.00	631	57
	1	D_51_2	72	72	72	72	72	72	72	72	72	72	72	11.00	790	72
	2	D_54	176	176	176	176	176	176	176	176	176	176	176	11.00	1931	176
	1	D_90_2	45	45	45	45	45	45	45	45	45	45	45	11.00	500	45
	1	D_94	93	93	93	93	93	93	93	93	93	93	93	11.00	1025	93
	1	FairdaleD_26	155	155	155	155	155	155	155	155	155	155	155	11.00	1705	155
	1	Glenshire_1	43	43	43	43	43	43	43	43	43	43	43	11.00	478	43
	1	Glenshire_2	38	38	38	38	38	38	38	38	38	38	38	11.00	413	38
		Houston_3														
	1	Manning	47	47	47	47	47	47	47	47	47	47	47	11.00	512	47
	1	Meyerland_1	50	50	50	50	50	50	50	50	50	50	50	11.00	545	50
		Meyerland_2														
	1	MUD_98	54	54	54	54	54	54	54	54	54	54	54	11.00	594	54
	1	ParkglenWest	43	43	43	43	43	43	43	43	43	43	43	11.00	470	43
	1	Parkglen_1	34	34	34	34	34	34	34	34	34	34	34	11.00	371	34
	1	Ridgemont	48	48	48	48	48	48	48	48	48	48	48	11.00	525	48
	1	Rosewood_1	140	140	140	140	140	140	140	140	140	140	140	11.00	1535	140
	1	Rosewood_2	37	37	37	37	37	37	37	37	37	37	37	11.00	406	37
	1	Sharpstown_1	140	140	140	140	140	140	140	140	140	140	140	11.00	1542	140
	1	Sharpstown_2	101	101	101	101	101	101	101	101	101	101	101	11.00	1109	101
	1	SimsBayou	484	484	484	484	484	484	484	484	484	484	484	11.00	5321	484
	4	SouthEnd	306	306	306	306	306	306	306	306	306	306	306	11.00	3364	306
		Southwest	931	931	931	931	931	931	931	931	931	931	931	11.00	10237	931
	1	Westbury_1	71	71	71	71	71	71	71	71	71	71	71	11.00	782	71
	1	Westbury_2	93	93	93	93	93	93	93	93	93	93	93	11.00	1020	93
	1	Willowbend	21	21	21	21	21	21	21	21	21	21	21	11.00	233	21
	2	Linkwood	53	53	53	53	53	53	53	53	53	53	53	11.00	585	53
	1	BraeburnWest	40	40	40	40	40	40	40	40	40	40	40	11.00	441	40

Figure 5.1. Plant Capacity Table (Based on Historical/Nominal Capacity from Monthly Well Reports)

Simulation-Optimization Results using Average Production Cost Model

The following section shows the results of a set of simulation-optimization runs using the integrated model. We performed two sets of computer runs with different objectives. The first set was to let the computer attempt to find the least cost supply allocation strategy without regard to drawdown. Pressure constraints and the satisfying of demand were enforced. The second set of simulation-optimization runs was to let the computer attempt to find a supply allocation that minimizes drawdown (used as a surrogate for subsidence). Again, pressure and demand constraints were enforced.

The distribution of water supply was allowed to vary from 50% groundwater derived supply to 7% groundwater derived supply. Three types of outcomes were observed: (1) the optimizer found a solution, (2) the optimizer had not found a solution after 16 hours of computer time, but its currrent solution was feasible and better that the starting guess, and (3) the optimizer could not find any feasible solution. When the third type of outcome was observed, we modified the network model to allow for a surface water supply to enter the system at the far western edge of the study area, and allowed the lower bound on acceptable pressure to 10 psi. These changes, a wider range of acceptable pressures and a fictitious water supply at the western edge of the study area, allowed the model to find solutions. These particular solutions imply that for these cases there is not sufficient surface water transmission capacity in our conceptualization to supply the network.

Figure 5.2 (a) and (b) below shows the study area pipeline network and the pumping stations (well field) locations that were used in this research. These maps and subsequent maps in this section are all printed at the same scale and are intended to serve as overlays.

The overlays are used to locate the pumping stations and orient the pipeline network with respect to the various contor maps. The codes on the lower figure (the pump stations) correspond to the codes in Table 5.1 on the next sheet.

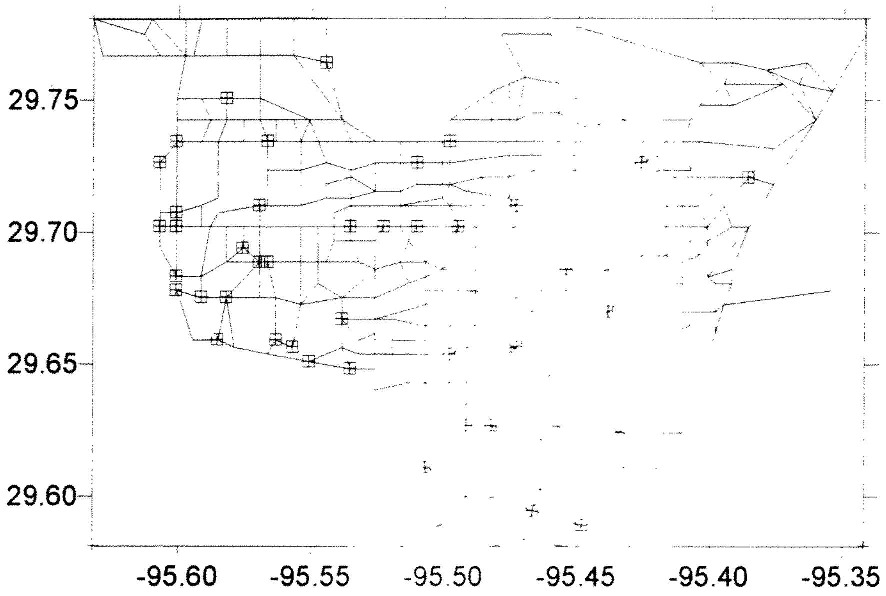

Figure5.2 (a). Distribution Network System Showing Pipelines and the Locations of Pumping Plants (Wellfields).

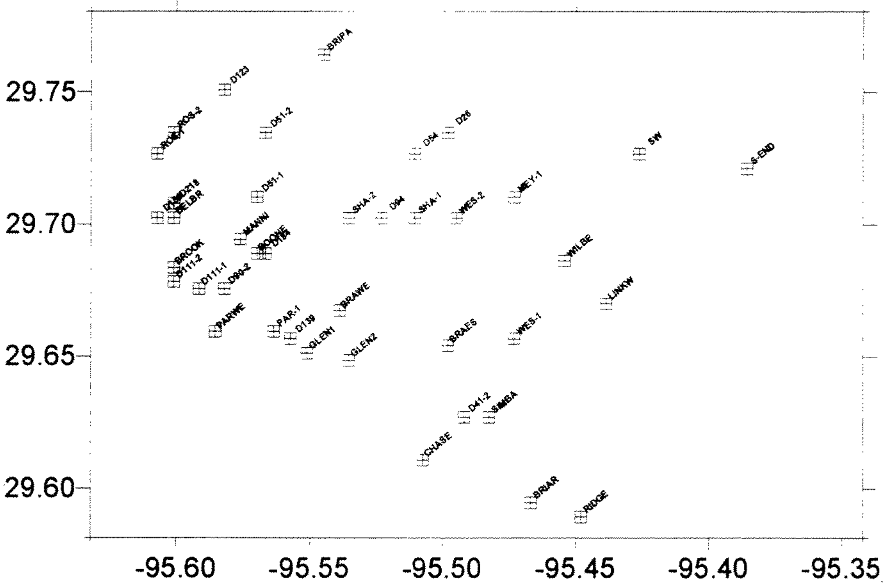

Figure 5.2(b). Locations and Plant Labels Corresponding to Key on Table 10 (Next Page).

Table 5.1. Plant Names and Plotting Labels for Figure5.1

PLANT NAME	Label	Node No.	Unit Cost
BELLAIRE BRAES	BELBR	92	153.14
BOONE ROAD	BOONE	303	202.83
BRAEBURN WEST	BRAWE	247	196.77
BRAESWOOD	BRAES	228	179.37
BRIARGROVE PARK	BRIPA	18	245.18
BRIARWICK	BRIAR	187	223.44
BROOKFIELD	BROOK	91	172.09
CHASEWOOD	CHASE	201	206.49
DISTRICT 111-1	D111-1	298	164.36
DISTRICT 111-2	D111-2	297	189.05
DISTRICT 123	D123	21	144.19
DISTRICT 139	D139	291	261.19
DISTRICT 184	D814	302	201.49
DISTRICT 185	D158	89	379.65
DISTRICT 218	D218	93	197.48
DISTRICT 41-2	D41-2	203	245.18
DISTRICT 51-1	D51-1	102	322.24
DISTRICT 51-2	D51-2	36	172.71
DISTRICT 54	D54	117	185.1
DISTRICT 90-2	D90-2	299	171.89
DISTRICT 94	D94	271	360.25
FAIRDALE(D26)	D26	46	193.05
GLENSHIRE-1	GLEN-1	246	142.11
GLENSHIRE-2	GLEN-2	245	145.13
LINKWOOD	LINKW	171	627.67
MANNING	MANNI	304	166.43
MEYERLAND-1	MEY-1	261	328.56
PARKGLEN WEST	PARWE	295	167.12
PARKGLEN-1	PAR-1	292	217.85
RIDGEMONT	RIDGE	188	601.01
ROSEWOOD	ROS-2	32	388.86
ROSEWOOD-1	ROS-1	87	245.18
SHARPSTOWN 2	SHA-2	270	200.84
SHARPSTOWN-1	SHA-1	273	178.89
SIMMS BAYOU	SIMBA	204	127.79
SOUTHEND	S-END	139	725.46
SOUTHWEST	SW	132	166.03
WESTBURY-1	WES-1	211	232.1
WESTBURY-2	WES-2	257	155.05
WILLOW BEND	WILBE	217	223.91

Results of Special Cases

Case 1. This simulation-optimization run studied a case where the total water demand was 4650 million gallons per month (high demand case) and 52% of this demand was satisfied by pumping from within the study area. All remaining demand was satisfied by external supplies applied at the eastern edge of the model. The optimization algorithm searches for a pumpage policy that minimizes total cost while attempting to maintain a system pressure between 10 and 110 psi, and produce a maximum drawdown no greater than 300 feet.

Figure 5.3 is a contour plot of the network distribution system pressures for this case. The smallest system pressures are along the western edge of the modeled area, and the high pressures are at the eastern edge. The smallest pressure within the network model occurs at the lower western corner of the model just west of the Parkwest Plant. The value in the model is slightly smaller than 20 psi. Although this value is lower than our target pressure of 35 psi, it is deemed acceptable in light of the many approximations inherent in the modeling effort. The largest pressure values are 110 psi. at the two eastern edge supply nodes.

Figure 5.4 shows the predicted drawdown for this solution. The maximum drawdown is 155 feet located north of the Meyerland -1 Plant. Another peak drawdown location is south of the plant, and a third large drawdown peak is located at the Southwest Plant. The maximum value of drawdown was used in Equation 1 to produce an estimated maximum land subsidence of roughly 0.93 inches. Details of the calculation are shown below:

Subsidence (inches) := 12*DDN(ft)*S/2		
Drawdown	155	ft
S (storage coefficient)	0.001	
δ	0.93	inches

Recall that this equation is a rough approximation and this value of land subsidence caused by this pumpage policy is an estimate. The drawdown contours around the Southwest Plant are consistent with that plant producting the most water in this scenario, but the drawdown peaks near the Meyerland Plant are not consistent with the amount of pumpage from that plant. Perhaps the hydraulics in the model reflects the effects of the Sharpstown Plants and pumpageform those plants (which in this scenario is large) is contributing to the drawdown values.

Table 5.2 shows the supply allocation for Case 1. The table is arranged in a ranking based on pumpage from each plant with the plants supplying the most water at the top. The negative values of pumpage are an artifact of the simulation model where supply to a node is actually modeled as a negative demand. The units of pumpage in the table are cubic feet per day. To convert these units into million gallons per month divide the tabulated value by 4456. Observe that several high unit cost plants are employed to satisfy the demand and still adhere to the minimum pressure requirements.

Two high unit cost plants (Ridgemont and Linkwood) are selected to produce water but at relatively small values. The highest unit cost plant, South End, is selected to produce a relatively large volume of water - probably to meet the upper bound pressure constraint. The cost of this secnario is $531,630/month to produce a total of 2423 million gallons from groundwater in the study area. The overall unit cost of this production policy is $219.41 per million gallons of groundwater. This case does not satisfy the subsidence district's required 20% groundwater allocation in the study area.

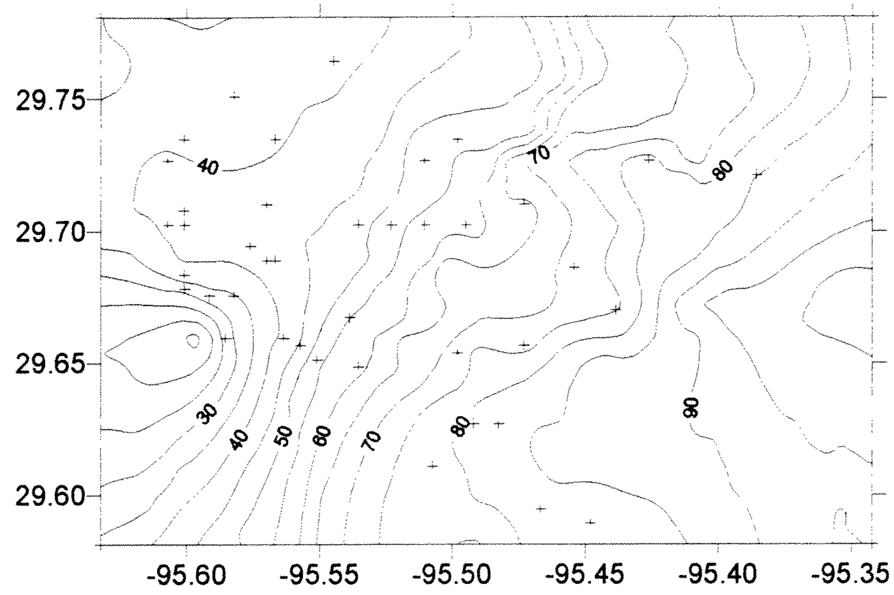

Figure 5.3. Distribution Network System Pressures for Case 1.

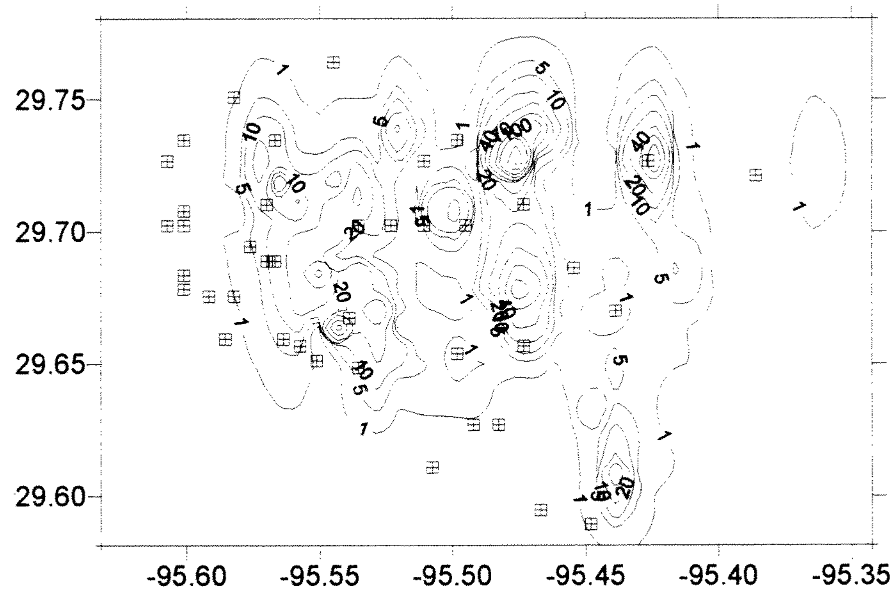

Figure 5.4. Predicted Drawdowns for Case 1.

Table 5.2. Groundwater Supply Allocations for Case 1. Minimum Cost. 50% Groundwater Derived Supply, High Water Demand Case. 2423 MG/Month Pumped

PLANT NAME	Label	Node No.	Unit Cost	Pumpage
SOUTHWEST	SW	132	166.03	-2510900
SIMS BAYOU	SIMBA	204	127.79	-1619700
BELLAIRE BRAES	BELBR	92	153.14	-1177800
SOUTHEND	S-END	139	725.46	-730190
CHASEWOOD	CHASE	201	206.49	-509060
SHARPSTOWN-1	SHA-1	273	178.89	-495920
DISTRICT 54	D54	117	185.1	-380610
DISTRICT 218	D218	93	197.48	-380390
ROSEWOOD-1	ROS-1	87	245.18	-380300
DISTRICT 184	D814	302	201.49	-295540
FAIRDALE(D26)	D26	46	193.05	-292940
DISTRICT 123	D123	21	144.19	-248030
DISTRICT 94	D94	271	360.25	-174180
SHARPSTOWN 2	SHA-2	270	200.84	-163750
DISTRICT 41-2	D41-2	203	245.18	-160800
WESTBURY-2	WES-2	257	155.05	-154480
BRAESWOOD	BRAES	228	179.37	-147810
DISTRICT 185	D158	89	379.65	-122960
DISTRICT 51-2	D51-2	36	172.71	-85274
BROOKFIELD	BROOK	91	172.09	-85192
DISTRICT 139	D139	291	261.19	-81936
WESTBURY-1	WES-1	211	232.1	-78763
DISTRICT 111-1	D111-1	298	164.36	-78371
BRIARWICK	BRIAR	187	223.44	-77381
MANNING	MANNI	304	166.43	-64542
DISTRICT 111-2	D111-2	297	189.05	-49608
RIDGEMONT	RIDGE	188	601.01	-47331
LINKWOOD	LINKW	171	627.67	-46357
DISTRICT 51-1	D51-1	102	322.24	-44189
ROSEWOOD	ROS-2	32	388.86	-27096
BRIARGROVE PARK	BRIPA	18	245.18	-26675
GLENSHIRE-2	GLEN-2	245	145.13	-21158
GLENSHIRE-1	GLEN-1	246	142.11	-19147
BOONE ROAD	BOONE	303	202.83	-7666
PARKGLEN WEST	PARWE	295	167.12	-6814
MEYERLAND-1	MEY-1	261	328.56	-4900
PARKGLEN-1	PAR-1	292	217.85	-1416
WILLOW BEND	WILBE	217	223.91	-21
BRAEBURN WEST	BRAWE	247	196.77	0
DISTRICT 90-2	D90-2	299	171.89	0

Case 2. This simulation-optimization run studied a case where the total water demand was 4650 million gallons per month (high demand case) and 20% of this demand was satisfied by pumping from within the study area. All remaining demand was satisfied by surface water supplies applied at the eastern edge of the model. The model attempts to find a minimum cost supply allocation that meets demand, maintains a system pressure between 10 and 110 psi, and produces a maximum drawdown no greater than 300 feet

Figure 5.5 is a contour plot of the network distribution system pressures for this case. The pressure distribution has the same general shape as the previous case, except the pressures are all lower throughout the network except at the surface water supply points where pressures are forced to set values. The smallest pressure within the network model occurs at the lower western corner of the model just west of the Parkwest Plant. The value in the model is slightly smaller than 15 psi. Although this value is lower than our target pressure of 35 psi, it is deemed acceptable in light of the many approximations inherent in the modeling effort. The largest pressure values are 110 psi at the two eastern edge supply nodes. Although we deemed this solution acceptable, some method to boost the pressures along the western edge of the study area should be considered.

Figure 5.6 shows the modeled drawdown for this solution. The drawdown pattern is similar to the previous pattern, but the magnitude of the drawdown is much less. The maximum drawdown is 20 feet , which is 87% smaller that the previous case. The estimated maximum land subsidence is 0.12 inches, with the details of the calculation are shown below:

Subsidence (inches) := 12*DDN(ft)*S/2		
Drawdown	20	ft
S (storage coefficient)	0.001	
δ	0.12	inches

Table 5.3 shows the supply allocation for Case 2. All the high unit cost plants are not selected to produce water in this scenario. The cost of this allocation is $153,493/month to produce a total of 930 million gallons from groundwater in the study area. The overall unit cost of this production policy is $165.04 per million gallons of groundwater. The required cost of additional surface water to make this case economically equivalent to the previous case is $253/million gallons; The calculations are summarized below:

Cost Case 1:	$531,630	Water Produced:	2423 Million Gallons
Cost Case 2:	$153,493	Water Produced:	930 Million Gallons
ΔCost :	$378,137	ΔWater Produced:	1493 Million Gallons

Cost of Added Surface Water (Δ Water) = $378,137/1493MGal = $253.27/MGal

If the unit cost of surface water is less than $253/million gallons, then this scenario will satisfy demand at a lower cost that the previous production policy. Observe that the reduced dependence on pumpage to satisfy demand has allowed sufficient freedom for the overall unit cost of produced groundwater to decrease 25%.

This particular case appears to be feasible, using our current conceptualization of the system (which may have changed since the computer model was built). The pressures on the western edge of the model are relatively low and some means of transferring water to the western edge, or boosting pressures along the western edge should be implemented. This scenario makes a remarkable impact on reducing drawdown (and thus subsidence) and satisfies the subsidence district's required 20% groundwater allocation in the study area.

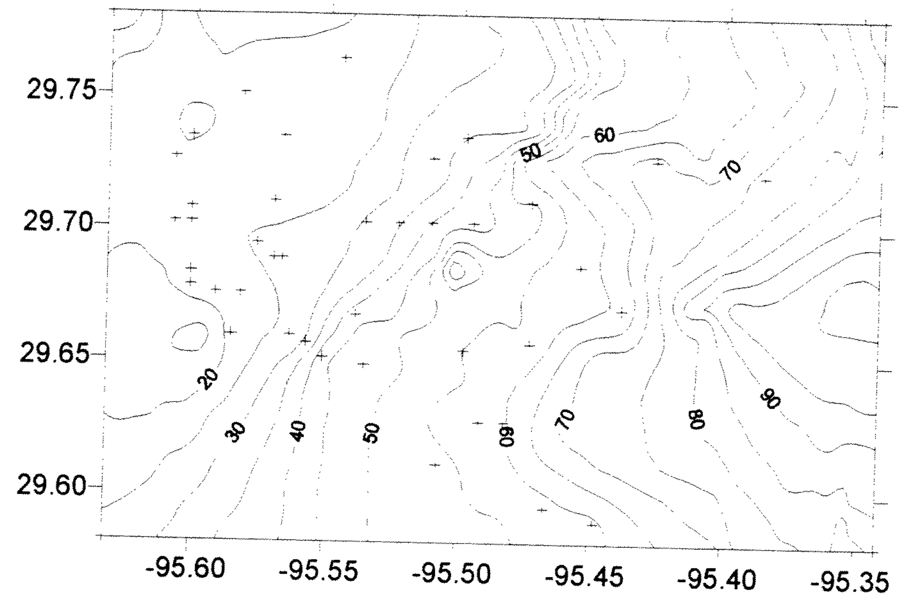

Figure 5.5. Distribution Network System Pressures for Case 2.

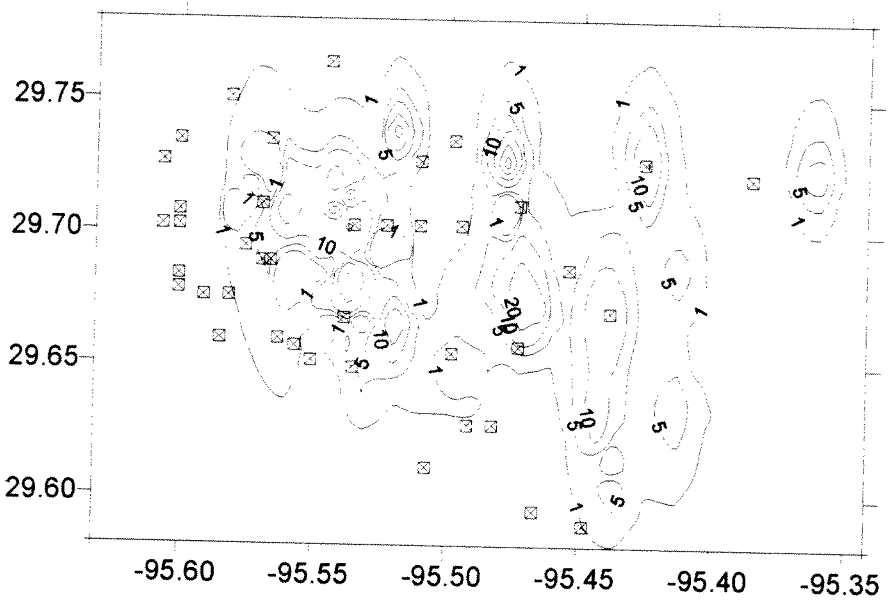

Figure 5.6. Predicted Drawdowns for Case 2.

Table 5.3. Groundwater Supply Allocations for Case 2. Minimum Cost. 20% Groundwater Derived Supply. High Water Demand Case. 930 MGal Pumped

PLANT NAME	Label	Node No.	Unit Cost	Pumpage
SIMS BAYOU	SIMBA	204	127.79	-413900
SOUTHWEST	SW	132	166.03	-378250
DISTRICT 51-2	D51-2	36	172.71	-311890
BELLAIRE BRAES	BELBR	92	153.14	-286610
DISTRICT 111-1	D111-1	298	164.36	-222830
DISTRICT 123	D123	21	144.19	-222230
DISTRICT 111-2	D111-2	297	189.05	-214000
MANNING	MANNI	304	166.43	-209440
DISTRICT 90-2	D90-2	299	171.89	-200550
GLENSHIRE-1	GLEN-1	246	142.11	-191640
PARKGLEN WEST	PARWE	295	167.12	-191640
WESTBURY-2	WES-2	257	155.05	-173420
GLENSHIRE-2	GLEN-2	245	145.13	-169350
BROOKFIELD	BROOK	91	172.09	-155980
BRAEBURN WEST	BRAWE	247	196.77	-144240
SHARPSTOWN-1	SHA-1	273	178.89	-122370
DISTRICT 54	D54	117	185.1	-102100
BRAESWOOD	BRAES	228	179.37	-94059
BOONE ROAD	BOONE	303	202.83	-79899
FAIRDALE(D26)	D26	46	193.05	-67246
DISTRICT 218	D218	93	197.48	-61703
CHASEWOOD	CHASE	201	206.49	-45672
PARKGLEN-1	PAR-1	292	217.85	-30886
SHARPSTOWN 2	SHA-2	270	200.84	-28456
DISTRICT 184	D814	302	201.49	-26335
SOUTHEND	S-END	139	725.46	0
ROSEWOOD-1	ROS-1	87	245.18	0
DISTRICT 94	D94	271	360.25	0
DISTRICT 41-2	D41-2	203	245.18	0
DISTRICT 185	D158	89	379.65	0
DISTRICT 139	D139	291	261.19	0
WESTBURY-1	WES-1	211	232.1	0
BRIARWICK	BRIAR	187	223.44	0
RIDGEMONT	RIDGE	188	601.01	0
LINKWOOD	LINKW	171	627.67	0
DISTRICT 51-1	D51-1	102	322.24	0
ROSEWOOD	ROS-2	32	388.86	0
BRIARGROVE PARK	BRIPA	18	245.18	0
MEYERLAND-1	MEY-1	261	328.56	0
WILLOW BEND	WILBE	217	223.91	0

Case 3. This simulation-optimization run studied a case where the total water demand was 4650 million gallons per month (high demand case) and 10% of this demand was satisfied by pumping from within the study area. All remaining demand was satisfied by surface water supplies applied at the eastern edge of the model. The model attempts to find a minimum cost supply allocation that meets demand, maintains a system pressure between 10 and 110 psi, and produces a maximum drawdown no greater than 300 feet

Figure 5.7 is a contour plot of the network distribution system pressures for this case. Although the pattern is the same as the previous cases, this case is considered infeasible as the entire western edge of the network has pressures at the lower pressure limit in the optimization model. It is possible to increase the western edge water pressures in the model by adding an additional supply node at the high pressure setting (110 psi.)along the western edge.

Figure 5.8 below, shows the simulated drawdown for this solution. The maximum drawdown is 20 feet again located north of the Meyerland - 1 Plant. Using this drawdown value in Equation 1 produces and estimated maximum land subsidence figure of 0.12 inches. The details of the calculation are shown below.

Subsidence (inches) := 12*DDN(ft)*S/2		
Drawdown	20	ft
S (storage coefficient)	0.001	
δ	0.12	inches

The maximum drawdown is unaffected by the additional decrease in groundwater supply, but the average drawdown throughout the modeled area is much less than in the previous two cases.

Table 5.4 shows the supply allocation for Case 3. Again, none of the high unit cost plants are selected to produce water in this scenario. The cost of this allocation is \$79,140/month to produce a total of 464 million gallons of groundwater from the study area. The overall unit cost of this production policy is \$170.56 per million gallons of groundwater; slightly higher than the previous case. The required cost for surface water to the western edge to make this case economically equivalent to Case 2 is \$160/million gallons; The calculations are summarized below:

Cost Case 2:	\$153,493	Water Produced:	930 Million Gallons
Cost Case 3:	\$ 79,140	Water Produced:	464 Million Gallons
ΔCost :	\$ 74,353	ΔWater Produced:	464 Million Gallons

Cost of Added Surface Water (Δ Water) = \$74,353/464MGal = \$160.24/MGal

This unit cost of surface water is nearly the same as the overall unit cost of Case 2 groundwater production. If the surface water can be provided at lower cost, then again this scenario will satisfy demand at lower cost, however this case is considered infeasible because much of the western edge is underpressured.

This scenario reduces average drawdown quite effectively, and should produce relatively little measurable land subsidence based on our approximation. Although this case satisfies the subsidence district's required 20% groundwater allocation in the study area, the allocation is infeasible unless some method of transmission of surface water to the western edge of the modeled region is implemented.

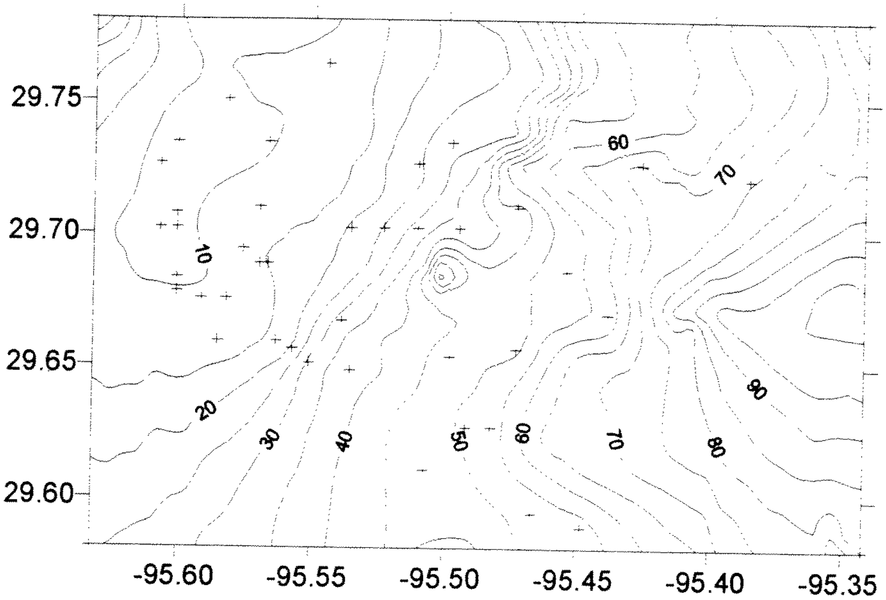

Figure 5.7. Distribution Network System Pressures for Case 3.

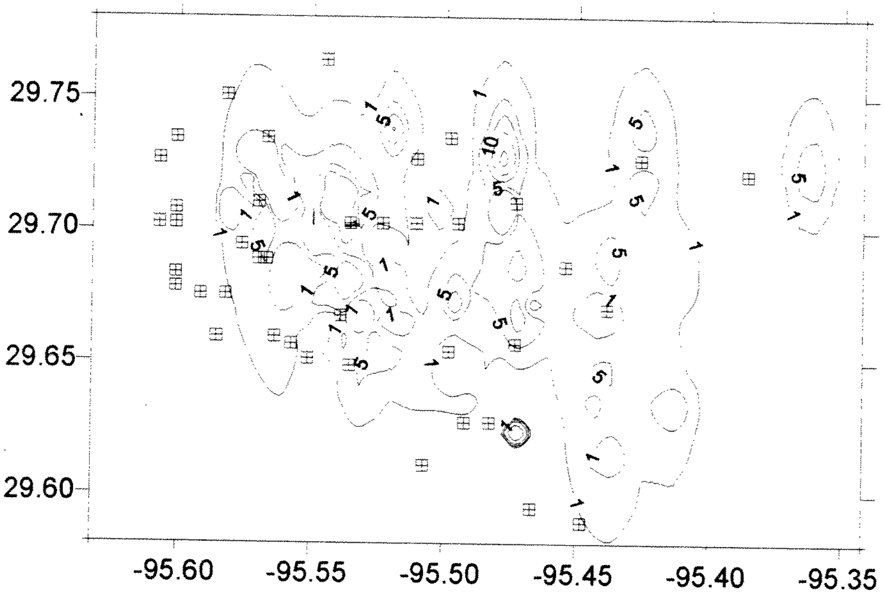

Figure 5.8. Predicted Drawdowns for Case 3.

Table 5.4. Groundwater Supply Allocations for Case 3. Minimum Cost. 10% Groundwater Derived Supply. High Water Demand Case. 464 MGal Pumped.

PLANT NAME	Label	Node No.	Unit Cost	Pumpage
SOUTHWEST	SW	132	166.03	-299760
SIMS BAYOU	SIMBA	204	127.79	-247060
BELLAIRE BRAES	BELBR	92	153.14	-178340
BROOKFIELD	BROOK	91	172.09	-115720
DISTRICT 123	D123	21	144.19	-93279
BOONE ROAD	BOONE	303	202.83	-86435
SHARPSTOWN-1	SHA-1	273	178.89	-73591
PARKGLEN-1	PAR-1	292	217.85	-72128
WESTBURY-2	WES-2	257	155.05	-69563
GLENSHIRE-1	GLEN-1	246	142.11	-68521
DISTRICT 54	D54	117	185.1	-67675
GLENSHIRE-2	GLEN-2	245	145.13	-65644
CHASEWOOD	CHASE	201	206.49	-60662
DISTRICT 218	D218	93	197.48	-55881
DISTRICT 111-1	D111-1	298	164.36	-51780
FAIRDALE(D26)	D26	46	193.05	-51188
DISTRICT 51-2	D51-2	36	172.71	-48293
BRAESWOOD	BRAES	228	179.37	-46393
MANNING	MANNI	304	166.43	-45356
PARKGLEN WEST	PARWE	295	167.12	-44694
WILLOW BEND	WILBE	217	223.91	-44071
DISTRICT 90-2	D90-2	299	171.89	-40150
DISTRICT 139	D139	291	261.19	-30839
SHARPSTOWN 2	SHA-2	270	200.84	-30394
DISTRICT 184	D814	302	201.49	-29781
DISTRICT 111-2	D111-2	297	189.05	-28259
BRAEBURN WEST	BRAWE	247	196.77	-16453
ROSEWOOD-1	ROS-1	87	245.18	-10438
SOUTHEND	S-END	139	725.46	0
DISTRICT 94	D94	271	360.25	0
DISTRICT 41-2	D41-2	203	245.18	0
DISTRICT 185	D158	89	379.65	0
WESTBURY-1	WES-1	211	232.1	0
BRIARWICK	BRIAR	187	223.44	0
RIDGEMONT	RIDGE	188	601.01	0
LINKWOOD	LINKW	171	627.67	0
DISTRICT 51-1	D51-1	102	322.24	0
ROSEWOOD	ROS-2	32	388.86	0
BRIARGROVE PARK	BRIPA	18	245.18	0
MEYERLAND-1	MEY-1	261	328.56	0

Case 4. This simulation-optimization run studied a case where the total water demand was 3000 million gallons per month (low demand case) with 30% of this demand satisfied by pumping ground water. All remaining demand was satisfied by surface water supplies applied at the eastern edge of the model. The model attempts to find a minimum cost supply allocation that meets demand, maintains a system pressure between 10 and 110 psi, and produces a maximum drawdown no greater than 300 feet

Figure 5.9 is a contour plot of the system pressures for this case. The trends are similar to the previous simulations, with the lowest pressures are on the order of 20 psi located just west of the Parkwest Plant. The largest pressure values are at the eastern edge supply nodes.

Figure 5.10 shows the simulated drawdown for this solution. The largest drawdowns for this scenario occur near the District-51, Braeburn West, Sharpstown, Meyerland, Linkwood, and the Southwest Plants. The maximum drawdown is 70 feet just north of the Braeburn West Plant. Using this value in Equation 1 produces an estimated maximum land subsidence 0.42 inches; the calculation is shown below:

Subsidence (inches) := 12*DDN(ft)*S/2		
Drawdown	70	ft
S (storage coefficient)	0.001	
δ	0.42	inches

The drawdown pattern is similar to Case 1 but with much the peak drawdown moved slightly north-west. The drawdown patterns are more consistent with the pumpage policies (as compared to Case 1) selected by the optimization algorithm. The maximum drawdowns are located near the high-pumpage plants.

Table 5.6 shows the supply allocation for Case 4. The highest unit cost plants are not selected to produce water in this scenario, although a portion of the selected plants have moderately high unit costs. The cost of this allocation is $247,344 to produce a total of 1404 million gallons per month from the study area. The overall unit cost of this production policy is $176.17 per million gallons of groundwater.

This case does not satisfy the subsidence district's required 20% groundwater allocation in the study area.

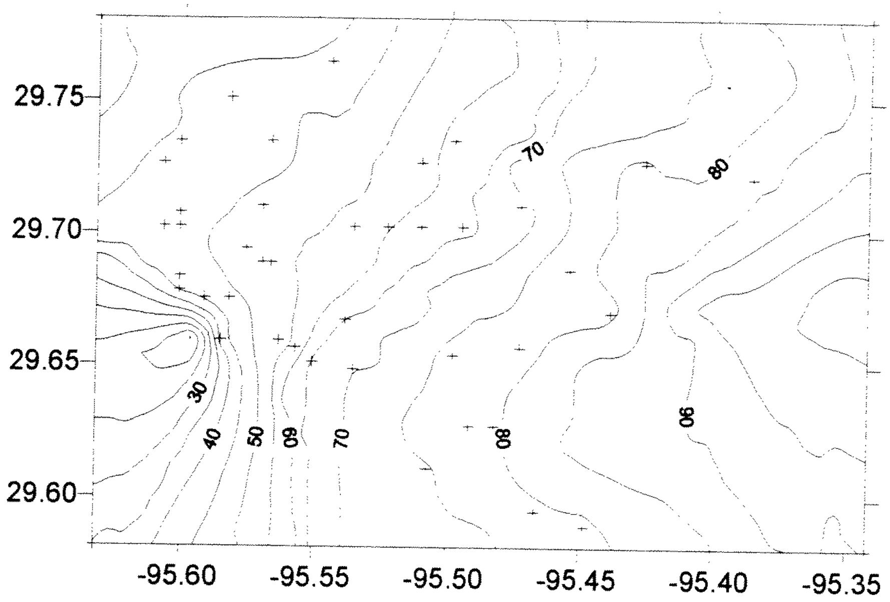

Figure 5.9. Distribution Network System Pressures for Case 4.

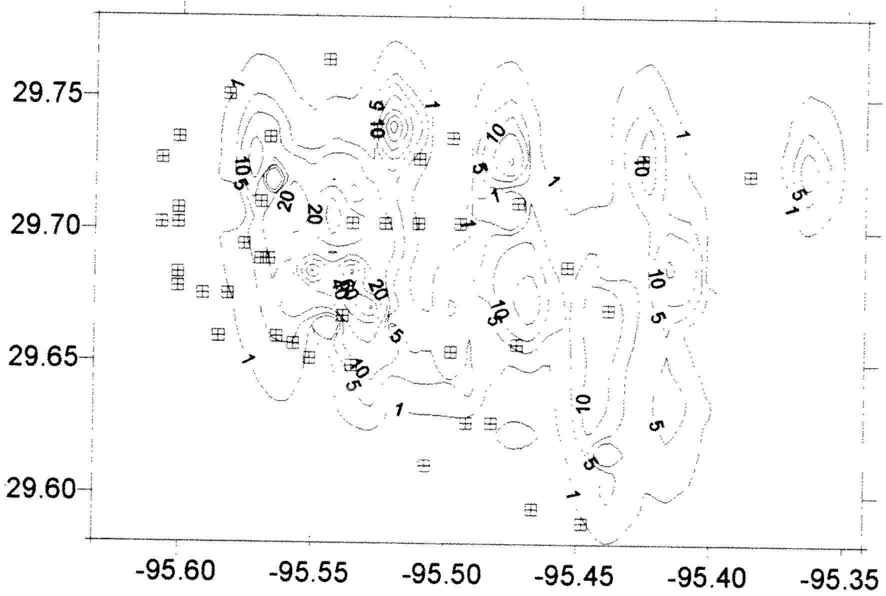

Figure 5.10. Predicted Drawdowns for Case 4.

Table 5.5. Groundwater Supply Allocations for Case 4. Minimum Cost, 30% Groundwater Derived Supply, Low Water Demand Case.

PLANT NAME	Label	Node No.	Unit Cost	Pumpage
SHARPSTOWN-1	SHA-1	273	178.89	-585000
DISTRICT 123	D123	21	144.19	-533830
FAIRDALE(D26)	D26	46	193.05	-462200
WESTBURY-2	WES-2	257	155.05	-374300
SIMS BAYOU	SIMBA	204	127.79	-349990
SOUTHWEST	SW	132	166.03	-348190
BRAESWOOD	BRAES	228	179.37	-316460
SHARPSTOWN 2	SHA-2	270	200.84	-309970
DISTRICT 184	D814	302	201.49	-295540
DISTRICT 51-2	D51-2	36	172.71	-287730
BELLAIRE BRAES	BELBR	92	153.14	-245140
DISTRICT 111-1	D111-1	298	164.36	-222830
DISTRICT 41-2	D41-2	203	245.18	-204520
DISTRICT 111-2	D111-2	297	189.05	-204310
GLENSHIRE-1	GLEN-1	246	142.11	-191640
PARKGLEN WEST	PARWE	295	167.12	-191640
GLENSHIRE-2	GLEN-2	245	145.13	-169350
BRIARWICK	BRIAR	187	223.44	-167090
BROOKFIELD	BROOK	91	172.09	-155510
WESTBURY-1	WES-1	211	232.1	-146500
BRAEBURN WEST	BRAWE	247	196.77	-141380
DISTRICT 54	D54	117	185.1	-88915
MANNING	MANNI	304	166.43	-64542
DISTRICT 218	D218	93	197.48	-59473
CHASEWOOD	CHASE	201	206.49	-51416
PARKGLEN-1	PAR-1	292	217.85	-46683
BRIARGROVE PARK	BRIPA	18	245.18	-26255
WILLOW BEND	WILBE	217	223.91	-9988
BOONE ROAD	BOONE	303	202.83	-7666
DISTRICT 90-2	D90-2	299	171.89	0
DISTRICT 139	D139	291	261.19	0
ROSEWOOD-1	ROS-1	87	245.18	0
SOUTHEND	S-END	139	725.46	0
DISTRICT 94	D94	271	360.25	0
DISTRICT 185	D158	89	379.65	0
RIDGEMONT	RIDGE	188	601.01	0
LINKWOOD	LINKW	171	627.67	0
DISTRICT 51-1	D51-1	102	322.24	0
ROSEWOOD	ROS-2	32	388.86	0
MEYERLAND-1	MEY-1	261	328.56	0

Case 5. This simulation-optimization run studied a case where the total water demand was 3000 million gallons per month with 18% of this demand satisfied by pumping ground water. The remaining demand was satisfied by surface water supply applied along eastern edge of the model. The optimization algorithm searches for a pumpage policy that minimizes total cost while attempting to maintain a system pressure between 10 and 110 psi, and produce a maximum drawdown no greater than 300 feet.

Figure 5.11 is a contour plot of the network distribution system pressures for this case. The minimum pressures are all above 15 psi with the lowest pressure in the extreme lower corner near the Parkwest plant. The highest pressures are in the eastern edge supply lines. This case is deemed feasible with respect to pressure predictions, but some method to boost pressure along the western edge should be explored.

Figure 5.12 shows the simulated drawdown for this scenario. The maximum drawdown is 15 feet, located near the Simms Bayou Plant. The drawdown in the western, central, and northern portion of the modeled area is about a third of this value around 5 feet. Using the maximum drawdown and Equation 1, the estimated maximum land subsidence is 0.09 inches.

Subsidence (inches) := 12*DDN(ft)*S/2		
Drawdown	15	ft
S (storage coefficient)	0.001	
δ	0.09	inches

Table 5.6 shows the supply allocation for Case 5. The cost of this allocation is $88.072 to produce 528 million gallons per month from the study area. The overall unit cost of this production policy is $166.80 per million gallons of groundwater. The required cost for surface water to the western edge to make this case economically equivalent to Case 4 is $180/million gallons; The calculations are summarized below:

Cost Case 4:	`$247,344`	Water Produced:	`1404 Million Gallons`
Cost Case 5:	`$ 88,072`	Water Produced:	`528 Million Gallons`
ΔCost :	`$159,272`	ΔWater Produced:	`876 Million Gallons`

Cost of Added Surface Water (Δ Water) = `$159,272/876 MGal = $181.82/MGal`

This case satisfies the subsidence district's required 20% groundwater allocation in the study area, as well as the pressure requirements of the distribution system, however pressure along the western portion of the modeled region should be boosted, or supplimented with surface water transmission at pressures above 90 psi.

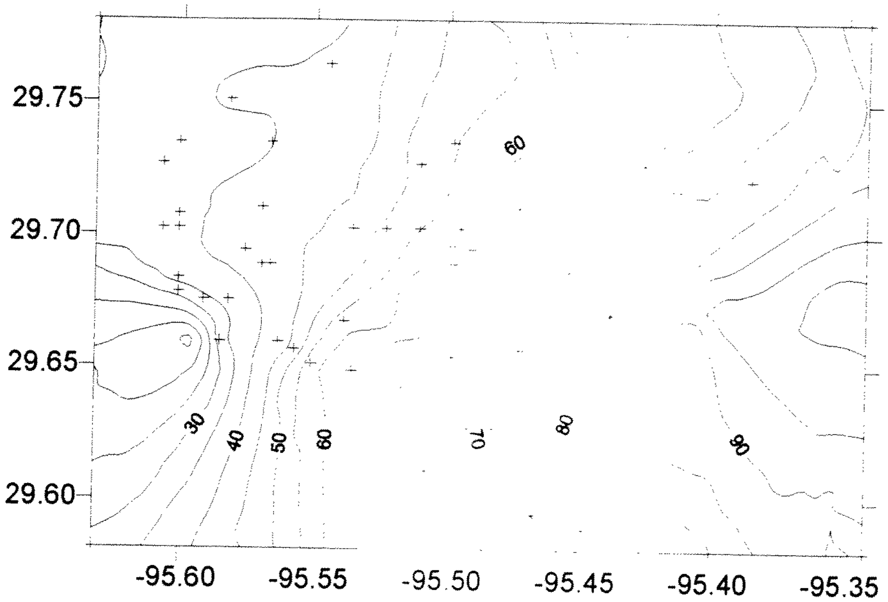

Figure 5.11. Distribution Network System Pressures for Case 5.

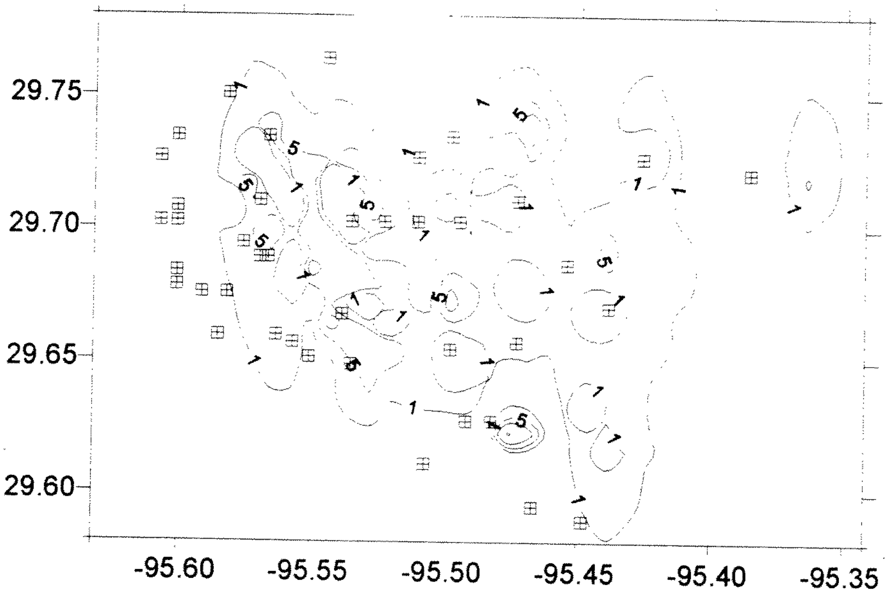

Figure 5.12. Predicted Drawdowns for Case 5.

Table 5.6. Groundwater Supply Allocations for Case 5. Minimum Cost, 11% Groundwater Derived Supply, Low Water Demand Case. 528 MGal Produced

PLANT NAME	Label	Node No.	Unit Cost	Pumpage
DISTRICT 123	D123	21	144.19	-456440
GLENSHIRE-1	GLEN-1	246	142.11	-191620
BELLAIRE BRAES	BELBR	92	153.14	-177880
GLENSHIRE-2	GLEN-2	245	145.13	-169350
PARKGLEN WEST	PARWE	295	167.12	-160450
BRAEBURN WEST	BRAWE	247	196.77	-123470
BROOKFIELD	BROOK	91	172.09	-109680
SIMS BAYOU	SIMBA	204	127.79	-93623
BOONE ROAD	BOONE	303	202.83	-86435
WESTBURY-2	WES-2	257	155.05	-68538
SHARPSTOWN-1	SHA-1	273	178.89	-65546
BRIARGROVE PARK	BRIPA	18	245.18	-63092
DISTRICT 54	D54	117	185.1	-57801
SOUTHWEST	SW	132	166.03	-54845
PARKGLEN-1	PAR-1	292	217.85	-52610
DISTRICT 111-1	D111-1	298	164.36	-48014
MANNING	MANNI	304	166.43	-45356
CHASEWOOD	CHASE	201	206.49	-44495
DISTRICT 218	D218	93	197.48	-42362
DISTRICT 51-2	D51-2	36	172.71	-42057
DISTRICT 90-2	D90-2	299	171.89	-40150
FAIRDALE(D26)	D26	46	193.05	-38973
BRAESWOOD	BRAES	228	179.37	-38208
DISTRICT 184	D814	302	201.49	-29781
WILLOW BEND	WILBE	217	223.91	-22769
DISTRICT 111-2	D111-2	297	189.05	-17222
SHARPSTOWN 2	SHA-2	270	200.84	-15888
DISTRICT 41-2	D41-2	203	245.18	0
BRIARWICK	BRIAR	187	223.44	0
WESTBURY-1	WES-1	211	232.1	0
DISTRICT 139	D139	291	261.19	0
ROSEWOOD-1	ROS-1	87	245.18	0
SOUTHEND	S-END	139	725.46	0
DISTRICT 94	D94	271	360.25	0
DISTRICT 185	D158	89	379.65	0
RIDGEMONT	RIDGE	188	601.01	0
LINKWOOD	LINKW	171	627.67	0
DISTRICT 51-1	D51-1	102	322.24	0
ROSEWOOD	ROS-2	32	388.86	0
MEYERLAND-1	MEY-1	261	328.56	0

Case 6. This simulation-optimization run studied a case where the total water demand was 3000 million gallons per month with 10% of this demand satisfied by pumping ground water. The remaining demand was satisfied by surface water supply applied along eastern edge of the model. The optimization algorithm searches for a pumpage policy that minimizes total cost while attempting to maintain a system pressure between 10 and 110 psi, and produce a maximum drawdown no greater than 300 feet.

Figure 5.13is a contour plot of the system pressures for this case. The pattern is similar to the other cases, but the pressures are lower throughout the system except at the supply nodes. This case is considered infeasible because the entire western region of the study area has low water pressures. These pressures can be increased by introducing an additional supply node along the western edge at 90+ psi.

Figure 5.14 shows the simulated drawdown for this scenario; The maximum drawdown is 10 feet located near the Sims Bayou, Sharpstown, and District 51 plants. Using Equation 1, this value of drawdwon produces an estimated maximum subsidence of 0.06 inches. The calculation is shown below:

Subsidence (inches) := 12*DDN(ft)*S/2		
Drawdown	10	ft
S (storage coefficient)	0.001	
δ	0.06	inches

The drawdown map is relatively "flat" and this map probably represents a best configuration from the standpoint of controlling subsidence (although network hydraulics is not satisfied).

Table 5.7 shows the supply allocation for Case 6. The cost of this allocation is $73,783 month to produce 300 million gallons per month from the study area. The overall unit cost of this production policy is $245.94 per million gallons of water produced. The required cost for surface water to the western edge to make this case economically equivalent to Case 5 is $ 111 per million gallons. The calculations are shown below:

Cost Case 5:	$ 88,072	Water Produced:	528 Million Gallons
Cost Case 6:	$ 73,783	Water Produced:	300 Million Gallons
ΔCost :	$ 14,289	ΔWater Produced:	128 Million Gallons

Cost of Added Surface Water (Δ Water) = $ 14,289/128MGal = $ 111.63/MGal

This particular case does not seem to posess any advantage over Case 5 since the estimated subsidence is nearly the same and the marginal cost of the additional surface water is probably unachieveable. This cost is over 10% smaller than the cheapest groundwater in the study area. This case satisfies the subsidence district's required 20% groundwater allocation in the study area; however the allocation is infeasible unless some transmission of surface water at higher pressures to the western edge of the region is implemented.

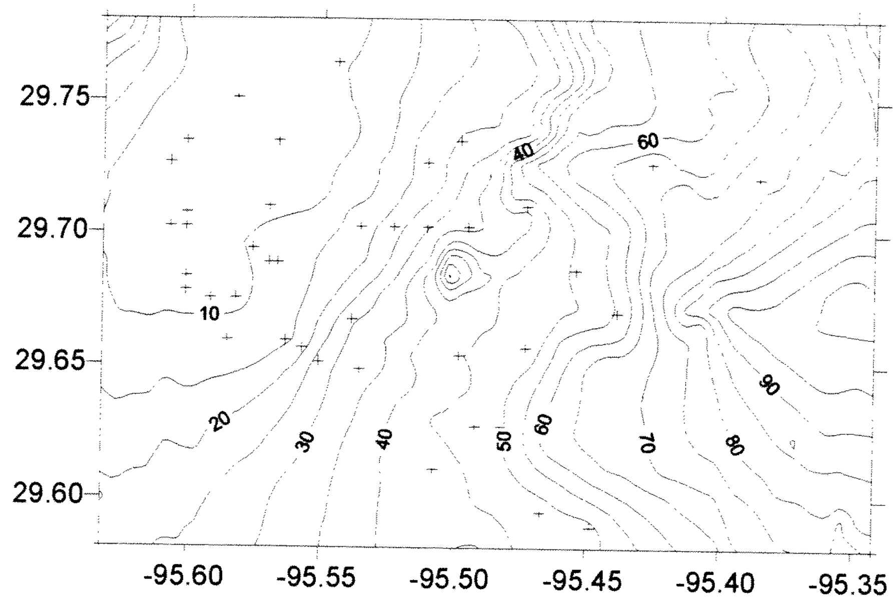

Figure 5.13. Distribution Network System Pressures for Case 6.

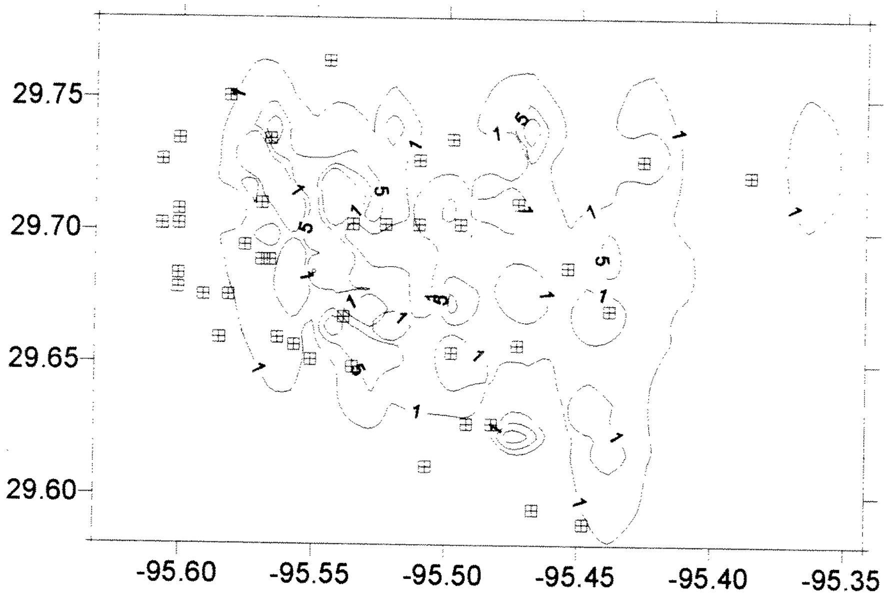

Figure 5.14. Predicted Drawdowns for Case 6.

Table 5.7. Groundwater Supply Allocations for Case 6. Minimum Cost. 6% Groundwater Derived Supply, Low Water Demand Case.

PLANT NAME	Label	Node No.	Unit Cost	Pumpage
BOONE ROAD	BOONE	303	202.83	-89839
PARKGLEN-1	PAR-1	292	217.85	-85162
BROOKFIELD	BROOK	91	172.09	-83835
DISTRICT 139	D139	291	261.19	-80872
SOUTHEND	S-END	139	725.46	-80273
DISTRICT 54	D54	117	185.1	-60024
CHASEWOOD	CHASE	201	206.49	-54930
BRIARGROVE PARK	BRIPA	18	245.18	-49652
DISTRICT 111-1	D111-1	298	164.36	-47943
WESTBURY-1	WES-1	211	232.1	-47809
ROSEWOOD-1	ROS-1	87	245.18	-47639
DISTRICT 123	D123	21	144.19	-46521
WILLOW BEND	WILBE	217	223.91	-46281
DISTRICT 218	D218	93	197.48	-45861
BELLAIRE BRAES	BELBR	92	153.14	-42426
FAIRDALE(D26)	D26	46	193.05	-42290
DISTRICT 185	D158	89	379.65	-40564
BRAEBURN WEST	BRAWE	247	196.77	-37214
SHARPSTOWN-1	SHA-1	273	178.89	-36948
DISTRICT 94	D94	271	360.25	-35686
DISTRICT 184	D814	302	201.49	-30674
SIMS BAYOU	SIMBA	204	127.79	-23613
PARKGLEN WEST	PARWE	295	167.12	-22303
DISTRICT 90-2	D90-2	299	171.89	-21922
MEYERLAND-1	MEY-1	261	328.56	-21381
BRAESWOOD	BRAES	228	179.37	-21326
DISTRICT 41-2	D41-2	203	245.18	-19391
DISTRICT 51-2	D51-2	36	172.71	-18845
ROSEWOOD	ROS-2	32	388.86	-18075
SHARPSTOWN 2	SHA-2	270	200.84	-13927
WESTBURY-2	WES-2	257	155.05	-8117
GLENSHIRE-1	GLEN-1	246	142.11	-7021
DISTRICT 51-1	D51-1	102	322.24	-4486
BRIARWICK	BRIAR	187	223.44	-4150
SOUTHWEST	SW	132	166.03	0
GLENSHIRE-2	GLEN-2	245	145.13	0
MANNING	MANNI	304	166.43	0
DISTRICT 111-2	D111-2	297	189.05	0
RIDGEMONT	RIDGE	188	601.01	0
LINKWOOD	LINKW	171	627.67	0

Case 7. This simulation studies the case where the total water demand is 4650 million gallons per month (high demand case) and 30 % of this demand is satisfied by pumping from within the study area. All remaining demand was satisfied by surface water supplies applied at the eastern edge of the model. The model searches for a minimum drawdown supply allocation that meets demand, maintains system pressure between 10 and 110 psi, and produces a maximum cost less than $950,000.

Figure 5.15 is a contour plot of the network distribution system pressures for this case. The pressures on the western edge of the model are at the lower bounds, and this case is considered hydraulically infeasible. Additional supply of water at higher pressures is required along the western edge of the study area.

Figure 5.16 shows the simulated drawdown for this solution. The largest drawdowns for this scenario occur near the District-51, Braeburn West, Sharpstown, Meyerland, Linkwood, and the Southwest Plants. The maximum drawdown is 70 feet just north of the Braeburn West Plant. Using this value in Equation 1 produces an estimated maximum land subsidence 0.42 inches, the calculation is shown below:

Subsidence (inches) := 12*DDN(ft)*S/2		
Drawdown	70	ft
S (storage coefficient)	0.001	
δ	0.42	inches

The drawdown patterns are more consistent with the pumpage policies selected by the optimization algorithm; The maximum drawdowns are located near the high-pumpage plants. The drawdown pattern is identical to Case 4 as is the pumpage policy.

Like the previous case, the drawdown pattern is quite desirable and the pumpage is fairly well distributed among the lower unit cost plants. The optimization algorithm did not select any of the higher unit cost plants to produce water in this scenario.

Table 5.7 shows the supply allocation for Case 7. The cost of this allocation is $247,344 a month to produce 1404 million gallons of water from within the study area. The overall unit cost of water in this case is $241.17 per million gallons of water, the same as Case 4.

This case does not satisfy the requirement that no more than 20% of the water in the study area be groundwater.

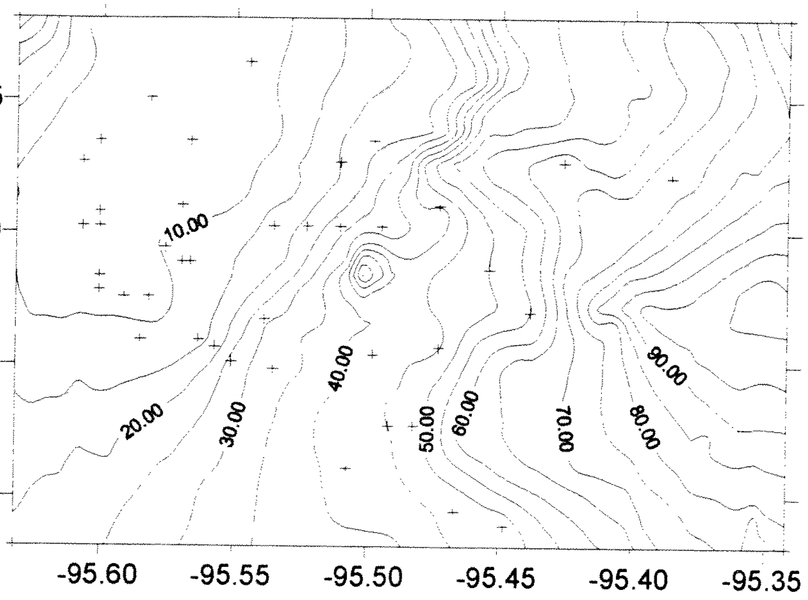

Figure 5.15. Distribution Network System Pressures for Case 7.

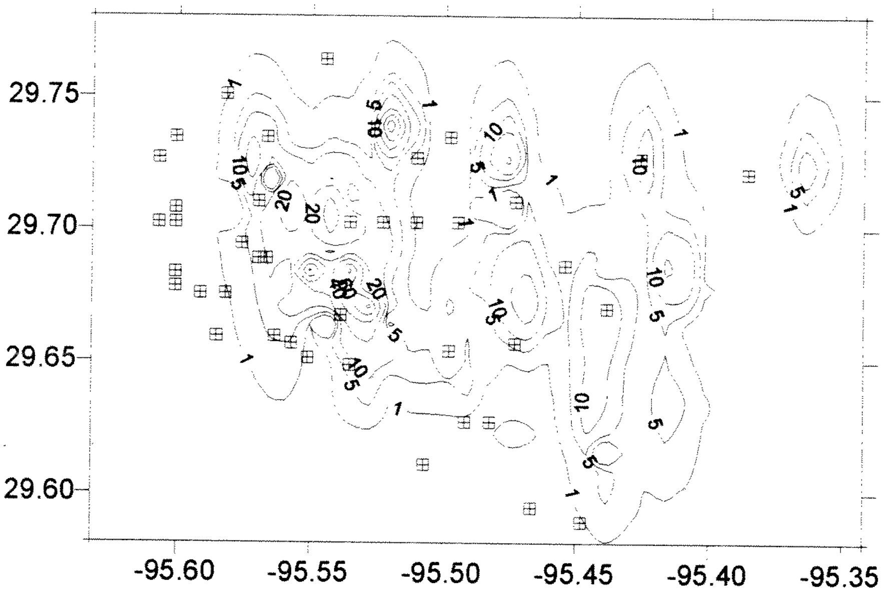

Figure 5.16. Predicted Drawdowns for Case 7.

Table 5.8. Groundwater Supply Allocations for Case 7. Minimum Subsidence, 30 % Groundwater Derived Supply, High Water Demand Case. 1410 MGal Pumped

PLANT NAME	Label	Node No.	Unit Cost	Pumpage
SHARPSTOWN-1	SHA-1	273	178.89	-585000
DISTRICT 123	D123	21	144.19	-533830
FAIRDALE(D26)	D26	46	193.05	-462200
WESTBURY-2	WES-2	257	155.05	-374300
SIMS BAYOU	SIMBA	204	127.79	-349990
SOUTHWEST	SW	132	166.03	-348190
BRAESWOOD	BRAES	228	179.37	-316460
SHARPSTOWN 2	SHA-2	270	200.84	-309970
DISTRICT 184	D814	302	201.49	-295540
DISTRICT 51-2	D51-2	36	172.71	-287730
BELLAIRE BRAES	BELBR	92	153.14	-245140
DISTRICT 111-1	D111-1	298	164.36	-222830
DISTRICT 41-2	D41-2	203	245.18	-204520
DISTRICT 111-2	D111-2	297	189.05	-204310
GLENSHIRE-1	GLEN-1	246	142.11	-191640
PARKGLEN WEST	PARWE	295	167.12	-191640
GLENSHIRE-2	GLEN-2	245	145.13	-169350
BRIARWICK	BRIAR	187	223.44	-167090
BROOKFIELD	BROOK	91	172.09	-155510
WESTBURY-1	WES-1	211	232.1	-146500
BRAEBURN WEST	BRAWE	247	196.77	-141380
DISTRICT 54	D54	117	185.1	-88915
MANNING	MANNI	304	166.43	-64542
DISTRICT 218	D218	93	197.48	-59473
CHASEWOOD	CHASE	201	206.49	-51416
PARKGLEN-1	PAR-1	292	217.85	-46683
BRIARGROVE PARK	BRIPA	18	245.18	-26255
WILLOW BEND	WILBE	217	223.91	-9988
BOONE ROAD	BOONE	303	202.83	-7666
DISTRICT 90-2	D90-2	299	171.89	0
DISTRICT 139	D139	291	261.19	0
ROSEWOOD-1	ROS-1	87	245.18	0
SOUTHEND	S-END	139	725.46	0
DISTRICT 94	D94	271	360.25	0
DISTRICT 185	D158	89	379.65	0
RIDGEMONT	RIDGE	188	601.01	0
LINKWOOD	LINKW	171	627.67	0
DISTRICT 51-1	D51-1	102	322.24	0
ROSEWOOD	ROS-2	32	388.86	0
MEYERLAND-1	MEY-1	261	328.56	0

Case 8. This simulation-optimization run studied a case where the total water demand was 4650 million gallons per month (high demand case) and 7% of this demand was satisfied by pumping from within the study area. All remaining demand was satisfied by surface water supplies applied at the eastern edge of the model. The model searches for a minimum drawdown supply allocation that meets demand, maintains system pressure between 10 and 110 psi, and produces a maximum cost less than $950,000.

Figure 5.17 is a contour plot of the network distribution system pressures for this case. Because the pressures along the western edge of the modeled region are at the lower pressure bound, this case is considered infeasible under our current configuration. It is possible to increase the western edge water pressures by adding an additional supply node along the western edge.

Figure 5.18 shows the predicted drawdown for this solution. The maximum drawdown is 10 feet located near District 51, and Braeburn West plants.

Subsidence (inches) := 12*DDN(ft)*S/2		
Drawdown	10	ft
S (storage coefficient)	0.001	
δ	0.06	inches

While this is an acceptable subsidence level, the allocation is hydraulically infeasible

Table 5.8 shows the allocation for this scenario. The cost of this allocation is $85,180 month to produce 326 million gallons of groundwater from the study area. The overall unit cost of this production policy is $261.28 per million gallons produced. The required cost for surface water to the western edge to make this case economically equivalent to Case 7 is $ 150 per million gallons. The calculations are shown below:

Cost Case 7:	$247,344	Water Produced:	1404 Million Gallons
Cost Case 8:	$ 85,180	Water Produced:	326 Million Gallons
ΔCost :	$162,164	ΔWater Produced:	1078 Million Gallons

Cost of Added Surface Water (Δ Water) = $162,164/1078MGal = $ 150.43/MGal

This case satisfies the subsidence district's required 20% groundwater allocation in the study area, however the allocation is infeasible unless some method of transmission of surface water to the western edge of the modeled region is implemented.

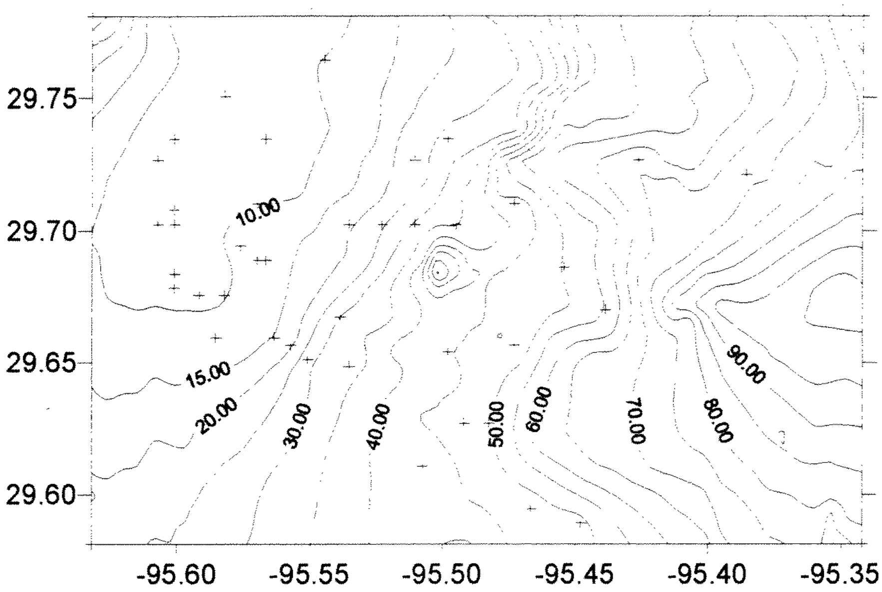

Figure 5.17. Distribution Network System Pressures for Case 8.

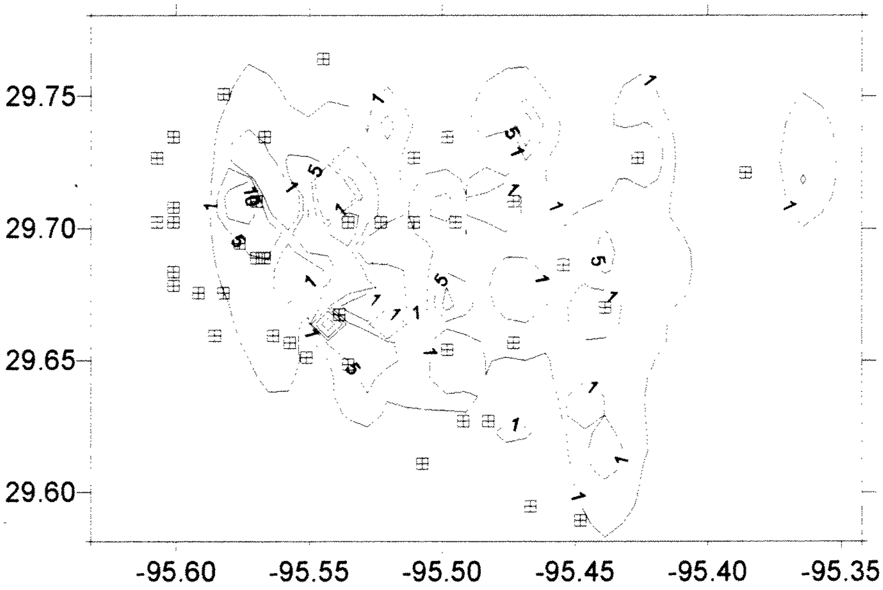

Figure 5.18. Predicted Drawdowns for Case 8.

Table 5.9. Groundwater Supply Allocations for Case 8. Minimum Subsidence, 7% Groundwater Derived Supply, High Water Demand Case. 326 MGal Pumped.

PLANT NAME	Label	Node No.	Unit Cost	Pumpage
ROSEWOOD	ROS-2	32	388.86	-132370
BRAEBURN WEST	BRAWE	247	196.77	-126480
SHARPSTOWN 2	SHA-2	270	200.84	-92830
DISTRICT 94	D94	271	360.25	-92830
BROOKFIELD	BROOK	91	172.09	-89133
PARKGLEN-1	PAR-1	292	217.85	-89133
BOONE ROAD	BOONE	303	202.83	-89133
DISTRICT 139	D139	291	261.19	-89133
SOUTHEND	S-END	139	725.46	-89133
CHASEWOOD	CHASE	201	206.49	-60057
SHARPSTOWN-1	SHA-1	273	178.89	-53480
DISTRICT 218	D218	93	197.48	-53480
ROSEWOOD-1	ROS-1	87	245.18	-53480
DISTRICT 54	D54	117	185.1	-48421
FAIRDALE(D26)	D26	46	193.05	-44567
DISTRICT 111-1	D111-1	298	164.36	-44010
DISTRICT 123	D123	21	144.19	-40110
DISTRICT 184	D814	302	201.49	-31197
WESTBURY-2	WES-2	257	155.05	-26740
SOUTHWEST	SW	132	166.03	-26740
DISTRICT 185	D158	89	379.65	-26740
BRAESWOOD	BRAES	228	179.37	-25935
GLENSHIRE-1	GLEN-1	246	142.11	-21100
WILLOW BEND	WILBE	217	223.91	-6685
SIMS BAYOU	SIMBA	204	127.79	0
DISTRICT 51-2	D51-2	36	172.71	0
BELLAIRE BRAES	BELBR	92	153.14	0
DISTRICT 41-2	D41-2	203	245.18	0
DISTRICT 111-2	D111-2	297	189.05	0
PARKGLEN WEST	PARWE	295	167.12	0
GLENSHIRE-2	GLEN-2	245	145.13	0
BRIARWICK	BRIAR	187	223.44	0
WESTBURY-1	WES-1	211	232.1	0
MANNING	MANNI	304	166.43	0
BRIARGROVE PARK	BRIPA	18	245.18	0
DISTRICT 90-2	D90-2	299	171.89	0
RIDGEMONT	RIDGE	188	601.01	0
LINKWOOD	LINKW	171	627.67	0
DISTRICT 51-1	D51-1	102	322.24	0
MEYERLAND-1	MEY-1	261	328.56	0

Case 9. This simulation-optimization run studied a case where the total water demand was 3000 million gallons per month (low demand case) and 25% of this demand was satisfied by pumping from within the study area. All remaining demand was satisfied by surface water supplies applied at the eastern edge of the model. The model searches for a minimum drawdown supply allocation that meets demand, maintains system pressure between 10 and 110 psi, and produces a maximum cost less than $950,000.

Figure 5.19 is a contour plot of the network distribution system pressures for this case. Because the pressures along the western edge of the modeled region are at the lower pressure bound, this case is considered infeasible under our current configuration. It is possible to increase the western edge water pressures by adding an additional supply node along the western edge.

Figure 5.20 shows the predicted drawdown for this solution. The maximum drawdown is 10 feet located near Sharpstown, and Braeburn West plants.

Subsidence (inches) := 12*DDN(ft)*S/2		
Drawdown	10	ft
S (storage coefficient)	0.001	
δ	0.06	inches

Table 5.10 shows the allocation for this scenario. The cost of this allocation is $182,699 per month to produce 754 million gallons of groundwater from the study area. The overall unit cost of this production policy is $242.3 per million gallons produced.

This case does not satisfy the subsidence district's required 20% groundwater allocation in the study area, although the drawdown is acceptable.

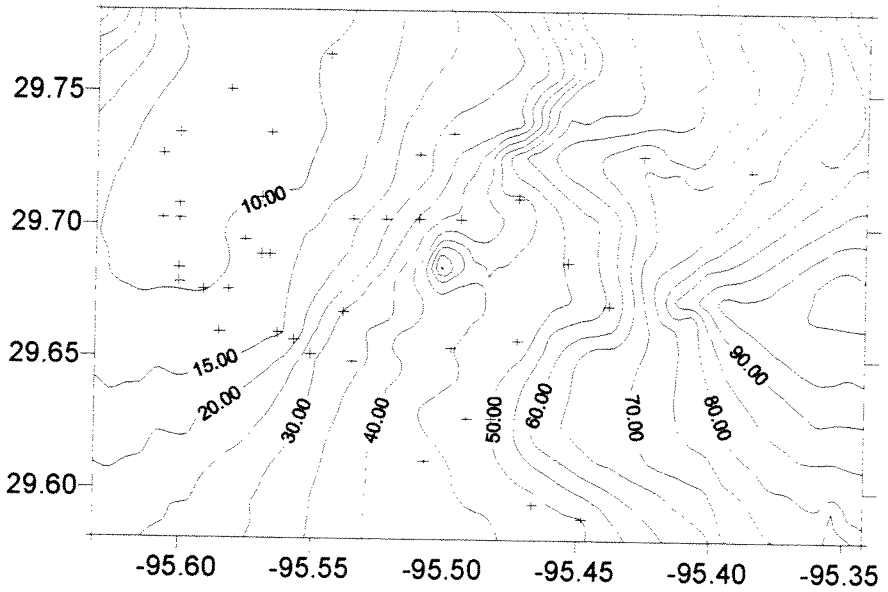

Figure 5.19. Distribution Network System Pressures for Case 9.

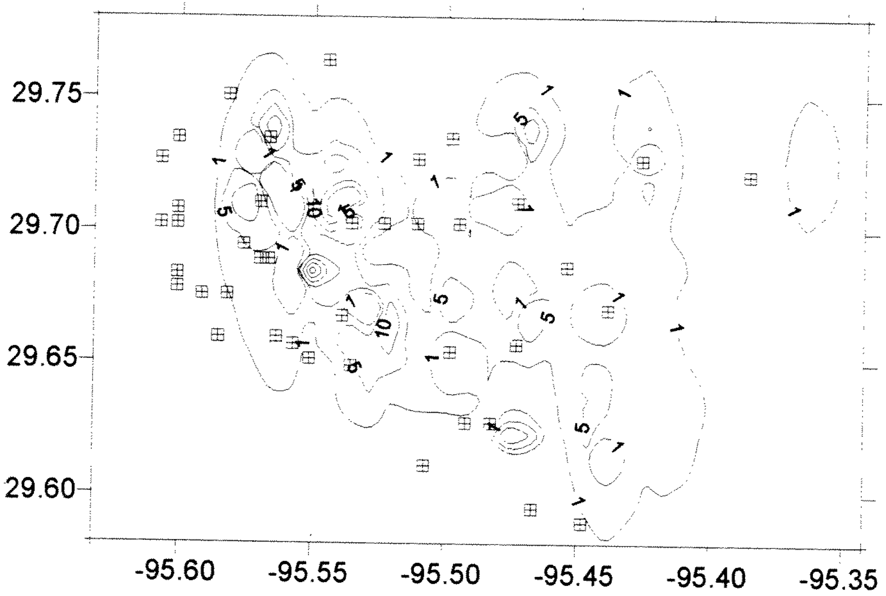

Figure 5.20. Predicted Drawdowns for Case 9.

Table 5.10. Groundwater Supply Allocations for Case 9, Minimum Subsidence, 30% Groundwater Derived Supply, Low Water Demand Case, 754 MGal Pumped.

PLANT NAME	Label	Node No.	Unit Cost	Pumpage
BROOKFIELD	BROOK	91	172.09	-162533
PARKGLEN-1	PAR-1	292	217.85	-162532
BOONE ROAD	BOONE	303	202.83	-162532
DISTRICT 139	D139	291	261.19	-162532
SOUTHEND	S-END	139	725.46	-162357
MANNING	MANNI	304	166.43	-131347
GLENSHIRE-2	GLEN-2	245	145.13	-131339
BELLAIRE BRAES	BELBR	92	153.14	-131337
BRIARGROVE PARK	BRIPA	18	245.18	-131337
DISTRICT 90-2	D90-2	299	171.89	-131337
GLENSHIRE-1	GLEN-1	246	142.11	-131336
PARKGLEN WEST	PARWE	295	167.12	-131336
ROSEWOOD	ROS-2	32	388.86	-131336
BRAEBURN WEST	BRAWE	247	196.77	-131335
MEYERLAND-1	MEY-1	261	328.56	-128517
WILLOW BEND	WILBE	217	223.91	-117966
CHASEWOOD	CHASE	201	206.49	-117893
SHARPSTOWN-1	SHA-1	273	178.89	-91226
DISTRICT 54	D54	117	185.1	-91226
DISTRICT 218	D218	93	197.48	-91226
ROSEWOOD-1	ROS-1	87	245.18	-91226
FAIRDALE(D26)	D26	46	193.05	-73398
SHARPSTOWN 2	SHA-2	270	200.84	-46659
DISTRICT 184	D814	302	201.49	-46659
DISTRICT 94	D94	271	360.25	-46658
DISTRICT 41-2	D41-2	203	245.18	-43272
DISTRICT 123	D123	21	144.19	-38637
WESTBURY-2	WES-2	257	155.05	-37746
SOUTHWEST	SW	132	166.03	-37746
DISTRICT 185	D158	89	379.65	-37746
BRAESWOOD	BRAES	228	179.37	-37745
DISTRICT 51-2	D51-2	36	172.71	-28832
BRIARWICK	BRIAR	187	223.44	-28832
WESTBURY-1	WES-1	211	232.1	-28832
DISTRICT 111-2	D111-2	297	189.05	-19920
DISTRICT 111-1	D111-1	298	164.36	-19919
RIDGEMONT	RIDGE	188	601.01	-19919
LINKWOOD	LINKW	171	627.67	-19919
SIMS BAYOU	SIMBA	204	127.79	-19918
DISTRICT 51-1	D51-1	102	322.24	-19918

Case 10. This simulation-optimization run studied a case where the total water demand was 3000 million gallons per month (low demand case) and 15% of this demand was satisfied by pumping from within the study area. All remaining demand was satisfied by surface water supplies applied at the eastern edge of the model. The model searches for a minimum drawdown supply allocation that meets demand, maintains system pressure between 10 and 110 psi, and produces a maximum cost less than $950,000.

Figure5.21 is a contour plot of the network distribution system pressures for this case. The minimum pressures are above 15 psi, except in two areas along the western edge of the modeled region where the pressures drop to 10 psi. This case is considered barely feasible because only a couple of network locations are at the low pressure limit, but some method of boosting pressure should be considered for similar scenarios.

Figure 5.22 shows the simulated drawdown for this solution. The maximum drawdown is 10 feet, located near the Braeburn West, and Sharpstown plants. The calculation for estimated maximum land subsidence produces a value of 0.06 inches. The calculation is shown below:

Subsidence (inches) := 12*DDN(ft)*S/2		
Drawdown	10	ft
S (storage coefficient)	0.001	
δ	0.06	inches

Table 5.11 shows the supply allocation for Case 10. The cost of this allocation is $105,096 per month to produce 452 million gallons of groundwater from the study area. The required cost for surface water to the western edge to make this case economically equivalent to Case 9 is $257 per million gallons of groundwater produced; The calculations are summarized below:

Cost Case 9:	$182,699	Water Produced:	754 Million Gallons
Cost Case 10:	$105,096	Water Produced:	452 Million Gallons
ΔCost :	$ 77,603	ΔWater Produced:	302 Million Gallons

Cost of Added Surface Water (Δ Water) = $77,603/302 MGal = $256.96/MGal.

This case satisfies the subsidence district's required 20% groundwater allocation in the study area and produces an acceptable drawdown.

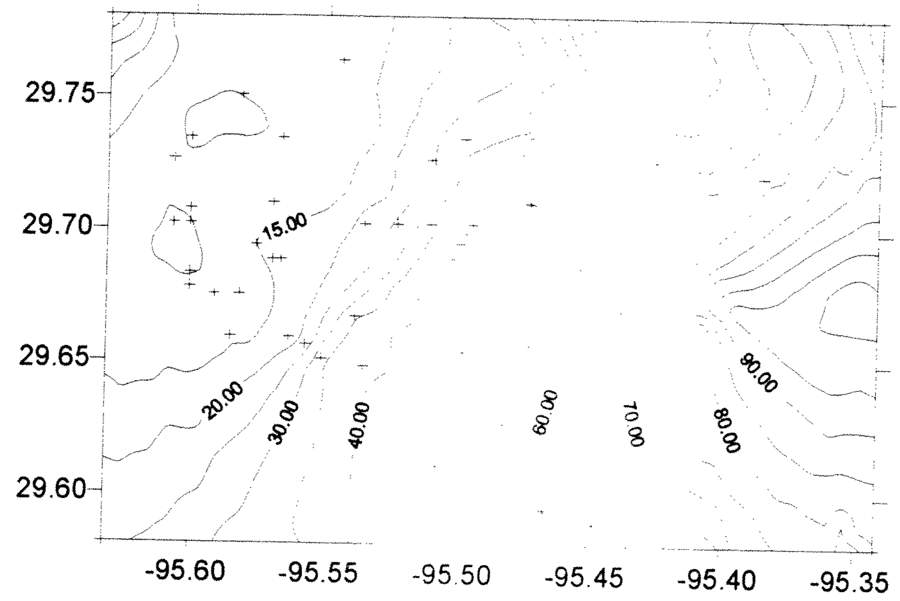

Figure 5.21. Distribution Network System Pressures for Case 10.

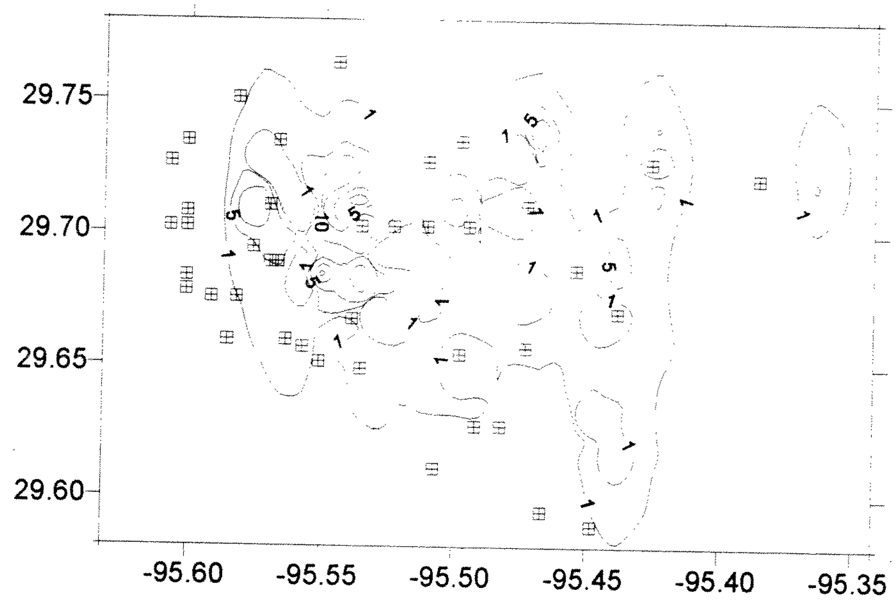

Figure 5.22. Predicted Drawdowns for Case 10.

Table 5.11. Groundwater Supply Allocations for Case 10 Minimum Subsidence, 11% Groundwater Derived Supply, Low Water Demand Case, 452 MGal Pumped.

PLANT NAME	Label	Node No.	Unit Cost	Pumpage
MANNING	MANNI	304	166.43	-119450
BELLAIRE BRAES	BELBR	92	153.14	-119440
GLENSHIRE-1	GLEN-1	246	142.11	-119440
PARKGLEN WEST	PARWE	295	167.12	-119440
GLENSHIRE-2	GLEN-2	245	145.13	-119440
BRAEBURN WEST	BRAWE	247	196.77	-119440
BRIARGROVE PARK	BRIPA	18	245.18	-119440
ROSEWOOD	ROS-2	32	388.86	-119440
DISTRICT 90-2	D90-2	299	171.89	-119440
MEYERLAND-1	MEY-1	261	328.56	-116620
BROOKFIELD	BROOK	91	172.09	-74872
PARKGLEN-1	PAR-1	292	217.85	-74872
BOONE ROAD	BOONE	303	202.83	-74872
DISTRICT 139	D139	291	261.19	-74872
SOUTHEND	S-END	139	725.46	-74872
WILLOW BEND	WILBE	217	223.91	-52589
CHASEWOOD	CHASE	201	206.49	-52516
SHARPSTOWN-1	SHA-1	273	178.89	-39219
DISTRICT 54	D54	117	185.1	-39219
DISTRICT 218	D218	93	197.48	-39219
ROSEWOOD-1	ROS-1	87	245.18	-39219
FAIRDALE(D26)	D26	46	193.05	-30305
SHARPSTOWN 2	SHA-2	270	200.84	-16935
DISTRICT 184	D814	302	201.49	-16935
DISTRICT 94	D94	271	360.25	-16935
DISTRICT 41-2	D41-2	203	245.18	-13548
WESTBURY-2	WES-2	257	155.05	-12479
SOUTHWEST	SW	132	166.03	-12479
BRAESWOOD	BRAES	228	179.37	-12479
DISTRICT 185	D158	89	379.65	-12479
DISTRICT 51-2	D51-2	36	172.71	-8022
BRIARWICK	BRIAR	187	223.44	-8022
WESTBURY-1	WES-1	211	232.1	-8022
SIMS BAYOU	SIMBA	204	127.79	-3565
DISTRICT 111-1	D111-1	298	164.36	-3565
DISTRICT 111-2	D111-2	297	189.05	-3565
RIDGEMONT	RIDGE	188	601.01	-3565
LINKWOOD	LINKW	171	627.67	-3565
DISTRICT 51-1	D51-1	102	322.24	-3565
DISTRICT 123	D123	21	144.19	0

Case 11. This simulation-optimization run studied a case where the total water demand was 3000 million gallons per month (low demand case) and 10% of this demand was satisfied by pumping from within the study area. All remaining demand was satisfied by surface water supplies applied at the eastern edge of the model. The model searches for a minimum drawdown supply allocation that meets demand, maintains system pressure between 10 and 110 psi, and produces a maximum cost less than $950,000

Figure 5.23 is a contour plot of the system pressures for this case. This case is infeasible because the entire western region of the study area has low water pressures. These pressures can be increased by introducing an additional supply node along the western edge representing water supplied water at 90+ psi.

Figure 5.24 shows the associated drawdown for this solution. The maximum drawdown is 10 feet, located near the Sims Bayou plant. The calculation for estimated maximum land subsidence produces a value of 0.06 inches. The calculation is shown below:

Subsidence (inches) := 12*DDN(ft)*S/2		
Drawdown	10	ft
S (storage coefficient)	0.001	
δ	0.06	inches

This case produces a desirable drawdown surface, but the system pressure is too low along the western edge to be feasible. Either boosting pressures by re-pumping or supplying water at 90 psi to this area is required to make this solution feasible.

Table 5.12 shows the supply allocation for Case 11. Obserev that every plant in the study area is producing water, but the higher unit cost plants are producing smaller volumes of water that the other plants. The cost of this allocation is $77,602 month to produce 304 million gallons of water in the study area. The overall unit cost of this production policy is $254.65 per million gallons of groundwater produced..

The required cost for surface water to the western edge to make this case economically equivalent to Case 10 is $165 per million gallons; The calculations are summarized below:

Cost Case 10:	`$105,096`	Water Produced:	`452 Million Gallons`
Cost Case 11:	`$ 77,602`	Water Produced:	`304 Million Gallons`
ΔCost :	`$ 24,494`	ΔWater Produced:	`148 Million Gallons`

Cost of Added Surface Water (Δ Water) = `$ 24,494/148MGal = $165.50/MGal`

This case satisfies the subsidence district's required 20% groundwater allocation in the study area, but the allocation is infeasible unless some method of transmission of surface water to the western edge of the modeled region is implemented.

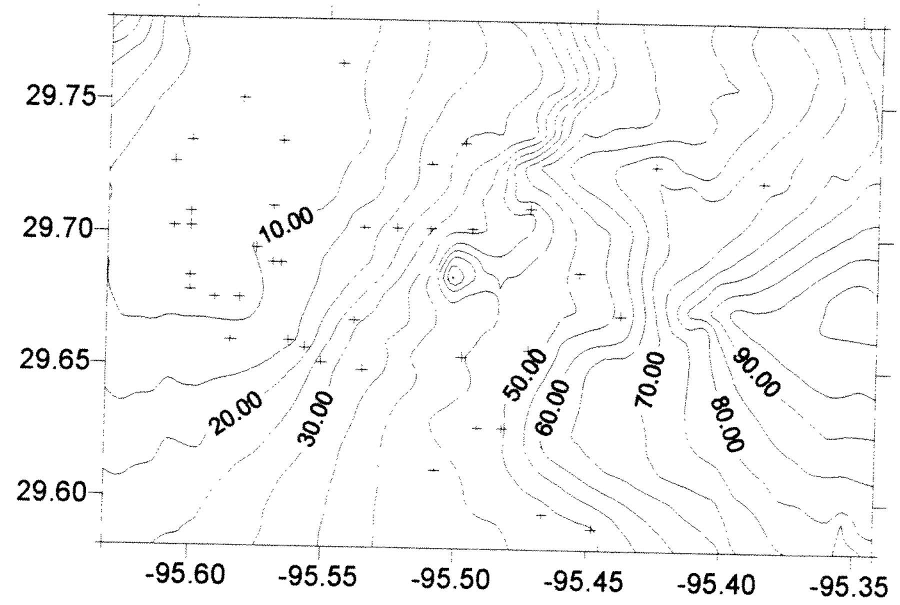

Figure 5.23. Distribution Network System Pressures for Case 11.

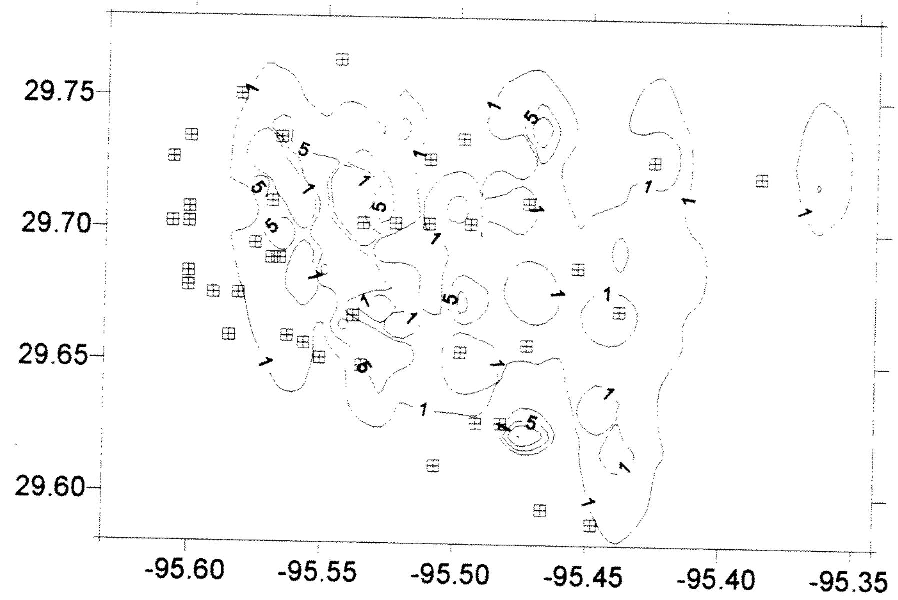

Figure 5.24. Predicted Drawdowns for Case 11.

Table 5.12. Groundwater Supply Allocations for Case 11. Minimum Subsidence, 7% Groundwater Derived Supply, Low Water Demand Case. 304 MGal Pumped.

PLANT NAME	Label	Node No.	Unit Cost	Pumpage
BROOKFIELD	BROOK	91	172.09	-87661
PARKGLEN-1	PAR-1	292	217.85	-87660
BOONE ROAD	BOONE	303	202.83	-87660
DISTRICT 139	D139	291	261.19	-87660
SOUTHEND	S-END	139	725.46	-87485
WILLOW BEND	WILBE	217	223.91	-65377
CHASEWOOD	CHASE	201	206.49	-65377
SHARPSTOWN-1	SHA-1	273	178.89	-52007
DISTRICT 54	D54	117	185.1	-52007
DISTRICT 218	D218	93	197.48	-52007
ROSEWOOD-1	ROS-1	87	245.18	-52007
FAIRDALE(D26)	D26	46	193.05	-43093
DISTRICT 123	D123	21	144.19	-38637
SHARPSTOWN 2	SHA-2	270	200.84	-29724
DISTRICT 184	D814	302	201.49	-29724
DISTRICT 41-2	D41-2	203	245.18	-29724
DISTRICT 94	D94	271	360.25	-29723
WESTBURY-2	WES-2	257	155.05	-25267
SOUTHWEST	SW	132	166.03	-25267
DISTRICT 185	D158	89	379.65	-25267
BRAESWOOD	BRAES	228	179.37	-25266
DISTRICT 51-2	D51-2	36	172.71	-20810
BRIARWICK	BRIAR	187	223.44	-20810
WESTBURY-1	WES-1	211	232.1	-20810
DISTRICT 111-2	D111-2	297	189.05	-16355
DISTRICT 111-1	D111-1	298	164.36	-16354
RIDGEMONT	RIDGE	188	601.01	-16354
LINKWOOD	LINKW	171	627.67	-16354
SIMS BAYOU	SIMBA	204	127.79	-16353
DISTRICT 51-1	D51-1	102	322.24	-16353
GLENSHIRE-2	GLEN-2	245	145.13	-11899
MANNING	MANNI	304	166.43	-11897
BELLAIRE BRAES	BELBR	92	153.14	-11897
BRIARGROVE PARK	BRIPA	18	245.18	-11897
DISTRICT 90-2	D90-2	299	171.89	-11897
MEYERLAND-1	MEY-1	261	328.56	-11897
GLENSHIRE-1	GLEN-1	246	142.11	-11896
PARKGLEN WEST	PARWE	295	167.12	-11896
ROSEWOOD	ROS-2	32	388.86	-11896
BRAEBURN WEST	BRAWE	247	196.77	-11895

Summary of First Approximation

The eleven special cases predicted the pressures and drawdowns in the study area for a variety of different total production and two different demand scenarios. Figure 54 below is a plot showing the overall unit cost of production as a function of groundwater produced and the predicted maximum drawdowns for each optimization goal (minimum cost or minimum subsidence).

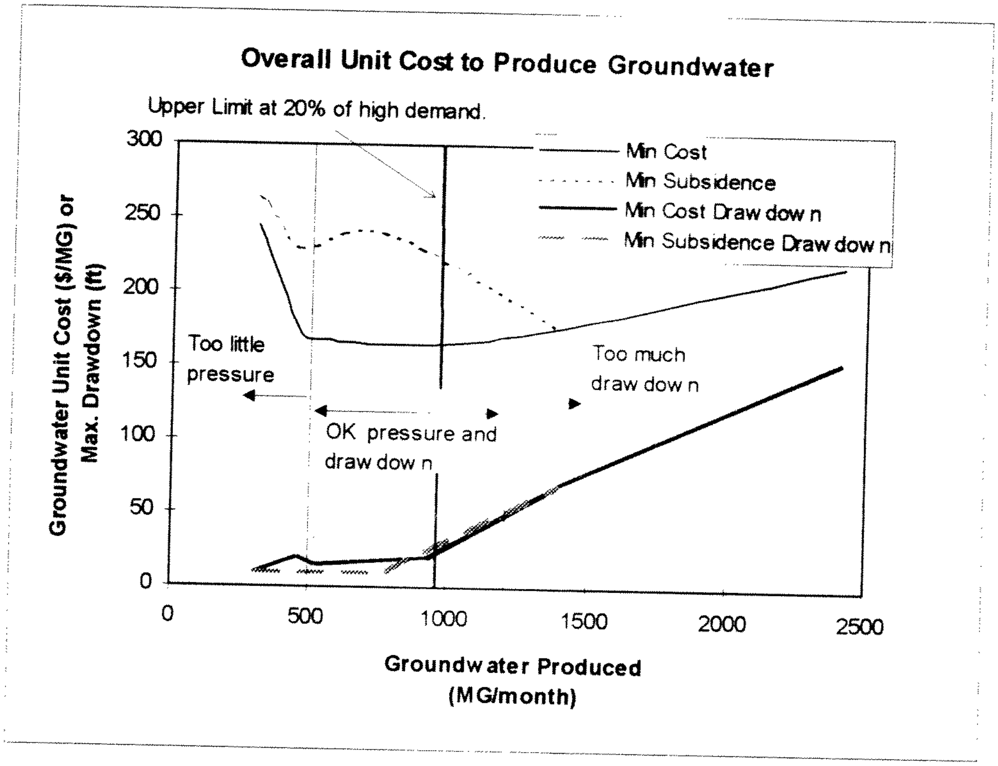

Figure 54. Overall Unit Cost Versus Produced Ground Water.

The upper two curves show the overall unit production cost from the modeling effort as a function of the groundwater production within the study area. For total production less than 500 million gallons per month, the system pressures are too low along the western edge of the network to be condisered feasible. This result is shown as the left solid vertical line in the figure. Using a value of 50 feet as a maximum acceptable drawdown from the model, the upper limit to total production should be around 1200 million gallons per month. This value is indicated by the solid vertical line to the right in the figure. At this value, the model predicts that the difference in drawdowns produced by operating the system to minimize cost of to minimize drawdown is about the same, however the unit cost is probably less for the minimum cost solution.

The shaded vertical line that falls between the two solid vertical lines represents a production rate of 20% of the maximum demand in our database (1993-1995). This value is 930 million gallons per month in the study area. At this production value the predicted drawdown using a minimum cost or minimum subsidence objective is nearly the same , but the cost of the minimum subsidence solution will be more.

Between the lower production limit, and the intermediate production limit, the minimum subsidence solution produces smaller maximum drawdowns at a unit cost 30% greater than the minimum cost model. The minimum subsidence solution produces drawdowns nearly 50% smaller than the minimum cost solution, although in both cases the drawdowns are acceptable .

The value of required surface water unit costs to make all the solutions cost the same ranges from $111 to $256 per million gallons of water, with an average required surface water cost of $182 per million gallons of water. If surface water is delivered at this unit cost with sufficient pressure then all cases are feasible.

The eleven cases were studied to identify plant suitability based on the optimization selections. Table 22 shows the plants ranked by the number of times they were selected to produce water.

Table 5.13. Plants Ranked by Selction Frequency in Eleven Special Cases

PLANT NAME	Label	Node No.	Unit Cost	Selection Frequency	Category
CHASEWOOD	CHASE	201	$206	11	Base
SHARPSTOWN-1	SHA-1	273	$179	11	Base
DISTRICT 54	D54	117	$185	11	Base
DISTRICT 218	D218	93	$197	11	Base
DISTRICT 184	D814	302	$201	11	Base
FAIRDALE(D26)	D26	46	$193	11	Base
SHARPSTOWN 2	SHA-2	270	$201	11	Base
WESTBURY-2	WES-2	257	$155	11	Base
BRAESWOOD	BRAES	228	$179	11	Base
BROOKFIELD	BROOK	91	$172	11	Base
DISTRICT 111-1	D111-1	298	$164	11	Base
GLENSHIRE-1	GLEN-1	246	$142	11	Base
BOONE ROAD	BOONE	303	$203	11	Base
PARKGLEN-1	PAR-1	292	$218	11	Base
SOUTHWEST	SW	132	$166	10	Base
SIMS BAYOU	SIMBA	204	$128	10	Base
BELLAIRE BRAES	BELBR	92	$153	10	Base
DISTRICT 123	D123	21	$144	10	Base
DISTRICT 51-2	D51-2	36	$173	10	Base
PARKGLEN WEST	PARWE	295	$167	10	Base
WILLOW BEND	WILBE	217	$224	10	Base
BRAEBURN WEST	BRAWE	247	$197	10	Base
MANNING	MANNI	304	$166	9	Peak
DISTRICT 111-2	D111-2	297	$189	9	Peak
BRIARGROVE PARK	BRIPA	18	$245	9	Peak
GLENSHIRE-2	GLEN-2	245	$145	9	Peak
DISTRICT 41-2	D41-2	203	$245	8	Peak
ROSEWOOD-1	ROS-1	87	$245	7	Peak
DISTRICT 139	D139	291	$261	7	Peak
WESTBURY-1	WES-1	211	$232	7	Peak
BRIARWICK	BRIAR	187	$223	7	Peak
DISTRICT 90-2	D90-2	299	$172	7	Peak
SOUTHEND	S-END	139	$725	6	Reserve
DISTRICT 94	D94	271	$360	6	Reserve
DISTRICT 158	D158	89	$380	6	Reserve
ROSEWOOD	ROS-2	32	$389	6	Reserve
DISTRICT 51-1	D51-1	102	$322	5	Reserve
MEYERLAND-1	MEY-1	261	$329	5	Reserve
RIDGEMONT	RIDGE	188	$601	4	Reserve
LINKWOOD	LINKW	171	$628	4	Reserve

These categories suggest a useful ranking system - certain plants should always be used for groundwater supply (Base category), and additional plants can be added to the production ensemble as demand increases (Peak category). Plants that were less frequently selected are placed in the reserve category. This category identifies plants that should either be held in reserve for special type of peak demands (fire fighting) of abandoned if the plants are relatively small. It is possible that this category will grow with time as different plants become costly to operate - suggesting need for maintenance.

Conclusions

This project developed data files and software modules for simulating flows and pressures in the Southwest Houston Study Area, and for predicting drawdowns and production costs. The following computer programs were used or created: KYPIPE2 (distribution network modeling), USGS-MODFLOW (aquifer drawdown modeling) , ATLAS-GIS (demand estimation), GRG2 (simulation-optimization modeling), and several problem specific custom programs. Data were analyzed to determine the unit costs of plants in the study area, and use these values in the models to perfrom "what-if" simulations.

The unit costs of the plants are important in determining the total cost of a production policy and these costs can be estimated by using average unit costs obtained from several months of data. The months studied should be months where reasonable amounts of water were produced, otherwise the costs will appear unusually high. It will be useful to contiually track the unit cost of each plant on a monthly basis to help identify inefficient plants and plants needing maintenance.

The simulation-optimization model showed that at low groundwater usage, the minimum cost approach produces only slightly more maximum drawdown than a minimum drawdown approach. At higher usages the difference is much greater. Using an arbritary value of 50 feet of drawdown, one can produce about 1200 million gallons per month from the study area and still achieve these acceptable drawdowns. Using a value of 20% of historical demand in the study area, one can produce 930 million gallons per month from the study area. This lower value represents the value that is required by a 20% groundwater/80% surface water allocation for 1994 high demand cases.

The simulation-optimization results were also interpreted to identify three categories of plants: base, peak, and reserve plants. Base plants appear to be the most cost effective plants to use routinely to produce the groundwater yield reported above, the peak plants should be used for peak demand situations such as fire-fighting. The reserve plants should either be decommissioned or rehabilitated to improve their production efficiency with respect to electric billing.

All the simulations suggest that the western edge of the study area will be a low pressure zone and, assuming our conceptualization of the network is reasonable correct, measures to increase surface water deliveries (at pressures around 95 psi.) to the western side of the study area, or measures to boost pressures should be implemented.

Additional simulation-optimization results are reported in Part VI of this report. In these simulations higher proportions of groundwater derived supply were studied. In these cases, minimum pressures were in the 70 psi range and represent more realistic, current conditions simulations.

Research into Production Cost Reduction by Energy Management of Houston's Surface and Groundwater Systems

Part VI

Uncertainty Analysis

by

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City of Houston Project # 33100
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General Approach

The sources of uncertainty (error) in the simulation-optimization model arise in the three distinct components of the system that are depicted in Figure 6.1 below. The supply was modeled using average unit costs obtained over an 11-month period, however the variation of unit cost at each different plant was not uniform. A linear cost model was shown to be a better predictor of production costs on a plant-by-plant basis, but the average unit cost model greatly simplifies the optimization scheme.

The distribution system uncertainty arises from the conceptualization of the real system (the simplifications required to perform simulations) and the valuse of different friction parameters and input flow values. The demand uncertainty arises from the component of billing records that are not sucessfully matched during the mathcing algorithm and the uniform assignment of the unmatched demand to the nodes of the model.

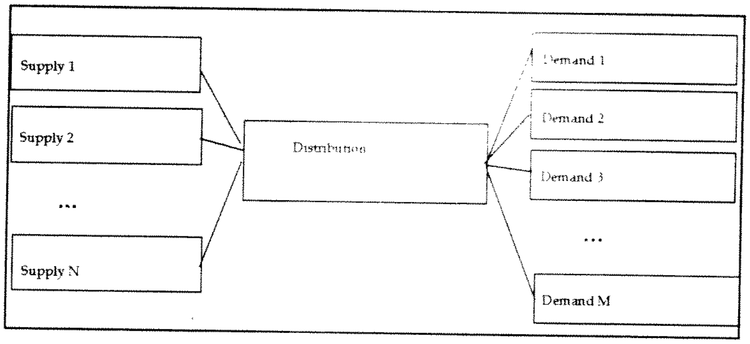


Figure 6.1 Schematic of Supply-Transmission-Demand System

Several methods to deal with uncertainty are discussed in the literature, the three most common methods are a Monte Carlo analysis, that requires thousands of simulations, a first-order linear analysis (Rosenblueth, 1975; Yen and Guymon, 1990) that requires fewer simulations, but still a very large number in this case, and a sensitivity analysis that requires one simulation for each uncertain input value. For this research we choose a sensitivity analysis approach as it requires far fewer simulations that the other two approaches.

The idea behind a sensitivity analysis is to start with a simulation using one set of input values (in our case, one set of unit costs, and demand amounts) and produce a set of output values (e.g. pressures, and supply amounts). Then the input values are varied one-at-a-time and subsequent simulations conducted. The change in output value divided by the change in input value is called the sensitivity of the simulation to the varied input value. Usually, if the change in output value (expressed as a percent of the initial value) is small relative to the change in input value, the model is said to be insensitive to small changes in the particular input value. When the converse is true, the model is said to be very sensitive to the input value, and that input value is further identified as a potential source of significant error.

For this research we have modified this procedure to reflect our model's goal of identifying good supply configurations, for given unit costs and demand distributions. In our procedure, we vary the unit costs one-at-a time and determine if changing the unit cost at a particular plant changes the selected supply configuration or not. Similarily, we varied the demands in one-sixth of the modeled area and recorded the same result.

The goal of this uncertainty analysis is to determine what effect on the decisions (allocations) that the model makes if the input data regarding plant costs and demand values is allowed to vary by 20%.

Unit Cost Analysis

Figure 6.2 below is a plot of the average unit cost for each plant in the model as well as the standard deviation values above and below this value. Additionally, a deviation of 20% is also shown about the average value. We used the 20% value as the purturbation value for the senstivity analysis.

Of the forty two plants, 33% had standard deviations much larger that the 20% deviation range, while the remainder of the plants had standard deviation values more or less near the 20% deviation range. Of the 33% high deviation plants, most reflect missing data values or very small productions in one or more months that makes the unit cost for a particular month unusually high (division by a near zero number in the calculation). The remainder appear to be plants with truly variable unit costs (Chasewood, Sharpstown 2, and Linkwood).

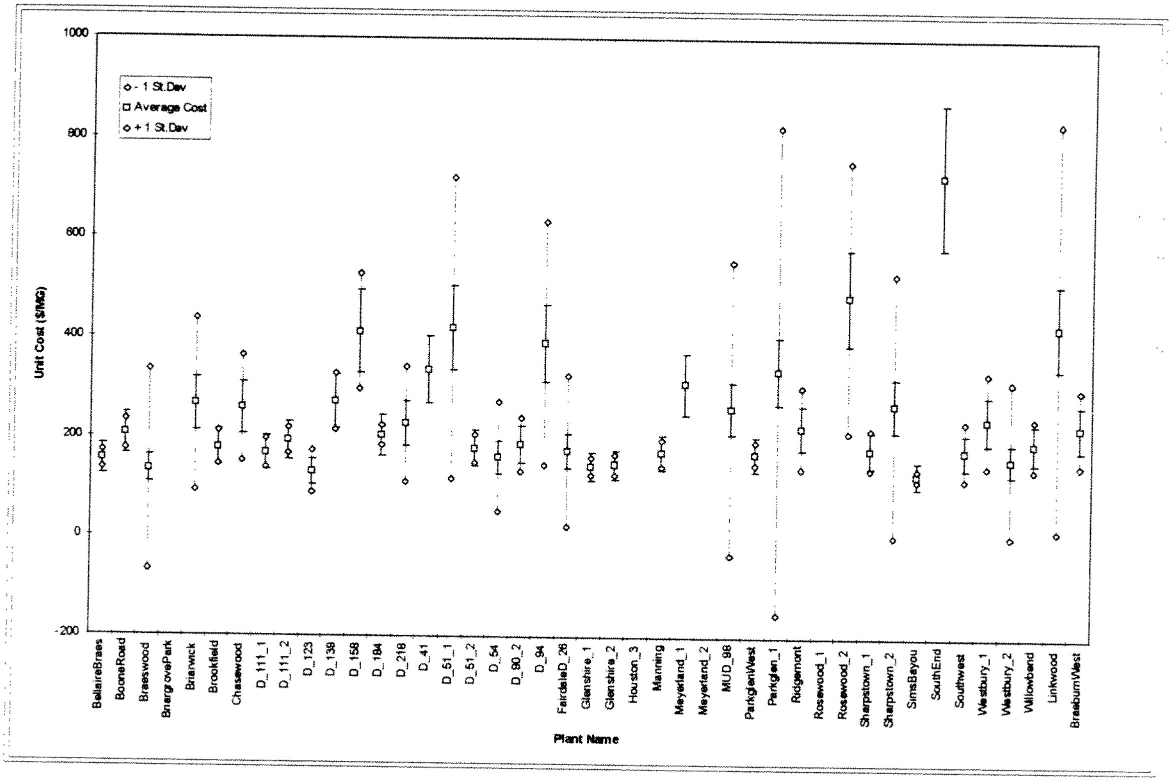
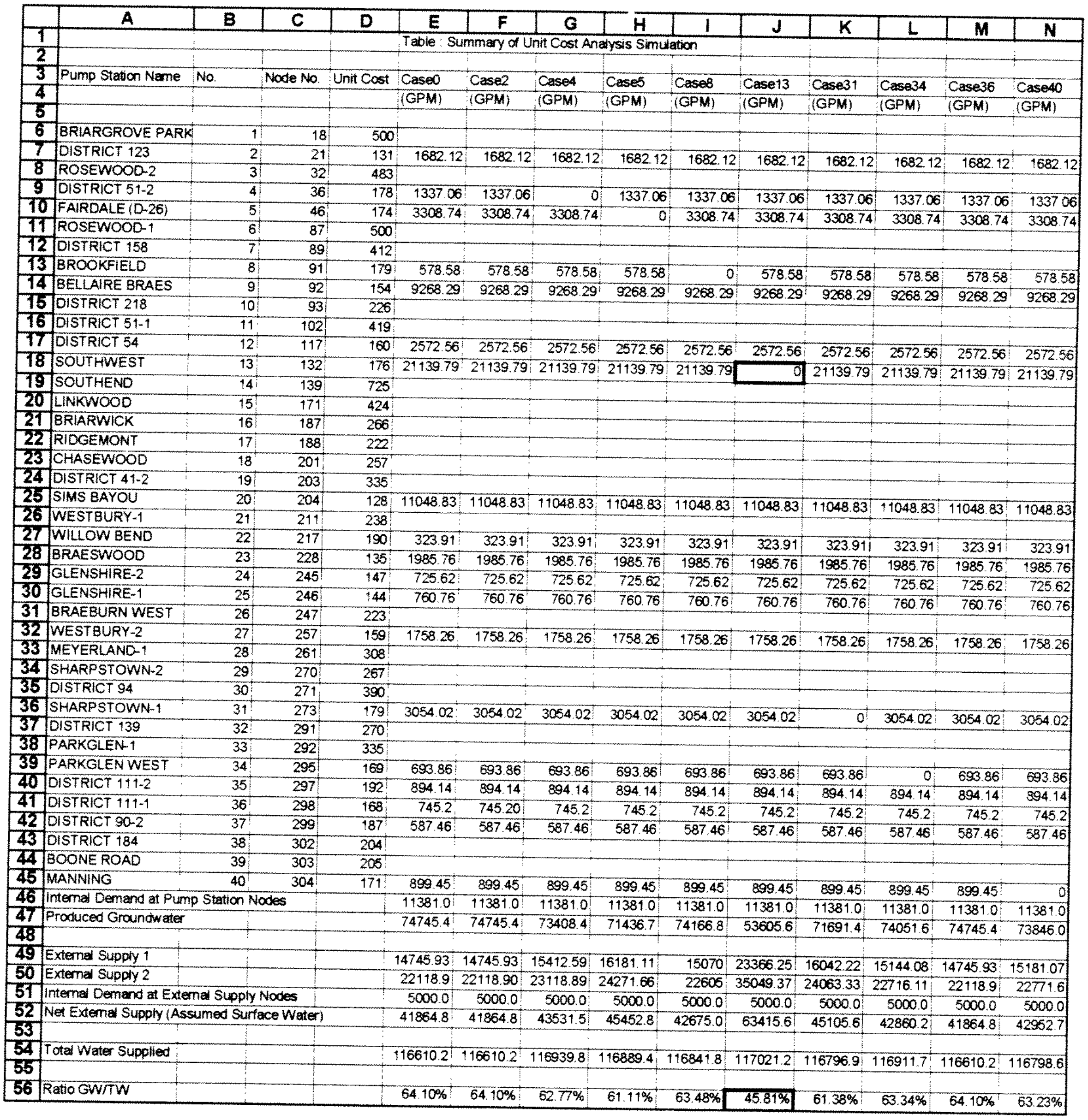


Figure 6.2 Unit Cost Average Values and Variations by Plant

The objective function in the unit cost sensitivity case is to minimize the total cost of groundwater production, subject to minimum and maximum allowable pipeline pressures. The unit cost of each pump station is increased to 120% of the original unit cost and a simulation-optimization run is performed. The results are saved and compared to the original (base) case to determine the sensitivity of the simulation to the change in the unit cost. Since there are forty variable pump stations in our study area, forty cases plus an original case are simulated in this sensitivity analysis.

Table 6.1 below lists the initial supply configurations and the configurations for variations in unit costs by each plant for the base case to which the other cases in the uncertainty analysis are compared. In the table, Case 0 is the base case. In the depicted table 60% of the water demanded by the network was supplied from groundwater pumpage, and 40% from external surface water supply applied at two nodes on the eastern edge of the model.

Table 6.1 Uncertainty Analysis Using Average Production Cost (Unit Cost) Model
60% Groundwater, 40% Surface Water



	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1					Table : Summary of Unit Cost Analysis Simulation									
2														
3	Pump Station Name	No.	Node No.	Unit Cost	Case0	Case2	Case4	Case5	Case8	Case13	Case31	Case34	Case36	Case40
4					(GPM)	(GPM)	(GPM)	(GPM)	(GPM)	(GPM)	(GPM)	(GPM)	(GPM)	(GPM)
5														
6	BRIARGROVE PARK	1	18	500										
7	DISTRICT 123	2	21	131	1682.12	1682.12	1682.12	1682.12	1682.12	1682.12	1682.12	1682.12	1682.12	1682.12
8	ROSEWOOD-2	3	32	483										
9	DISTRICT 51-2	4	36	178	1337.06	1337.06	0	1337.06	1337.06	1337.06	1337.06	1337.06	1337.06	1337.06
10	FAIRDALE (D-26)	5	46	174	3308.74	3308.74	3308.74	0	3308.74	3308.74	3308.74	3308.74	3308.74	3308.74
11	ROSEWOOD-1	6	87	500										
12	DISTRICT 158	7	89	412										
13	BROOKFIELD	8	91	179	578.58	578.58	578.58	578.58	0	578.58	578.58	578.58	578.58	578.58
14	BELLAIRE BRAES	9	92	154	9268.29	9268.29	9268.29	9268.29	9268.29	9268.29	9268.29	9268.29	9268.29	9268.29
15	DISTRICT 218	10	93	226										
16	DISTRICT 51-1	11	102	419										
17	DISTRICT 54	12	117	160	2572.56	2572.56	2572.56	2572.56	2572.56	2572.56	2572.56	2572.56	2572.56	2572.56
18	SOUTHWEST	13	132	176	21139.79	21139.79	21139.79	21139.79	21139.79	0	21139.79	21139.79	21139.79	21139.79
19	SOUTHEND	14	139	725										
20	LINKWOOD	15	171	424										
21	BRIARWICK	16	187	266										
22	RIDGEMONT	17	188	222										
23	CHASEWOOD	18	201	257										
24	DISTRICT 41-2	19	203	335										
25	SIMS BAYOU	20	204	128	11048.83	11048.83	11048.83	11048.83	11048.83	11048.83	11048.83	11048.83	11048.83	11048.83
26	WESTBURY-1	21	211	238										
27	WILLOW BEND	22	217	190	323.91	323.91	323.91	323.91	323.91	323.91	323.91	323.91	323.91	323.91
28	BRAESWOOD	23	228	135	1985.76	1985.76	1985.76	1985.76	1985.76	1985.76	1985.76	1985.76	1985.76	1985.76
29	GLENSHIRE-2	24	245	147	725.62	725.62	725.62	725.62	725.62	725.62	725.62	725.62	725.62	725.62
30	GLENSHIRE-1	25	246	144	760.76	760.76	760.76	760.76	760.76	760.76	760.76	760.76	760.76	760.76
31	BRAEBURN WEST	26	247	223										
32	WESTBURY-2	27	257	159	1758.26	1758.26	1758.26	1758.26	1758.26	1758.26	1758.26	1758.26	1758.26	1758.26
33	MEYERLAND-1	28	261	308										
34	SHARPSTOWN-2	29	270	267										
35	DISTRICT 94	30	271	390										
36	SHARPSTOWN-1	31	273	179	3054.02	3054.02	3054.02	3054.02	3054.02	3054.02	0	3054.02	3054.02	3054.02
37	DISTRICT 139	32	291	270										
38	PARKGLEN-1	33	292	335										
39	PARKGLEN WEST	34	295	169	693.86	693.86	693.86	693.86	693.86	693.86	693.86	0	693.86	693.86
40	DISTRICT 111-2	35	297	192	894.14	894.14	894.14	894.14	894.14	894.14	894.14	894.14	894.14	894.14
41	DISTRICT 111-1	36	298	168	745.2	745.20	745.2	745.2	745.2	745.2	745.2	745.2	745.2	745.2
42	DISTRICT 90-2	37	299	187	587.46	587.46	587.46	587.46	587.46	587.46	587.46	587.46	587.46	587.46
43	DISTRICT 184	38	302	204										
44	BOONE ROAD	39	303	205										
45	MANNING	40	304	171	899.45	899.45	899.45	899.45	899.45	899.45	899.45	899.45	899.45	0
46	Internal Demand at Pump Station Nodes				11381.0	11381.0	11381.0	11381.0	11381.0	11381.0	11381.0	11381.0	11381.0	11381.0
47	Produced Groundwater				74745.4	74745.4	73408.4	71436.7	74166.8	53605.6	71691.4	74051.6	74745.4	73846.0
48														
49	External Supply 1				14745.93	14745.93	15412.59	16181.11	15070	23366.25	16042.22	15144.08	14745.93	15181.07
50	External Supply 2				22118.9	22118.90	23118.89	24271.66	22605	35049.37	24063.33	22716.11	22118.9	22771.6
51	Internal Demand at External Supply Nodes				5000.0	5000.0	5000.0	5000.0	5000.0	5000.0	5000.0	5000.0	5000.0	5000.0
52	Net External Supply (Assumed Surface Water)				41864.8	41864.8	43531.5	45452.8	42675.0	63415.6	45105.6	42860.2	41864.8	42952.7
53														
54	Total Water Supplied				116610.2	116610.2	116939.8	116889.4	116841.8	117021.2	116796.9	116911.7	116610.2	116798.6
55														
56	Ratio GW/TW				64.10%	64.10%	62.77%	61.11%	63.48%	45.81%	61.38%	63.34%	64.10%	63.23%

Most of the supply allocations were unchanged by changing the value of the unit cost with the exception of Case 13 where a dramatic reallocation occured when the unit cost at the Southwest Plant was increased.

Figures 6.4 and 6.5 show the pipeline map and the pumping station locations that were used in the model and are listed in Table 6.1 above.

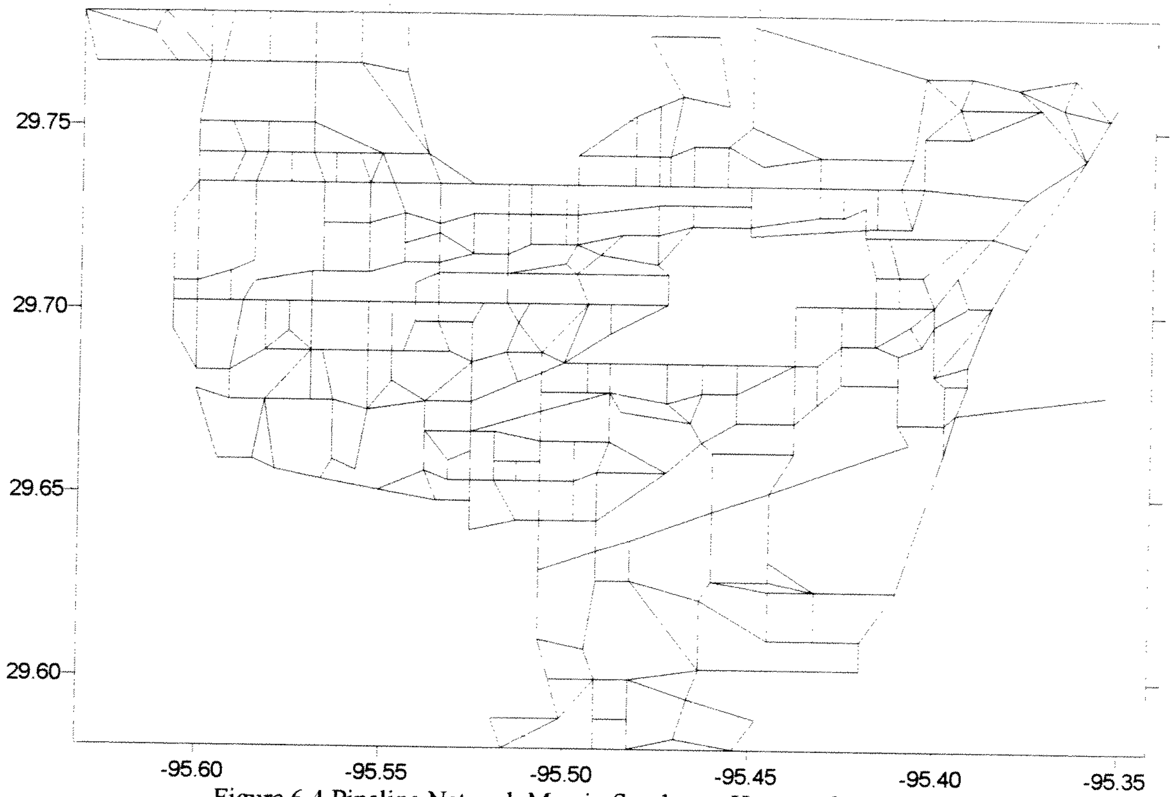


Figure 6.4 Pipeline Network Map in Southwest Houston Study Area

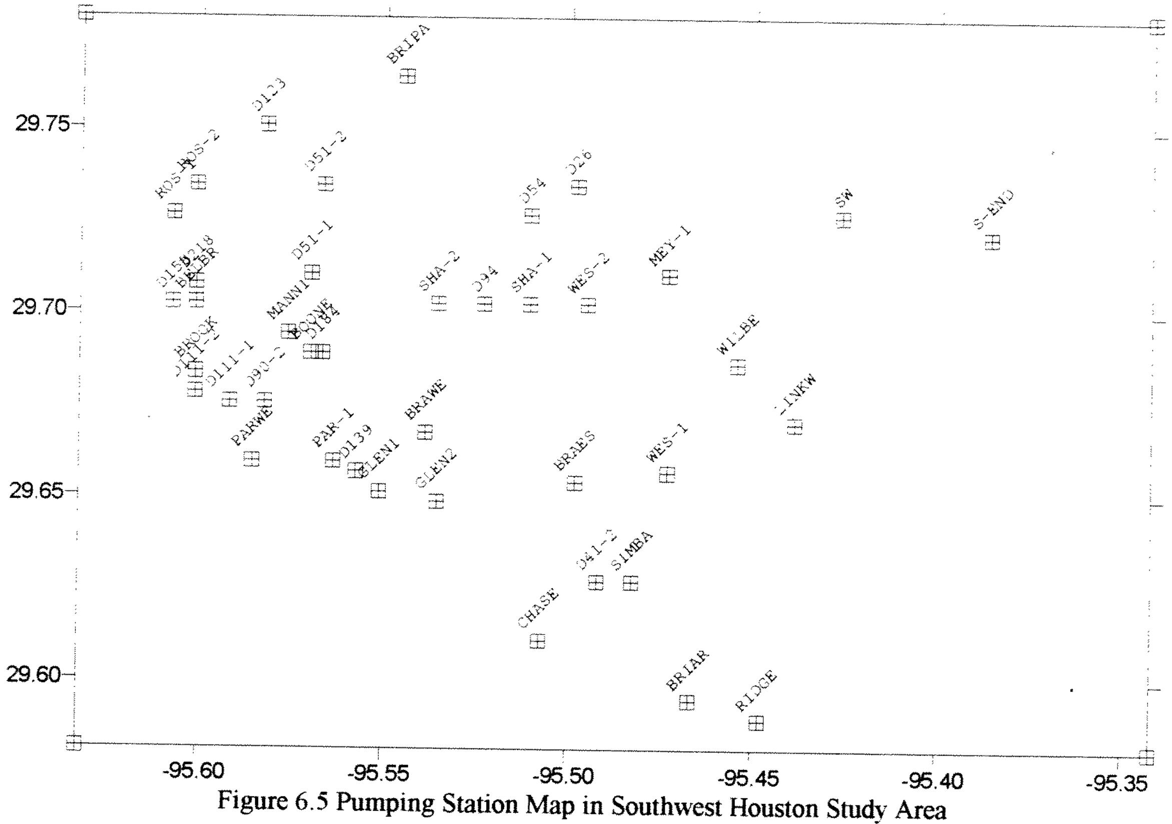


Figure 6.5 Pumping Station Map in Southwest Houston Study Area

In general it was determined that in our model the pump stations with a unit cost of greater than $187 or less than $168 did not change their pumpage in all simulation-optimization trials. Pump stations with unit costs between these ranges were sensitive to the changes in unit costs. These stations are shown in Table 6.2 below:

Table 6.2 Sensitivity to Uncertainty in Unit Costs

Plant Name	ΔPumpage/ΔUnitCost
District 51-2	-37.56
Fairdale	-95.06
Brookfield	-16.14
Southwest	-600.54
Sharpstown-I	-85.39
Parkglen West	-20.50
Manning	-26.30

Table 6.2 can suggests that the Southwest plant is the most sensitive to changes in unit costs. The high sensitivity is due to that plants relatively large contribution to groundwater pumpage in the model. The other plants exhibit smaller sensitivities with Fairdale and Sharpstown-I being the next highest while all the other plants have relatively small sensitivities compared to the three large sensitivity plants.

The limited number of sensitive plants suggests that these plants play an important role in supply costs in the model and that the other plants are too costly, or too economical to matter.

A limited number of the cases were further studied to see what effect the modified unit costs had on the overall pressures in the system. Figures 6.6 through 6.14 (following pages) show the pressure distributions in the network for the sensitive cases above. Generally the distributions look similar regardless of the particular case, with the most variation occuring in the southwestern corner of the study area.

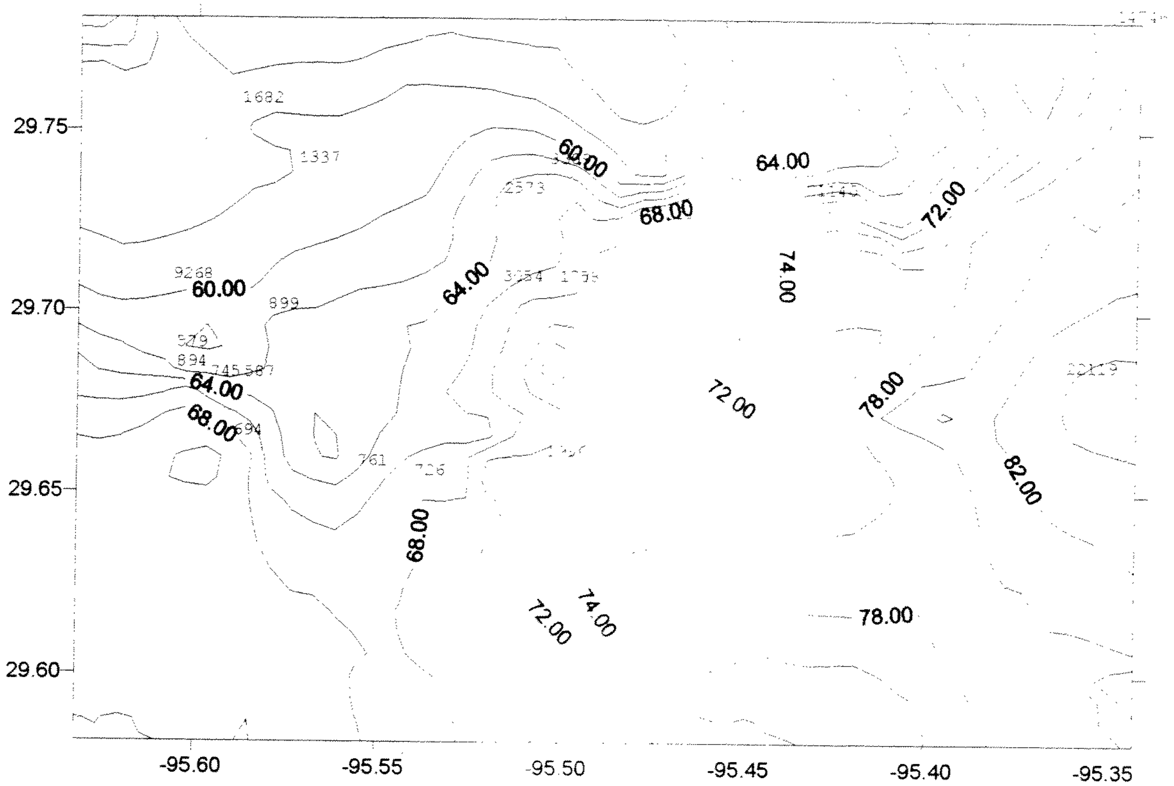


Figure 6.6 Pressure Distribution Map for Case 0 - Base Case for Unit Cost Uncertainty Analysis.

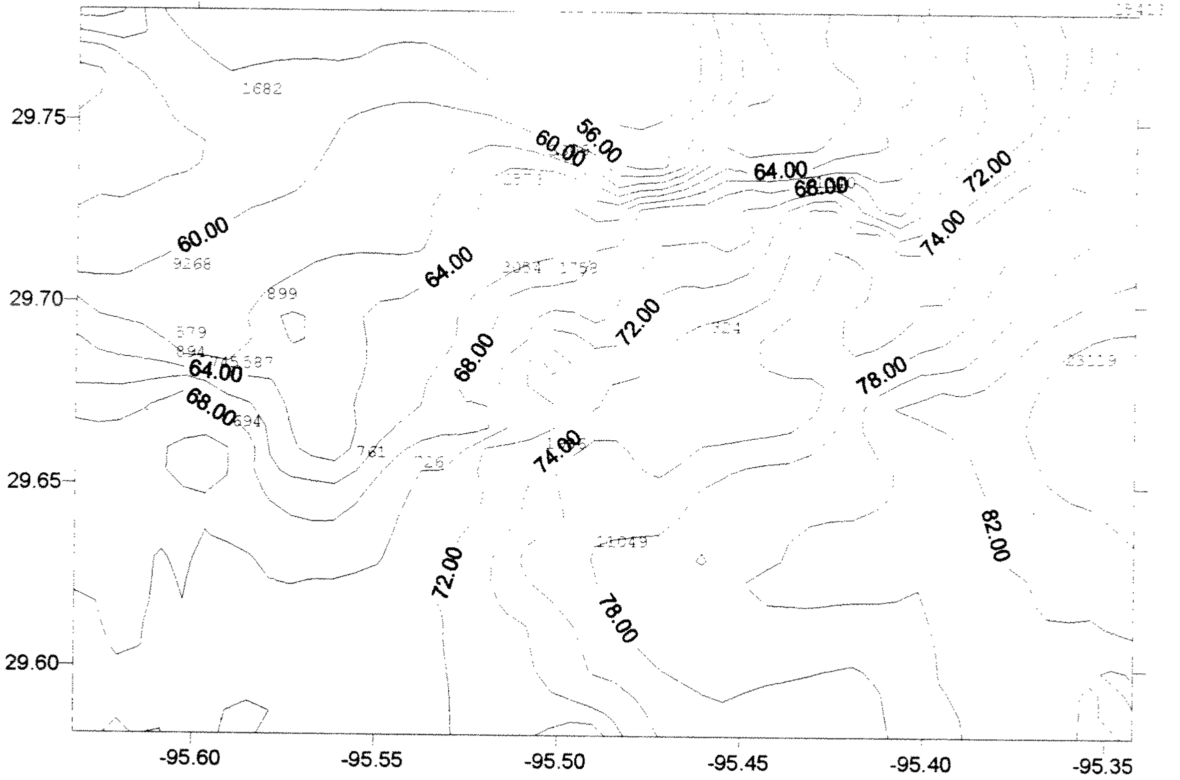


Figure 6.7 Pressure Distribution Map for Case 4 - Unit Cost at District 51-2 Increased by 20%

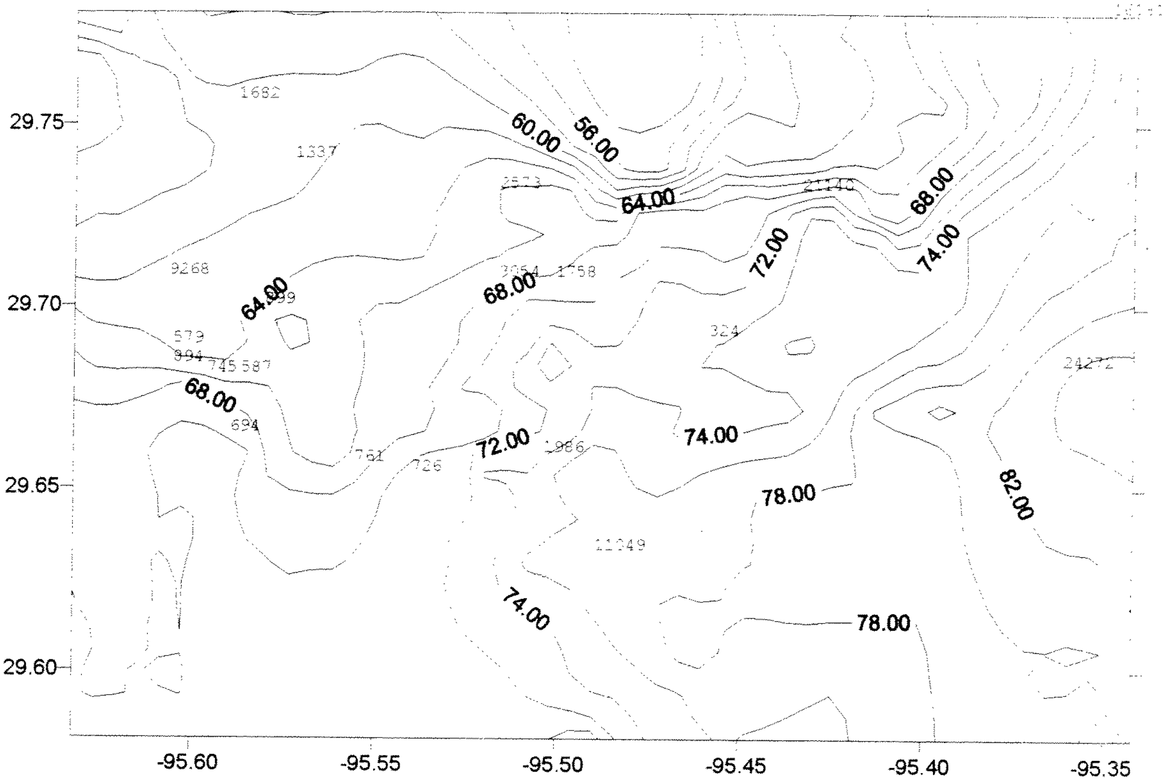


Figure 6.8 Pressure Distribution Map for Case 5 - Unit Cost at Fairdale Increased by 20%

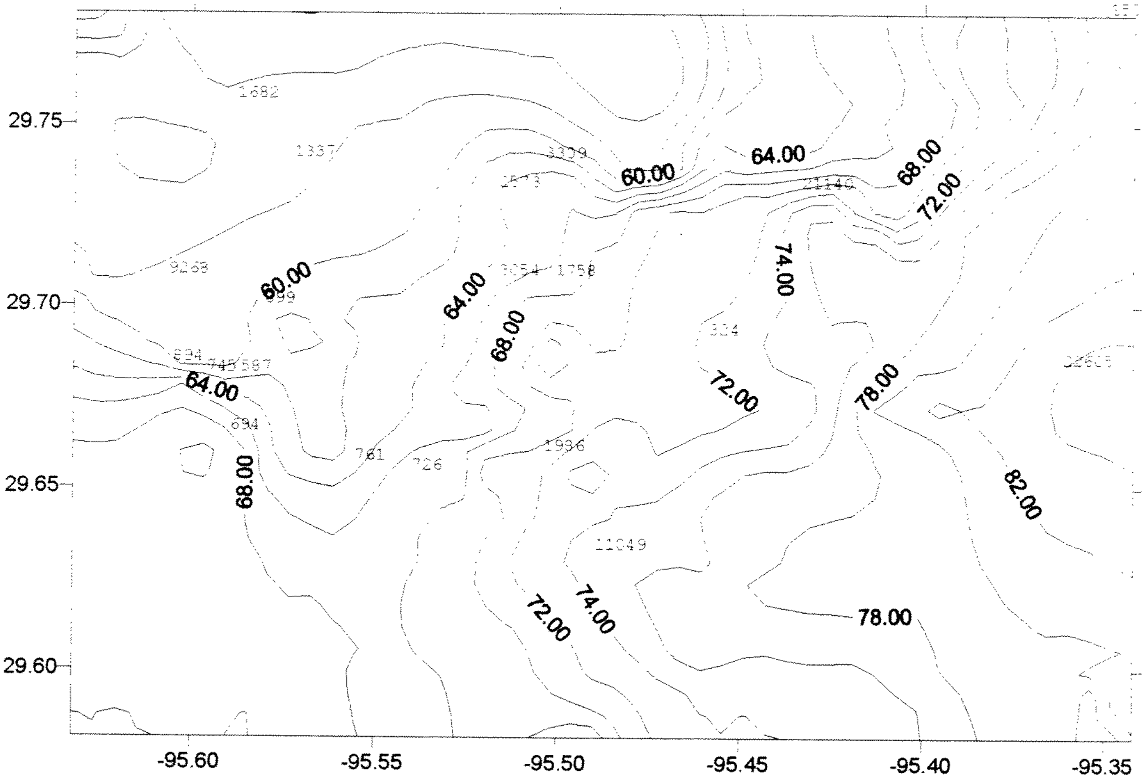


Figure 6.9 Pressure Distribution Map for Case 8 - Unit Cost at Brookfield Increased by 20%

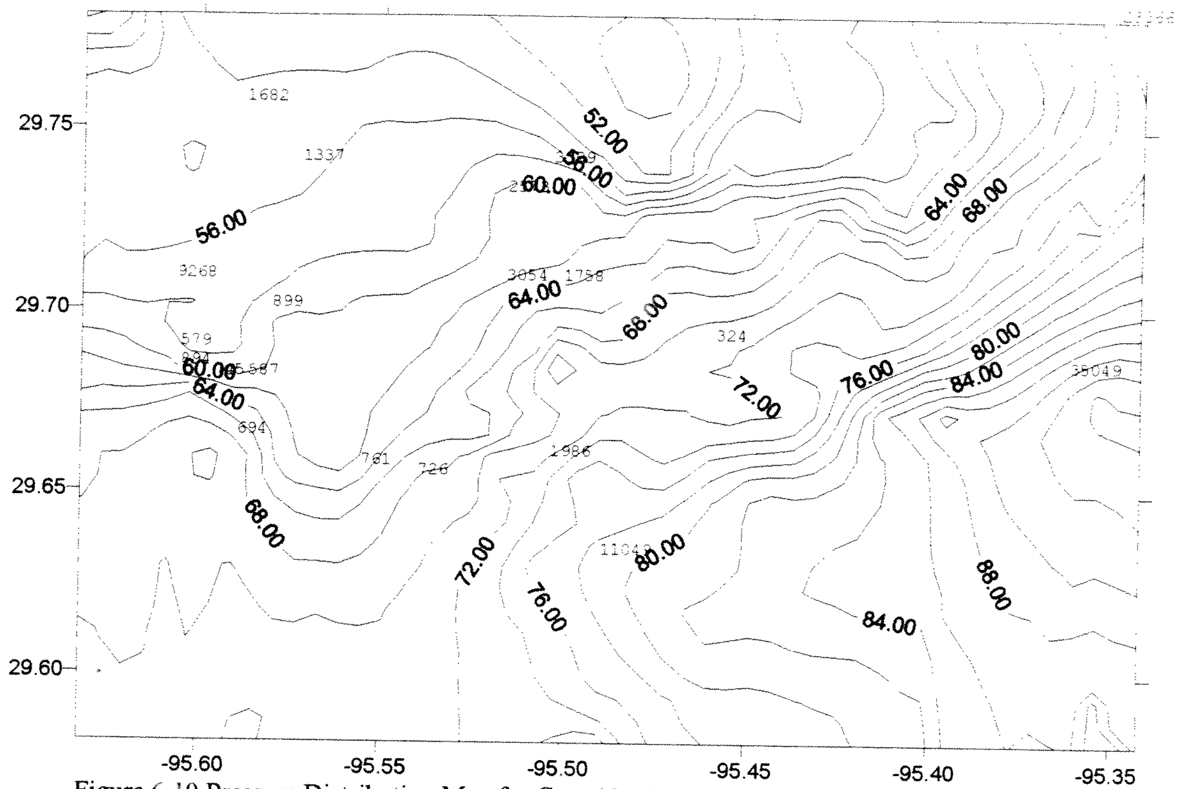


Figure 6.10 Pressure Distribution Map for Case 13 - Unit Cost at Southwest Increased by 20%

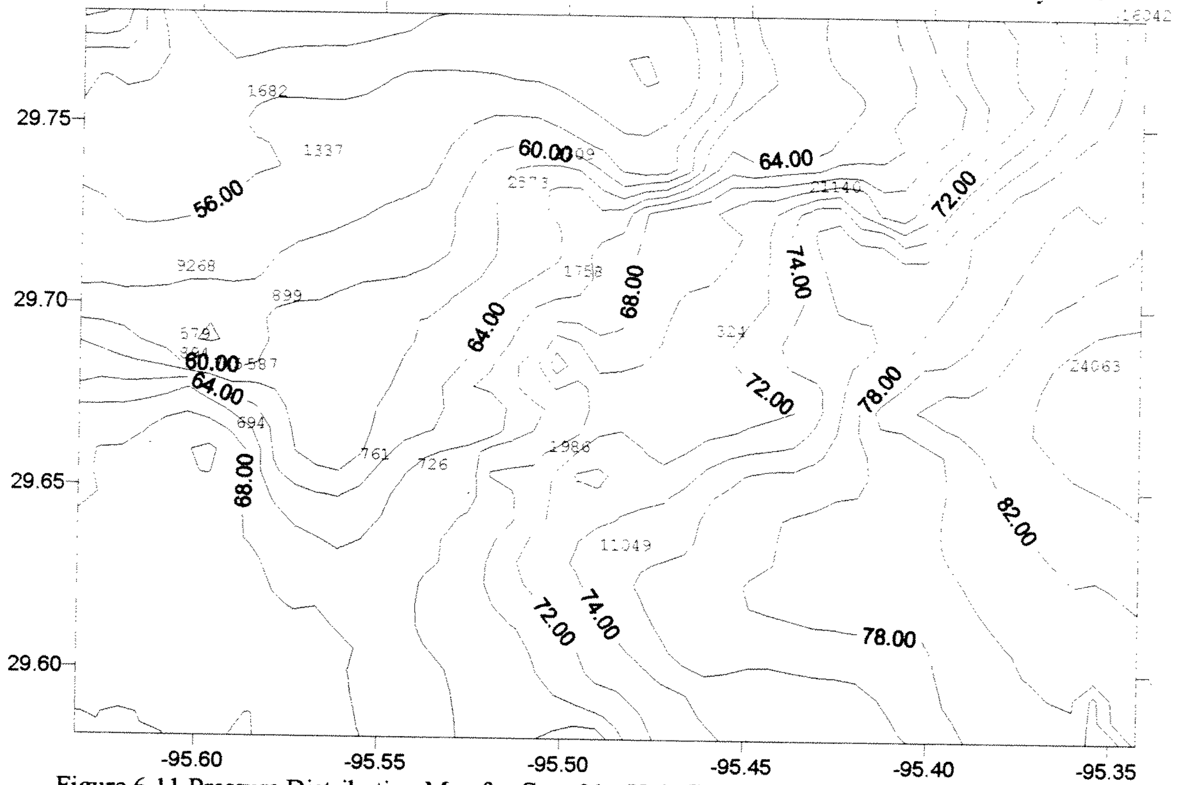


Figure 6.11 Pressure Distribution Map for Case 31 - Unit Cost at Sharpstown-I Increased by 20%

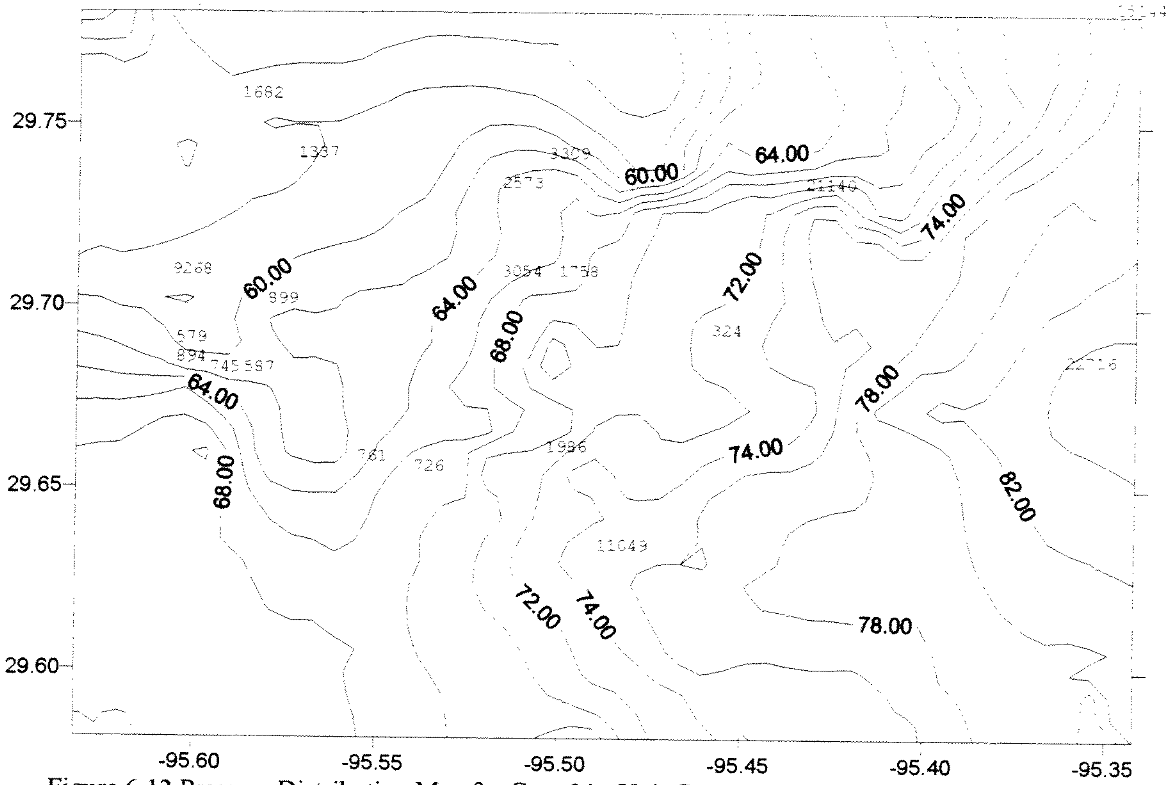


Figure 6.12 Pressure Distribution Map for Case 34 - Unit Cost at Parkglen West Increased by 20%

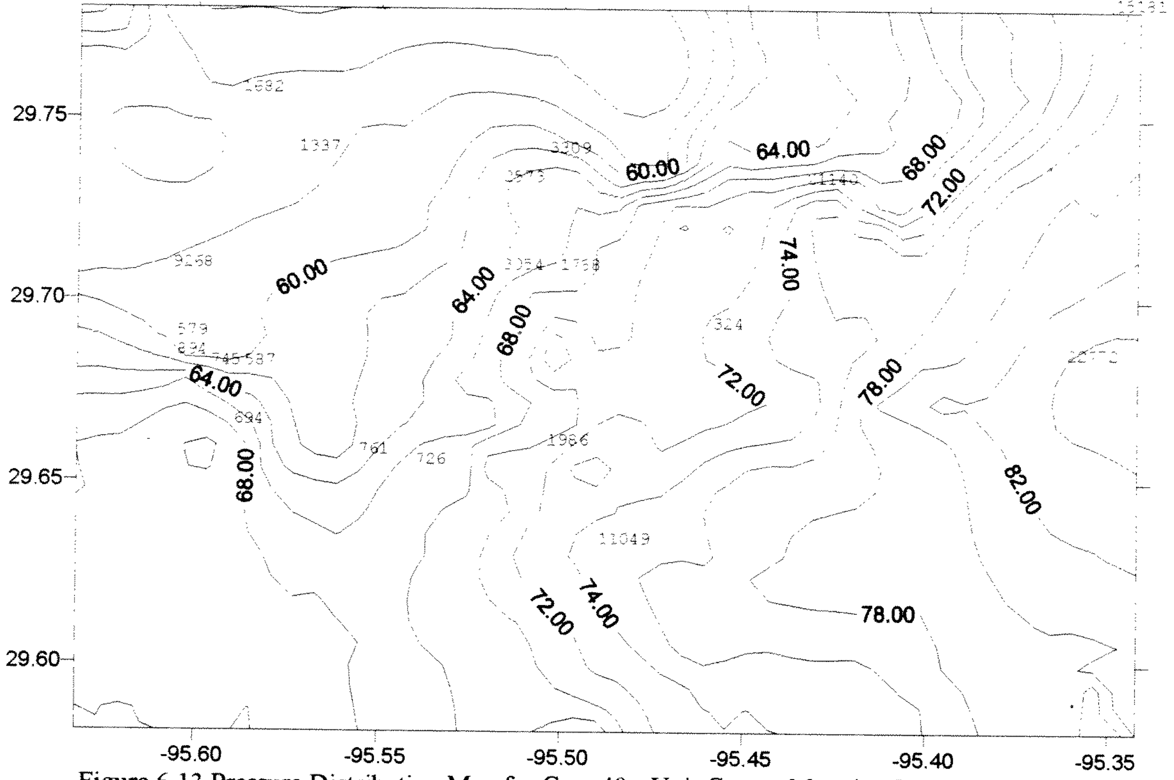


Figure 6.13 Pressure Distribution Map for Case 40 - Unit Cost at Manning Increased by 20%

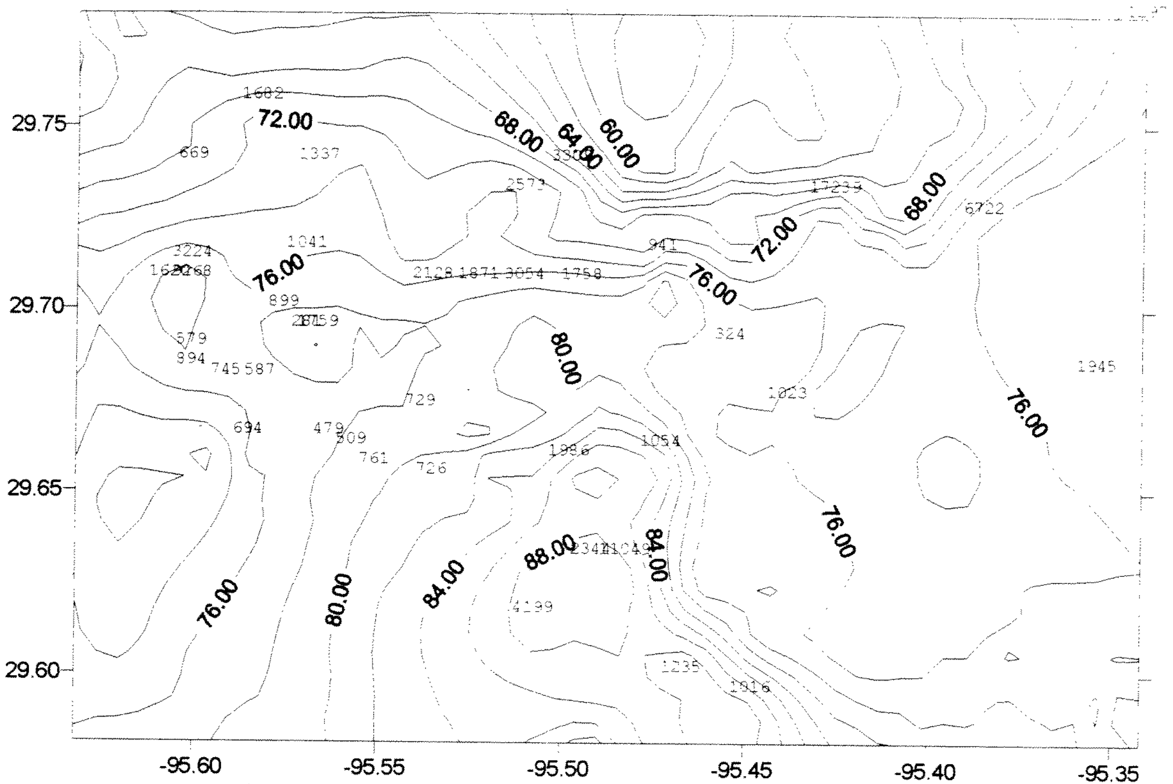


Figure 6.14. Pressure Distribution for 92% Groundwater Supply.

Examination of these pressure maps shows that when the unit costs at the sensitive plants are varied the lower pressure zones move westward, except for the Southwest and Sharpstown-I cases where the low pressure zones move eastward. This result for these two plants suggests that supply at their locations is important for maintaining good pressure distribution to the western edge of the service area.

Table 6.3 below lists the initial supply configurations and the configurations for variations in unit costs by each plant for the base case to which the other cases in the uncertainty analysis are compared. In the table, Case 0 is the base case. In the depicted table 92% of the water demanded by the network was supplied from groundwater pumpage, and 8% from external surface water supply applied at two nodes on the eastern edge of the model.

None of the supply allocations changed with change in unit cost in this case. At high levels of required groundwater supply the model is insensitive to costs. This result makes sense, since at high required groundwater supply, there is no choice for how to redsitribute the system demand - such decisions are completely dictated by the hydraulics resuirements (minimum system pressures). Figure 6.14 shows the associated pressure distribution for the 92% groundwater case.

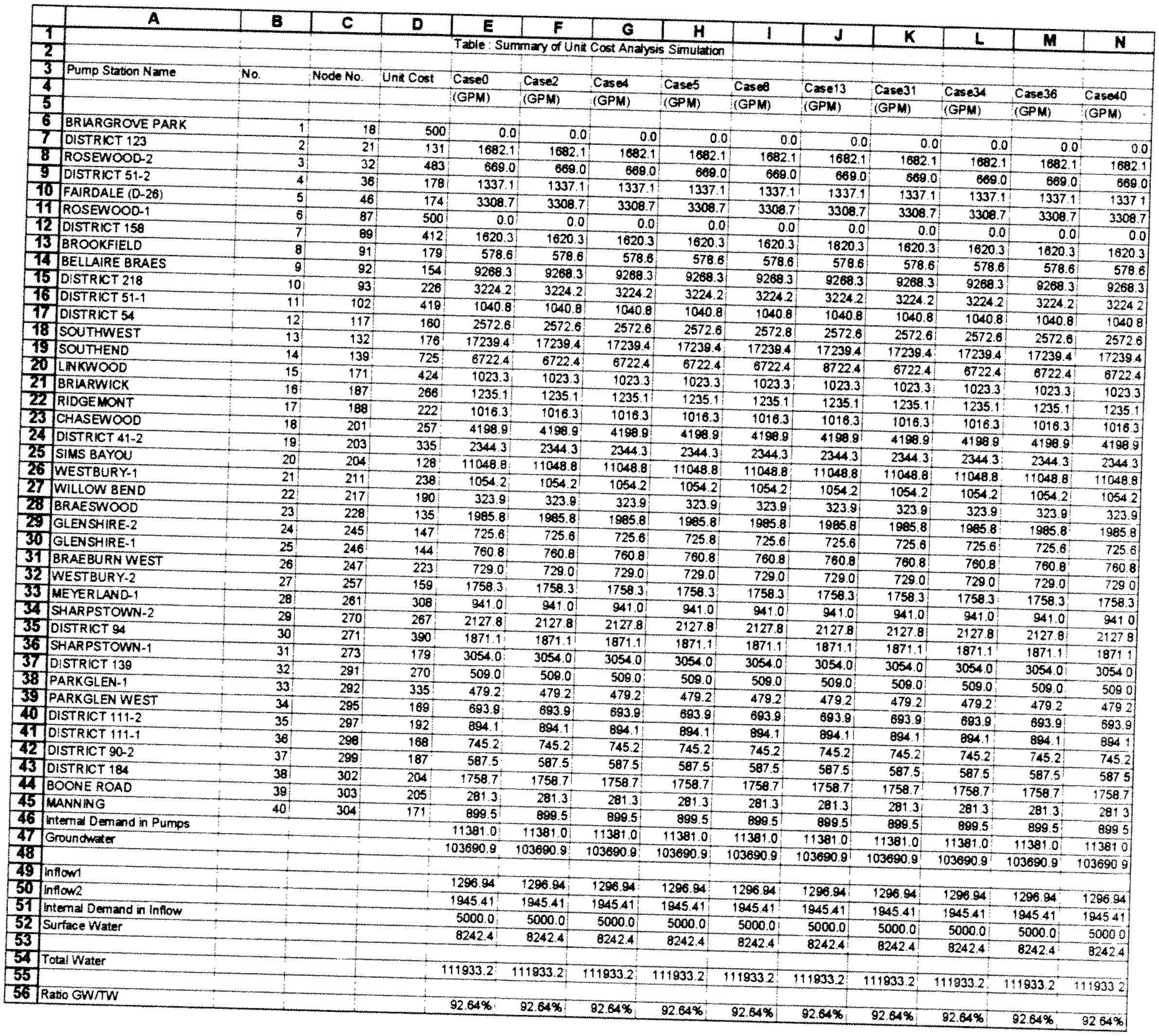
Linear Production Cost Model Analysis

In this section the sensitivity to a different production cost model is tested to determine the uncertainty associated with using the average cost (unit cost) model instead of the linear production cost model. The models form a simulation perspective are identical except that the linear model has different "unit" costs that are equal to the slope of the regression lines.

Table 6.4 below shows the configurations produced using the unit cost model and the average unit cost model. The results show that the supply allocation is unchanged regardless of which cost model is used. This result is interpreted to indicate that at high required groundwater production rates there is no flexibility in allocations - all the allocations are made based on hydraulic requirements of the system.

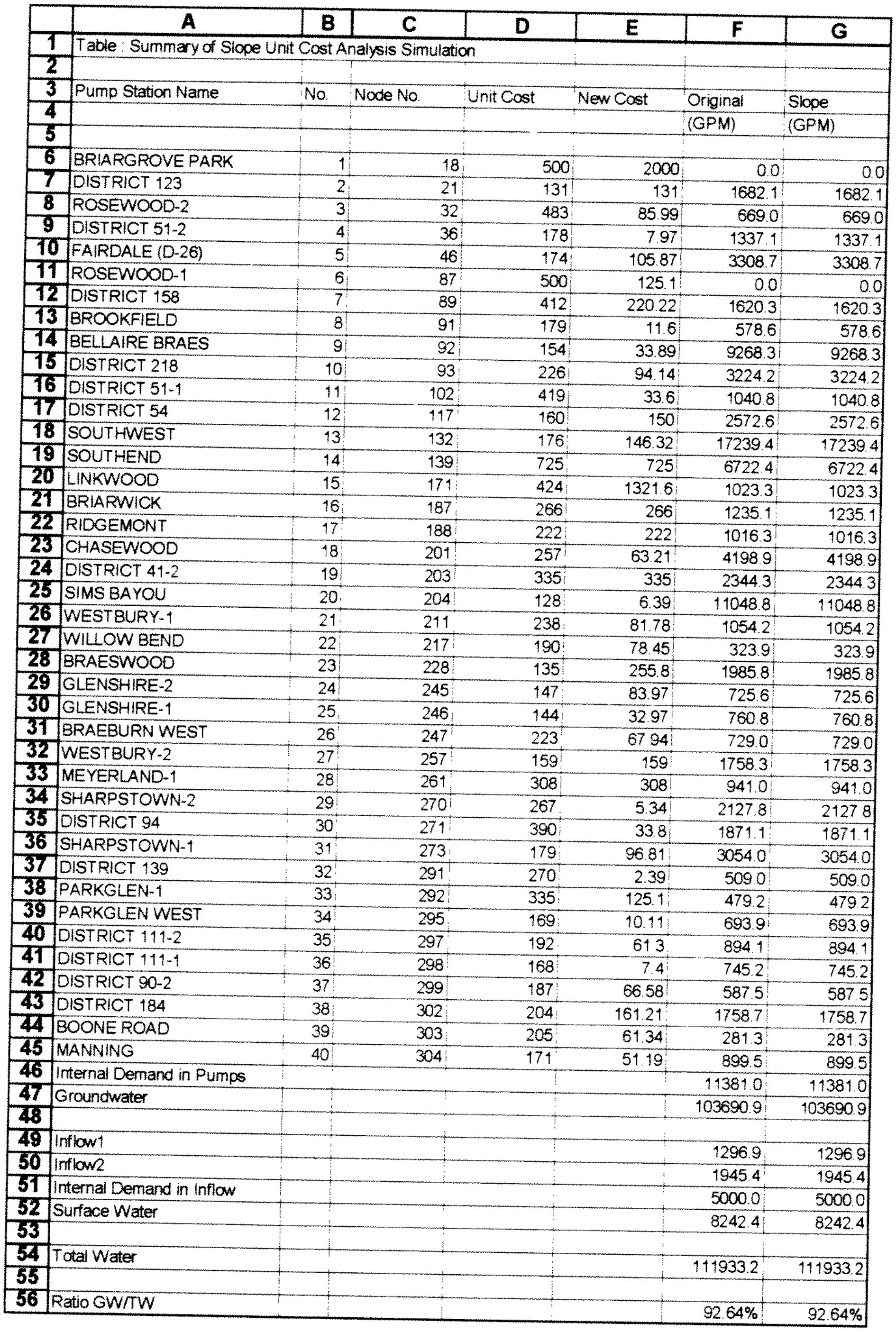
The column labeled "Original" is the base case for the 92% groundwater production rate using the average cost model and the column labeled "Slope" is the Linear Production Cost Model results.

Table 6.3 Uncertainty Analysis Using Average Production Cost (Unit Cost) Model
92% Groundwater, 8% Surface Water



	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1														
2					Table : Summary of Unit Cost Analysis Simulation									
3	Pump Station Name	No.	Node No.	Unit Cost	Case0	Case2	Case4	Case5	Case8	Case13	Case31	Case34	Case36	Case40
4					(GPM)	(GPM)	(GPM)	(GPM)	(GPM)	(GPM)	(GPM)	(GPM)	(GPM)	(GPM)
5														
6	BRIARGROVE PARK	1	18	500	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	DISTRICT 123	2	21	131	1682.1	1682.1	1682.1	1682.1	1682.1	1682.1	1682.1	1682.1	1682.1	1682.1
8	ROSEWOOD-2	3	32	483	669.0	669.0	669.0	669.0	669.0	669.0	669.0	669.0	669.0	669.0
9	DISTRICT 51-2	4	36	178	1337.1	1337.1	1337.1	1337.1	1337.1	1337.1	1337.1	1337.1	1337.1	1337.1
10	FAIRDALE (D-26)	5	46	174	3308.7	3308.7	3308.7	3308.7	3308.7	3308.7	3308.7	3308.7	3308.7	3308.7
11	ROSEWOOD-1	6	87	500	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	DISTRICT 158	7	89	412	1620.3	1620.3	1620.3	1620.3	1620.3	1620.3	1620.3	1620.3	1620.3	1620.3
13	BROOKFIELD	8	91	179	578.6	578.6	578.6	578.6	578.6	578.6	578.6	578.6	578.6	578.6
14	BELLAIRE BRAES	9	92	154	9268.3	9268.3	9268.3	9268.3	9268.3	9268.3	9268.3	9268.3	9268.3	9268.3
15	DISTRICT 218	10	93	226	3224.2	3224.2	3224.2	3224.2	3224.2	3224.2	3224.2	3224.2	3224.2	3224.2
16	DISTRICT 51-1	11	102	419	1040.8	1040.8	1040.8	1040.8	1040.8	1040.8	1040.8	1040.8	1040.8	1040.8
17	DISTRICT 54	12	117	160	2572.6	2572.6	2572.6	2572.6	2572.6	2572.6	2572.6	2572.6	2572.6	2572.6
18	SOUTHWEST	13	132	176	17239.4	17239.4	17239.4	17239.4	17239.4	17239.4	17239.4	17239.4	17239.4	17239.4
19	SOUTHEND	14	139	725	6722.4	6722.4	6722.4	6722.4	6722.4	6722.4	6722.4	6722.4	6722.4	6722.4
20	LINKWOOD	15	171	424	1023.3	1023.3	1023.3	1023.3	1023.3	1023.3	1023.3	1023.3	1023.3	1023.3
21	BRIARWICK	16	187	266	1235.1	1235.1	1235.1	1235.1	1235.1	1235.1	1235.1	1235.1	1235.1	1235.1
22	RIDGEMONT	17	188	222	1016.3	1016.3	1016.3	1016.3	1016.3	1016.3	1016.3	1016.3	1016.3	1016.3
23	CHASEWOOD	18	201	257	4198.9	4198.9	4198.9	4198.9	4198.9	4198.9	4198.9	4198.9	4198.9	4198.9
24	DISTRICT 41-2	19	203	335	2344.3	2344.3	2344.3	2344.3	2344.3	2344.3	2344.3	2344.3	2344.3	2344.3
25	SIMS BAYOU	20	204	128	11048.8	11048.8	11048.8	11048.8	11048.8	11048.8	11048.8	11048.8	11048.8	11048.8
26	WESTBURY-1	21	211	238	1054.2	1054.2	1054.2	1054.2	1054.2	1054.2	1054.2	1054.2	1054.2	1054.2
27	WILLOW BEND	22	217	190	323.9	323.9	323.9	323.9	323.9	323.9	323.9	323.9	323.9	323.9
28	BRAESWOOD	23	228	135	1985.8	1985.8	1985.8	1985.8	1985.8	1985.8	1985.8	1985.8	1985.8	1985.8
29	GLENSHIRE-2	24	245	147	725.6	725.6	725.6	725.6	725.6	725.6	725.6	725.6	725.6	725.6
30	GLENSHIRE-1	25	246	144	760.8	760.8	760.8	760.8	760.8	760.8	760.8	760.8	760.8	760.8
31	BRAEBURN WEST	26	247	223	729.0	729.0	729.0	729.0	729.0	729.0	729.0	729.0	729.0	729.0
32	WESTBURY-2	27	257	159	1758.3	1758.3	1758.3	1758.3	1758.3	1758.3	1758.3	1758.3	1758.3	1758.3
33	MEYERLAND-1	28	261	308	941.0	941.0	941.0	941.0	941.0	941.0	941.0	941.0	941.0	941.0
34	SHARPSTOWN-2	29	270	267	2127.8	2127.8	2127.8	2127.8	2127.8	2127.8	2127.8	2127.8	2127.8	2127.8
35	DISTRICT 94	30	271	390	1871.1	1871.1	1871.1	1871.1	1871.1	1871.1	1871.1	1871.1	1871.1	1871.1
36	SHARPSTOWN-1	31	273	179	3054.0	3054.0	3054.0	3054.0	3054.0	3054.0	3054.0	3054.0	3054.0	3054.0
37	DISTRICT 139	32	291	270	509.0	509.0	509.0	509.0	509.0	509.0	509.0	509.0	509.0	509.0
38	PARKGLEN-1	33	292	335	479.2	479.2	479.2	479.2	479.2	479.2	479.2	479.2	479.2	479.2
39	PARKGLEN WEST	34	295	169	693.9	693.9	693.9	693.9	693.9	693.9	693.9	693.9	693.9	693.9
40	DISTRICT 111-2	35	297	192	894.1	894.1	894.1	894.1	894.1	894.1	894.1	894.1	894.1	894.1
41	DISTRICT 111-1	36	298	168	745.2	745.2	745.2	745.2	745.2	745.2	745.2	745.2	745.2	745.2
42	DISTRICT 90-2	37	299	187	587.5	587.5	587.5	587.5	587.5	587.5	587.5	587.5	587.5	587.5
43	DISTRICT 184	38	302	204	1758.7	1758.7	1758.7	1758.7	1758.7	1758.7	1758.7	1758.7	1758.7	1758.7
44	BOONE ROAD	39	303	205	281.3	281.3	281.3	281.3	281.3	281.3	281.3	281.3	281.3	281.3
45	MANNING	40	304	171	899.5	899.5	899.5	899.5	899.5	899.5	899.5	899.5	899.5	899.5
46	Internal Demand in Pumps				11381.0	11381.0	11381.0	11381.0	11381.0	11381.0	11381.0	11381.0	11381.0	11381.0
47	Groundwater				103690.9	103690.9	103690.9	103690.9	103690.9	103690.9	103690.9	103690.9	103690.9	103690.9
48														
49	Inflow1				1296.94	1296.94	1296.94	1296.94	1296.94	1296.94	1296.94	1296.94	1296.94	1296.94
50	Inflow2				1945.41	1945.41	1945.41	1945.41	1945.41	1945.41	1945.41	1945.41	1945.41	1945.41
51	Internal Demand in Inflow				5000.0	5000.0	5000.0	5000.0	5000.0	5000.0	5000.0	5000.0	5000.0	5000.0
52	Surface Water				8242.4	8242.4	8242.4	8242.4	8242.4	8242.4	8242.4	8242.4	8242.4	8242.4
53														
54	Total Water				111933.2	111933.2	111933.2	111933.2	111933.2	111933.2	111933.2	111933.2	111933.2	111933.2
55														
56	Ratio GW/TW				92.64%	92.64%	92.64%	92.64%	92.64%	92.64%	92.64%	92.64%	92.64%	92.64%

Table 6.5. Linear Production Cost Model Results.



	A	B	C	D	E	F	G
1	Table : Summary of Slope Unit Cost Analysis Simulation						
2							
3	Pump Station Name	No.	Node No.	Unit Cost	New Cost	Original	Slope
4						(GPM)	(GPM)
5							
6	BRIARGROVE PARK	1	18	500	2000	0.0	0.0
7	DISTRICT 123	2	21	131	131	1682.1	1682.1
8	ROSEWOOD-2	3	32	483	85.99	669.0	669.0
9	DISTRICT 51-2	4	36	178	7.97	1337.1	1337.1
10	FAIRDALE (D-26)	5	46	174	105.87	3308.7	3308.7
11	ROSEWOOD-1	6	87	500	125.1	0.0	0.0
12	DISTRICT 158	7	89	412	220.22	1620.3	1620.3
13	BROOKFIELD	8	91	179	11.6	578.6	578.6
14	BELLAIRE BRAES	9	92	154	33.89	9268.3	9268.3
15	DISTRICT 218	10	93	226	94.14	3224.2	3224.2
16	DISTRICT 51-1	11	102	419	33.6	1040.8	1040.8
17	DISTRICT 54	12	117	160	150	2572.6	2572.6
18	SOUTHWEST	13	132	176	146.32	17239.4	17239.4
19	SOUTHEND	14	139	725	725	6722.4	6722.4
20	LINKWOOD	15	171	424	1321.6	1023.3	1023.3
21	BRIARWICK	16	187	266	266	1235.1	1235.1
22	RIDGEMONT	17	188	222	222	1016.3	1016.3
23	CHASEWOOD	18	201	257	63.21	4198.9	4198.9
24	DISTRICT 41-2	19	203	335	335	2344.3	2344.3
25	SIMS BAYOU	20	204	128	6.39	11048.8	11048.8
26	WESTBURY-1	21	211	238	81.78	1054.2	1054.2
27	WILLOW BEND	22	217	190	78.45	323.9	323.9
28	BRAESWOOD	23	228	135	255.8	1985.8	1985.8
29	GLENSHIRE-2	24	245	147	83.97	725.6	725.6
30	GLENSHIRE-1	25	246	144	32.97	760.8	760.8
31	BRAEBURN WEST	26	247	223	67.94	729.0	729.0
32	WESTBURY-2	27	257	159	159	1758.3	1758.3
33	MEYERLAND-1	28	261	308	308	941.0	941.0
34	SHARPSTOWN-2	29	270	267	5.34	2127.8	2127.8
35	DISTRICT 94	30	271	390	33.8	1871.1	1871.1
36	SHARPSTOWN-1	31	273	179	96.81	3054.0	3054.0
37	DISTRICT 139	32	291	270	2.39	509.0	509.0
38	PARKGLEN-1	33	292	335	125.1	479.2	479.2
39	PARKGLEN WEST	34	295	169	10.11	693.9	693.9
40	DISTRICT 111-2	35	297	192	61.3	894.1	894.1
41	DISTRICT 111-1	36	298	168	7.4	745.2	745.2
42	DISTRICT 90-2	37	299	187	66.58	587.5	587.5
43	DISTRICT 184	38	302	204	161.21	1758.7	1758.7
44	BOONE ROAD	39	303	205	61.34	281.3	281.3
45	MANNING	40	304	171	51.19	899.5	899.5
46	Internal Demand in Pumps					11381.0	11381.0
47	Groundwater					103690.9	103690.9
48							
49	Inflow1					1296.9	1296.9
50	Inflow2					1945.4	1945.4
51	Internal Demand in Inflow					5000.0	5000.0
52	Surface Water					8242.4	8242.4
53							
54	Total Water					111933.2	111933.2
55							
56	Ratio GW/TW					92.64%	92.64%

Demand Analysis

Figure 6.15 below shows the distribution system network and the six sectors chosen for the demand uncertainty analysis. In each of the six sectors the demand was increased by 20 % while the demand was simultaneously decreased 4% in the other five sectors and the model was run. Changes in supply configuration were noted for these six cases to determine the sensitivity of supply configuration to uncertainty in demand. Observe that in these cases, the total demand is unchanged from the base case.

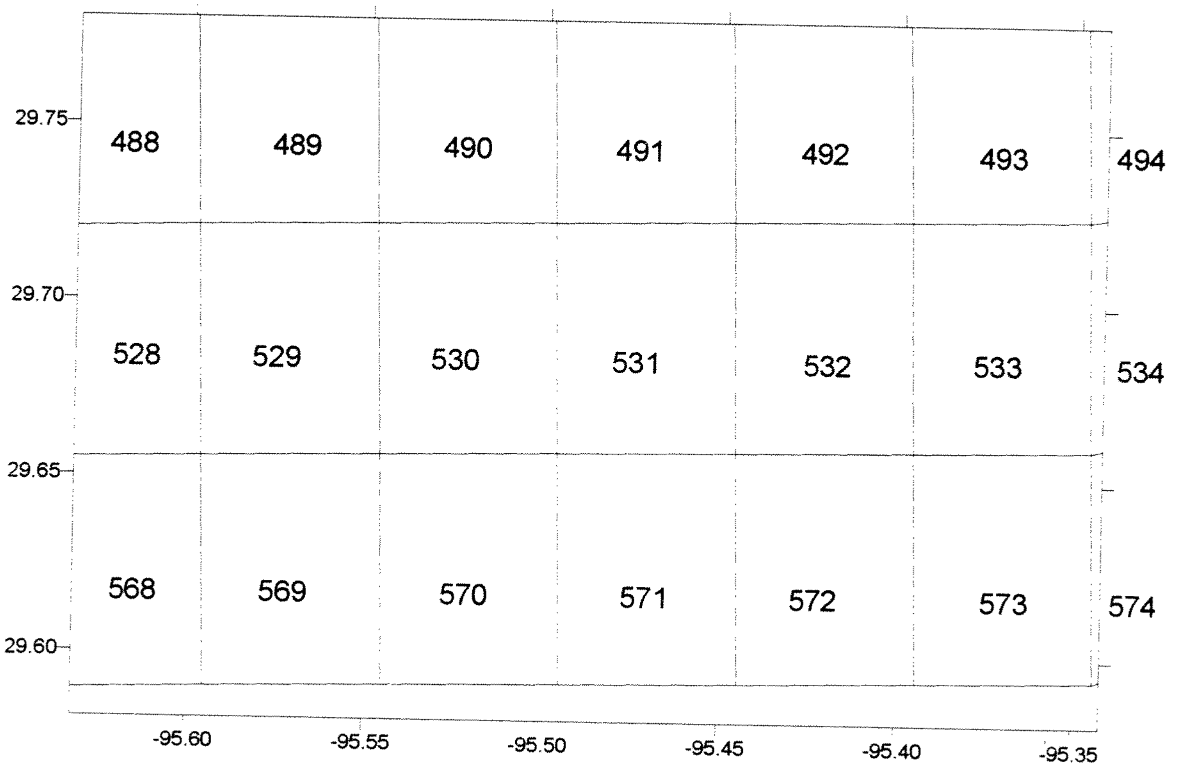


Figure 6.15 Block Map Outlines in Southwest Houston Study Area

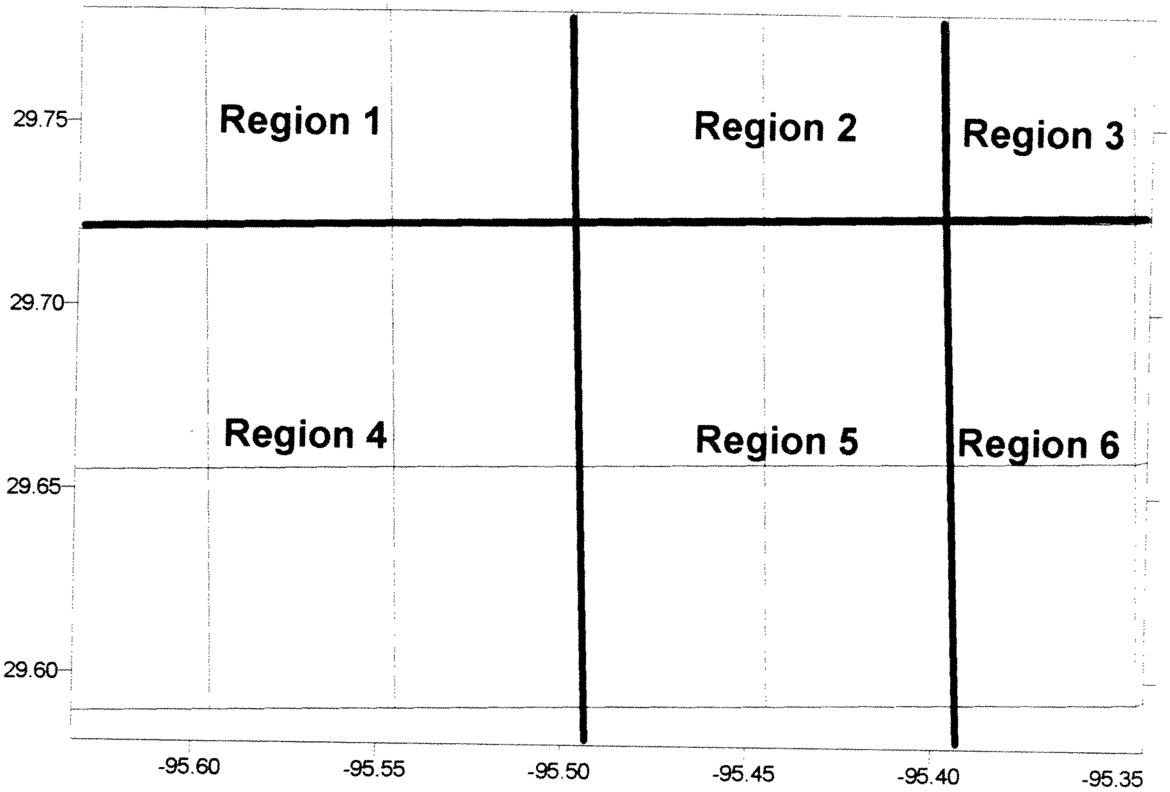


Figure 6.16. Six Sectors for Uncertainty Analysis based on Regional Demand Values

Figure 6.16 above shows the six sectors used for this portion of the analysis. The general approach was to increase the demand in each region by 120% of the base case and reduce the demands uniformily in the other regions to determine the sensitivity of solutions to regionalized changes in demand. In all cases the total demand is unchanged, juts the distribution of demand is adjusted.

The base demand for each region is shown in Table 6.6 below.

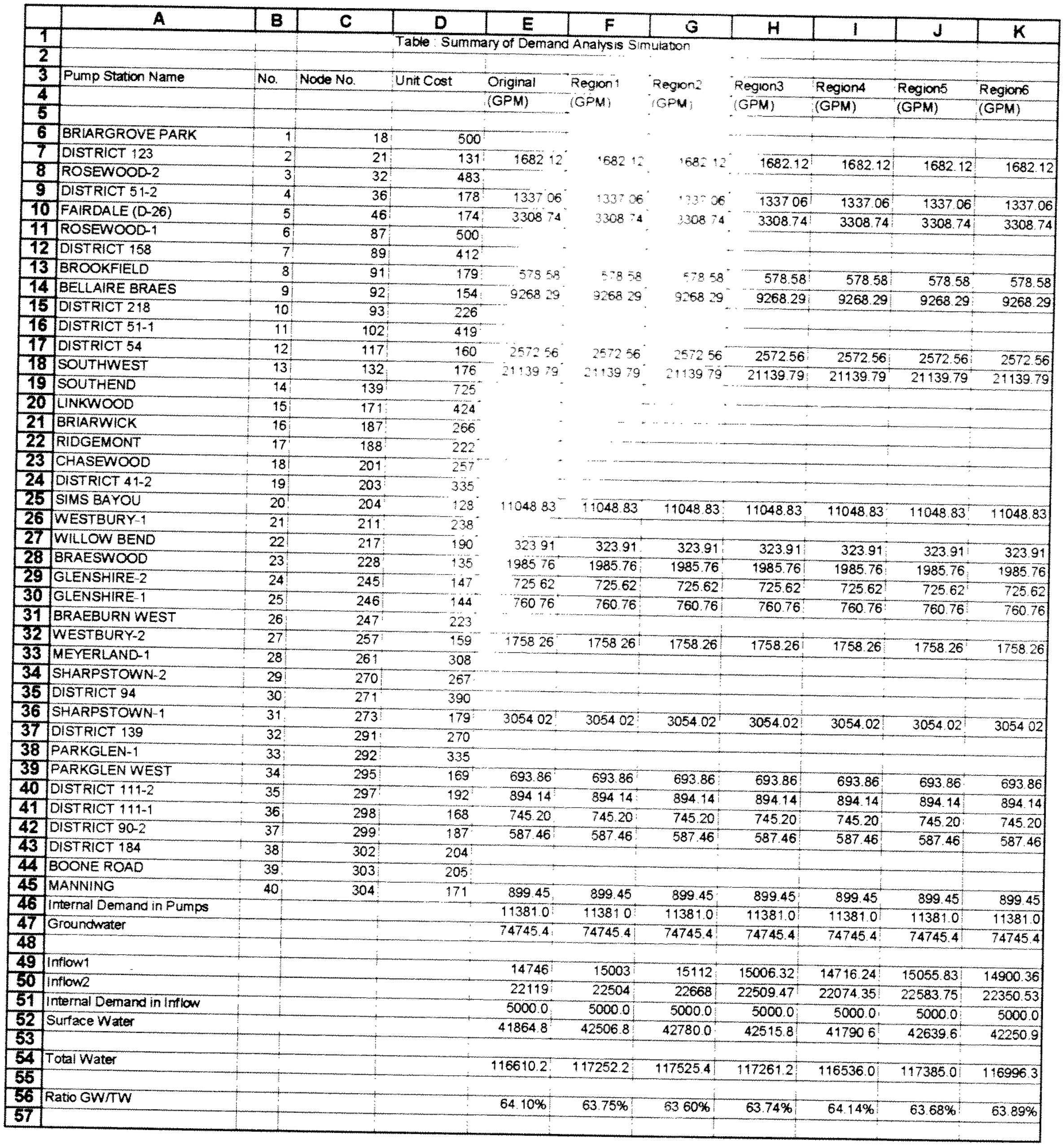
Table 6.6 Regional Water Demands (Base Case)

Region Number	Water Demand (GPM)
Region #1	21,048
Region #2	20,432
Region #3	13,455
Region #4	24,710
Region #5	21,343
Region #6	10,468

The simulation-optimization model is then run using the average unit cost model to determine the best supply allocation for the particular case. Two types of supply were studied: 60% groundwater derived supply, and 90% groundwater derived supply.

The results for the 60% groundwater derived supply situation are shown in Table 6.7. The results are identical for each region indicating that the supply allocation is unchanged regardless of regional variations in demand.

Table 6.7 Demand Sensitivity for 60% Groundwater Derived Supply



	A	B	C	D	E	F	G	H	I	J	K
1				Table : Summary of Demand Analysis Simulation							
2											
3	Pump Station Name	No.	Node No.	Unit Cost	Original	Region1	Region2	Region3	Region4	Region5	Region6
4					(GPM)	(GPM)	(GPM)	(GPM)	(GPM)	(GPM)	(GPM)
5											
6	BRIARGROVE PARK	1	18	500							
7	DISTRICT 123	2	21	131	1682.12	1682.12	1682.12	1682.12	1682.12	1682.12	1682.12
8	ROSEWOOD-2	3	32	483							
9	DISTRICT 51-2	4	36	178	1337.06	1337.06	1337.06	1337.06	1337.06	1337.06	1337.06
10	FAIRDALE (D-26)	5	46	174	3308.74	3308.74	3308.74	3308.74	3308.74	3308.74	3308.74
11	ROSEWOOD-1	6	87	500							
12	DISTRICT 158	7	89	412							
13	BROOKFIELD	8	91	179	578.58	578.58	578.58	578.58	578.58	578.58	578.58
14	BELLAIRE BRAES	9	92	154	9268.29	9268.29	9268.29	9268.29	9268.29	9268.29	9268.29
15	DISTRICT 218	10	93	226							
16	DISTRICT 51-1	11	102	419							
17	DISTRICT 54	12	117	160	2572.56	2572.56	2572.56	2572.56	2572.56	2572.56	2572.56
18	SOUTHWEST	13	132	176	21139.79	21139.79	21139.79	21139.79	21139.79	21139.79	21139.79
19	SOUTHEND	14	139	725							
20	LINKWOOD	15	171	424							
21	BRIARWICK	16	187	266							
22	RIDGEMONT	17	188	222							
23	CHASEWOOD	18	201	257							
24	DISTRICT 41-2	19	203	335							
25	SIMS BAYOU	20	204	128	11048.83	11048.83	11048.83	11048.83	11048.83	11048.83	11048.83
26	WESTBURY-1	21	211	238							
27	WILLOW BEND	22	217	190	323.91	323.91	323.91	323.91	323.91	323.91	323.91
28	BRAESWOOD	23	228	135	1985.76	1985.76	1985.76	1985.76	1985.76	1985.76	1985.76
29	GLENSHIRE-2	24	245	147	725.62	725.62	725.62	725.62	725.62	725.62	725.62
30	GLENSHIRE-1	25	246	144	760.76	760.76	760.76	760.76	760.76	760.76	760.76
31	BRAEBURN WEST	26	247	223							
32	WESTBURY-2	27	257	159	1758.26	1758.26	1758.26	1758.26	1758.26	1758.26	1758.26
33	MEYERLAND-1	28	261	308							
34	SHARPSTOWN-2	29	270	267							
35	DISTRICT 94	30	271	390							
36	SHARPSTOWN-1	31	273	179	3054.02	3054.02	3054.02	3054.02	3054.02	3054.02	3054.02
37	DISTRICT 139	32	291	270							
38	PARKGLEN-1	33	292	335							
39	PARKGLEN WEST	34	295	169	693.86	693.86	693.86	693.86	693.86	693.86	693.86
40	DISTRICT 111-2	35	297	192	894.14	894.14	894.14	894.14	894.14	894.14	894.14
41	DISTRICT 111-1	36	298	168	745.20	745.20	745.20	745.20	745.20	745.20	745.20
42	DISTRICT 90-2	37	299	187	587.46	587.46	587.46	587.46	587.46	587.46	587.46
43	DISTRICT 184	38	302	204							
44	BOONE ROAD	39	303	205							
45	MANNING	40	304	171	899.45	899.45	899.45	899.45	899.45	899.45	899.45
46	Internal Demand in Pumps				11381.0	11381.0	11381.0	11381.0	11381.0	11381.0	11381.0
47	Groundwater				74745.4	74745.4	74745.4	74745.4	74745.4	74745.4	74745.4
48											
49	Inflow1				14746	15003	15112	15006.32	14716.24	15055.83	14900.36
50	Inflow2				22119	22504	22668	22509.47	22074.35	22583.75	22350.53
51	Internal Demand in Inflow				5000.0	5000.0	5000.0	5000.0	5000.0	5000.0	5000.0
52	Surface Water				41864.8	42506.8	42780.0	42515.8	41790.6	42639.6	42250.9
53											
54	Total Water				116610.2	117252.2	117525.4	117261.2	116536.0	117385.0	116996.3
55											
56	Ratio GW/TW				64.10%	63.75%	63.60%	63.74%	64.14%	63.68%	63.89%
57											

Figures 6.17 through 6.22 shown the resulting pressure distributions from the different demand simulations. While the supply allocations are unchanged the pressure distributions vary as a function of the different regionalized demands. This behavoir is expected, of particular note is the region 4 simulation-optmization where the low pressure region increases in size in the southwestern corner of the model which was expected to be the most sensitive to changes in demands.

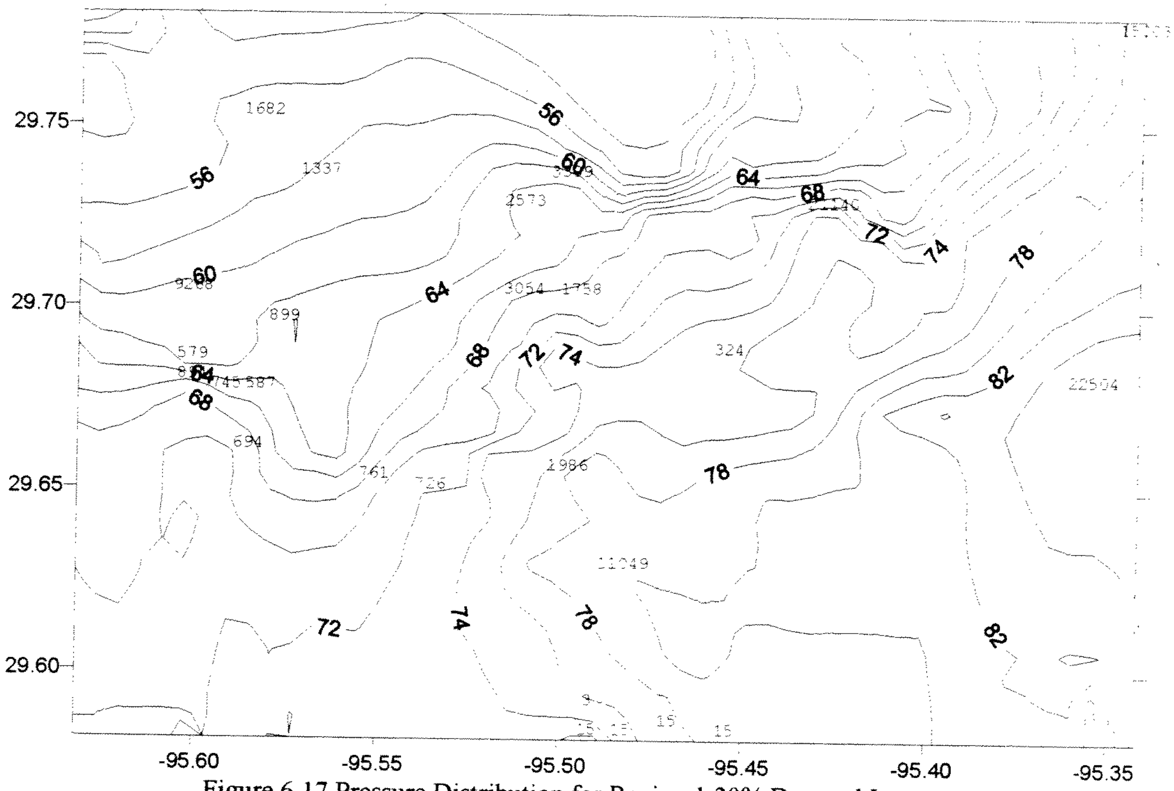


Figure 6.17 Pressure Distribution for Region 1 20% Demand Increase

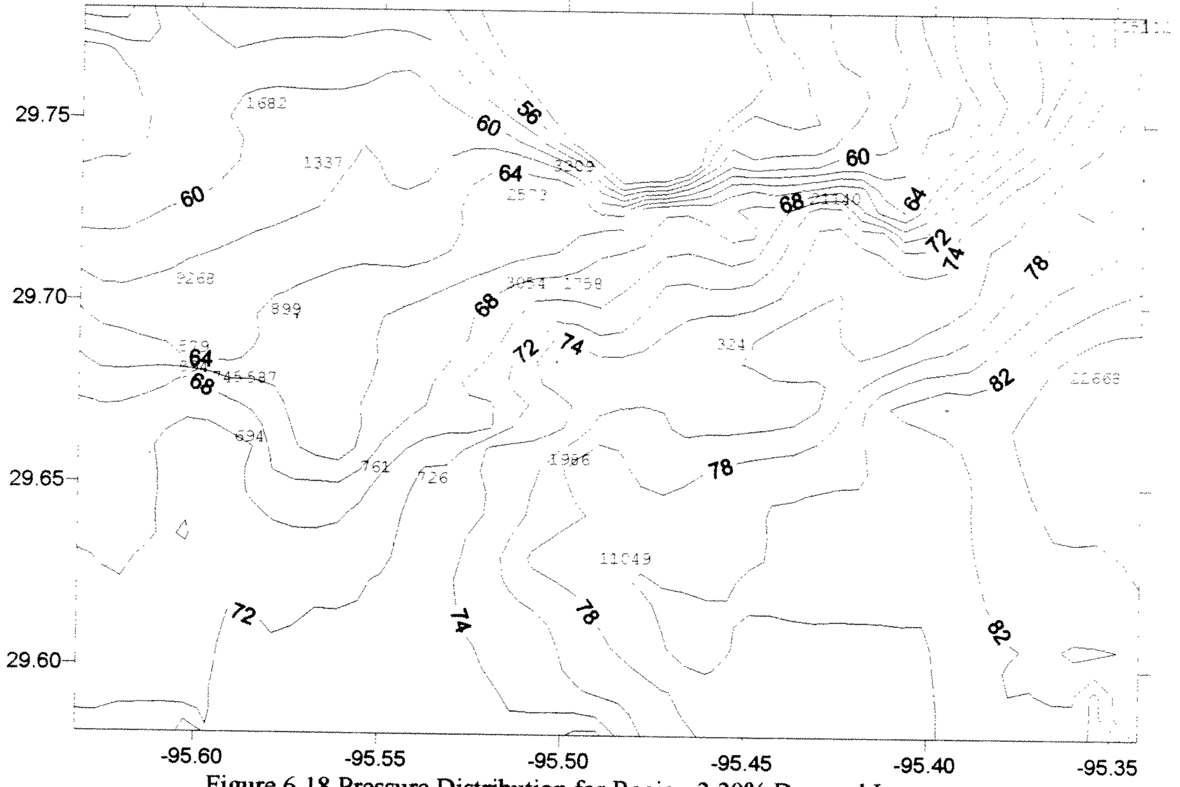


Figure 6.18 Pressure Distribution for Region 2 20% Demand Increase

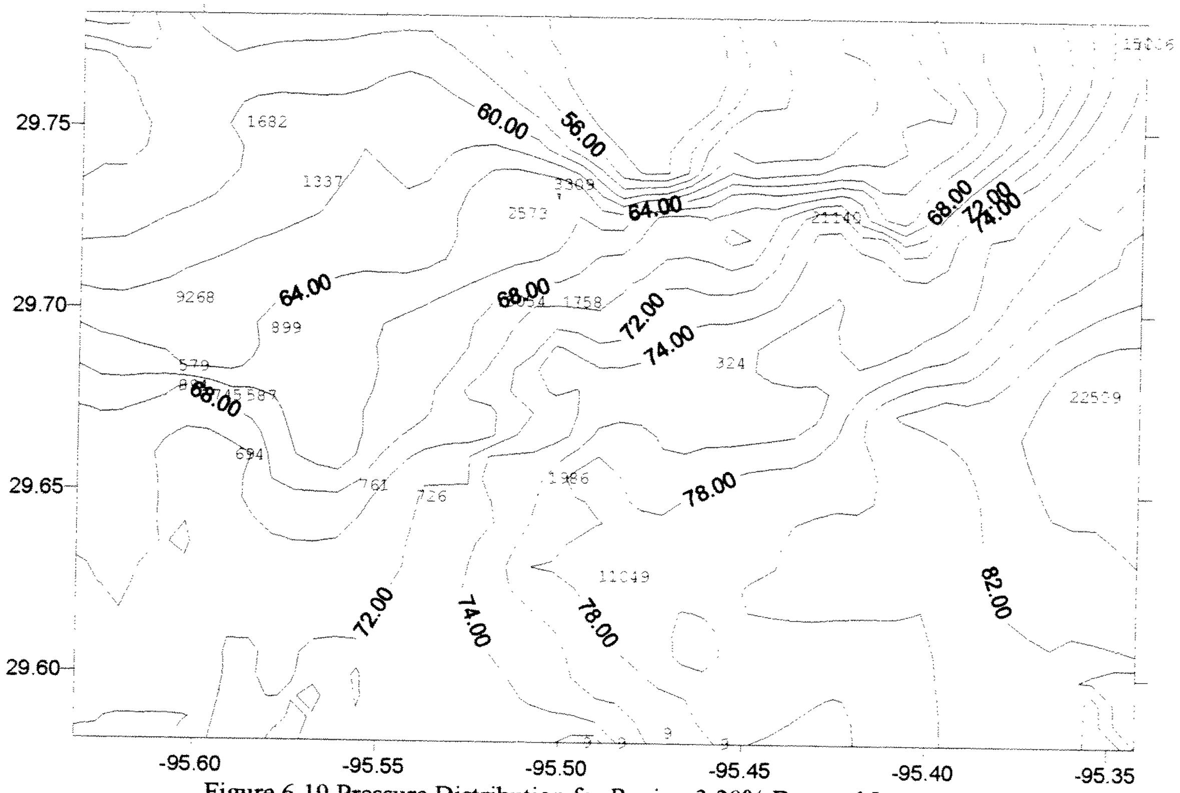


Figure 6.19 Pressure Distribution for Region 3 20% Demand Increase

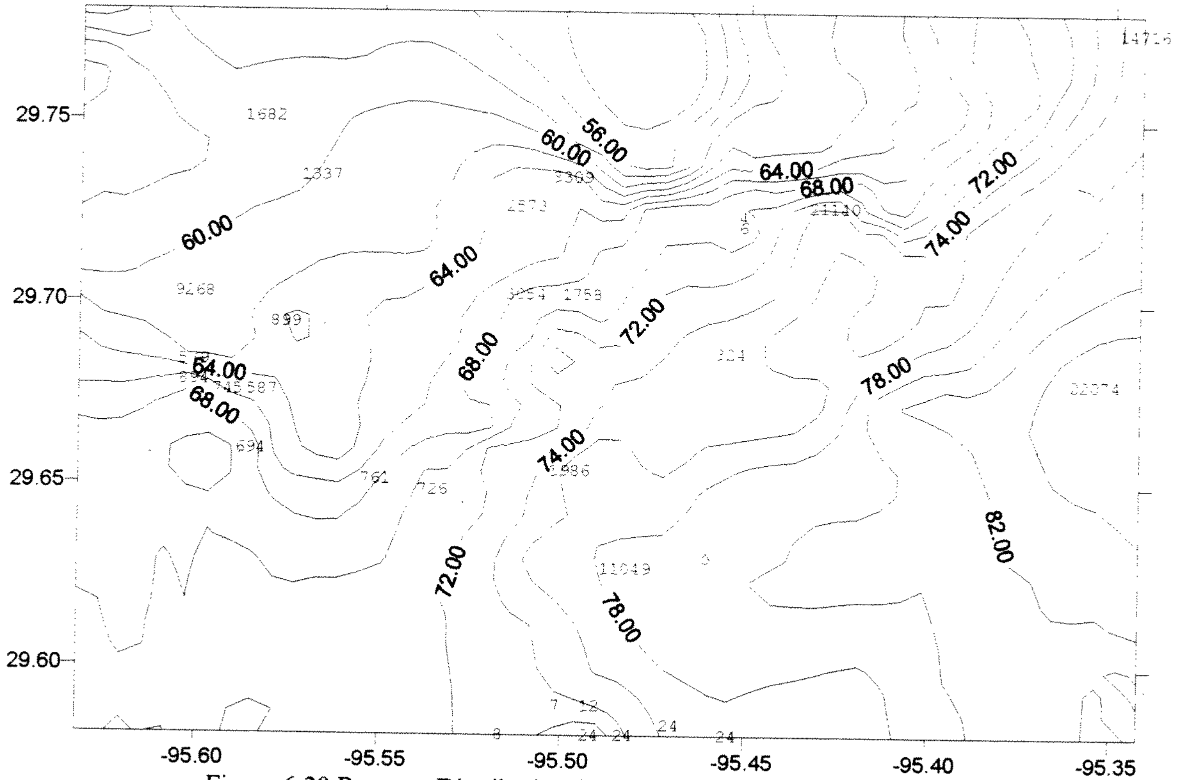


Figure 6.20 Pressure Distribution for Region 4 20% Demand Increase

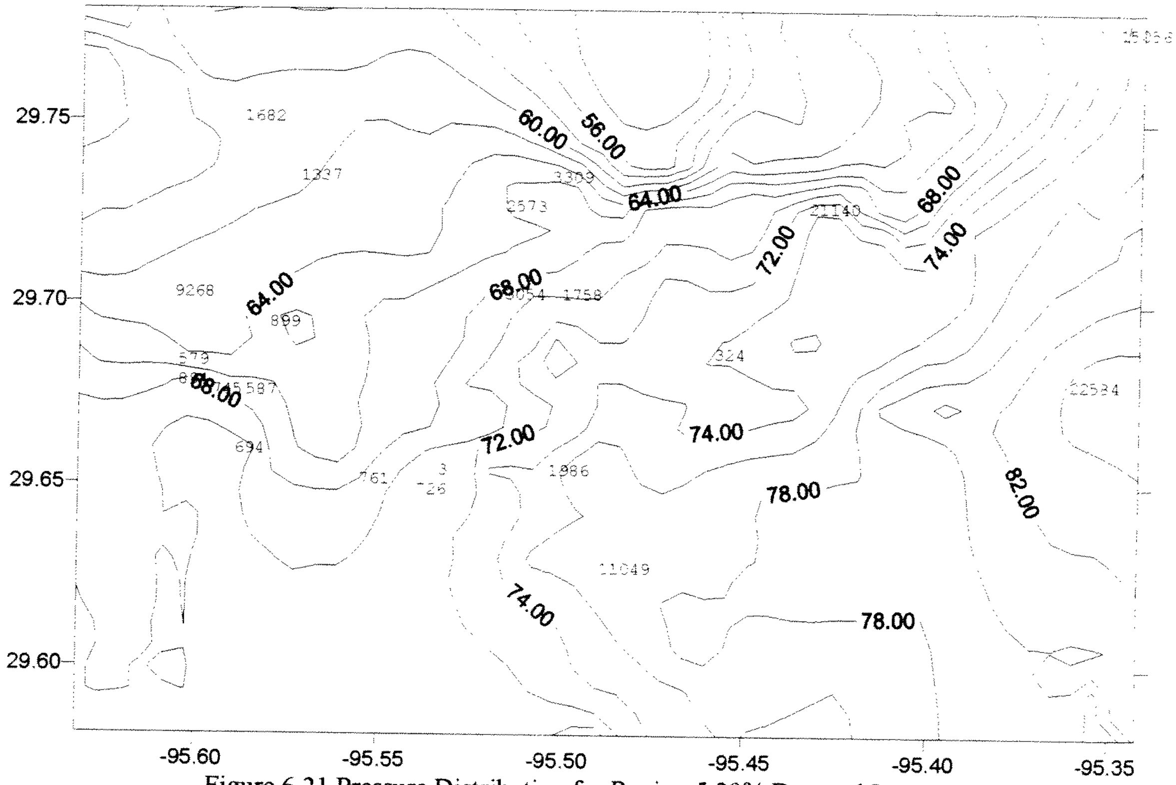


Figure 6.21 Pressure Distribution for Region 5 20% Demand Increase

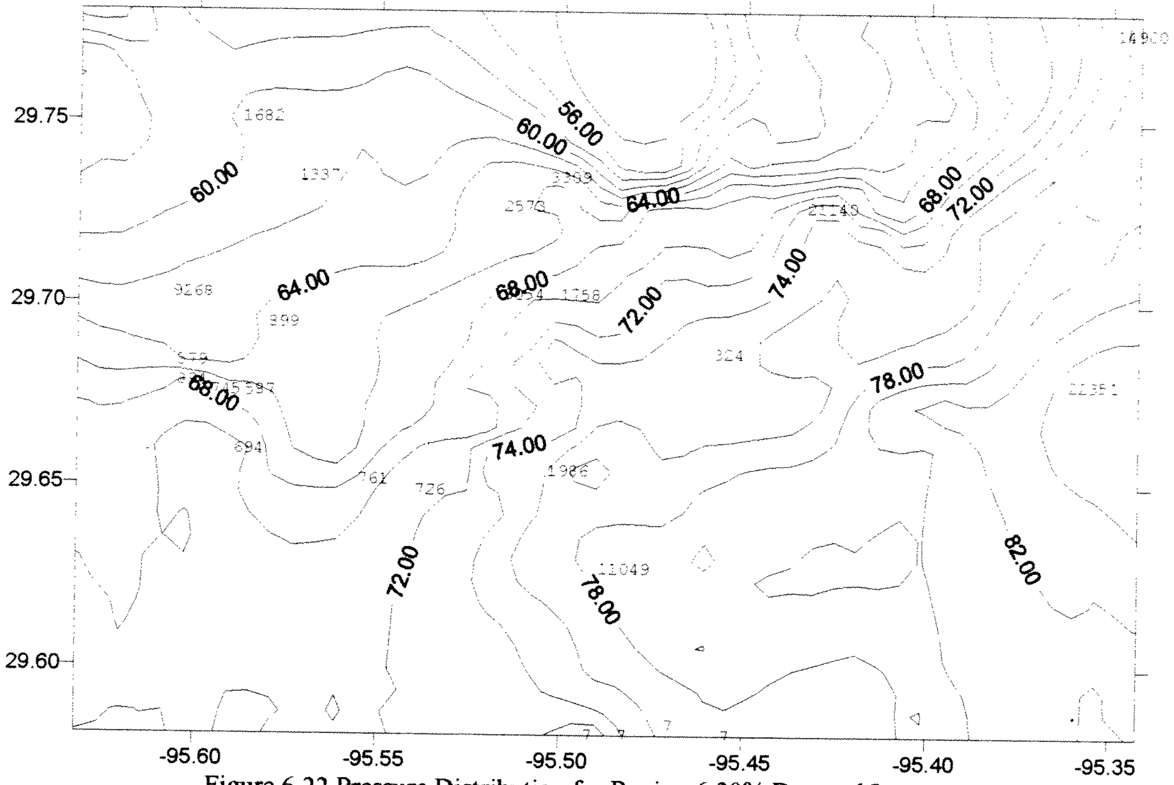


Figure 6.22 Pressure Distribution for Region 6 20% Demand Increase

The results for the 90% groundwater derived supply situation are shown in Table 6.8. The results are again identical for each region. From these results (60% and 90% cases) we conclude that the uncertainty in demand can be as much as 20% on a large regionwide basis without affecting what supply allocation decisions are made.

Figures 6.23 through 6.28 show the resulting pressure distributions from the different demand simulations.

Table 6.8 Demand Sensitivity for 90% Groundwater Derived Supply

	A	B	C	D	E	F	G	H	I	J	K
1				Table : Summary of Demand Analysis Simulation							
2											
3	Pump Station Name	No.	Node No.	Unit Cost	Original	Region1	Region2	Region3	Region4	Region5	Region6
4					(GPM)	(GPM)	(GPM)	(GPM)	(GPM)	(GPM)	(GPM)
5											
6	BRIARGROVE PARK	1	18	500	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	DISTRICT 123	2	21	131	1682.1	1682.1	1682.1	1682.1	1682.1	1682.1	1682.1
8	ROSEWOOD-2	3	32	483	669.0	669.0	669.0	669.0	669.0	669.0	669.0
9	DISTRICT 51-2	4	36	178	1337.1	1337.1	1337.1	1337.1	1337.1	1337.1	1337.1
10	FAIRDALE (D-26)	5	46	174	3308.7	3308.7	3308.7	3308.7	3308.7	3308.7	3308.7
11	ROSEWOOD-1	6	87	500	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	DISTRICT 158	7	89	412	1620.3	1620.3	1620.3	1620.3	1620.3	1620.3	1620.3
13	BROOKFIELD	8	91	179	578.6	578.6	578.6	578.6	578.6	578.6	578.6
14	BELLAIRE BRAES	9	92	154	9268.3	9268.3	9268.3	9268.3	9268.3	9268.3	9268.3
15	DISTRICT 218	10	93	226	3224.2	3224.2	3224.2	3224.2	3224.2	3224.2	3224.2
16	DISTRICT 51-1	11	102	419	1040.8	1040.8	1040.8	1040.8	1040.8	1040.8	1040.8
17	DISTRICT 54	12	117	160	2572.6	2572.6	2572.6	2572.6	2572.6	2572.6	2572.6
18	SOUTHWEST	13	132	176	17239.4	17239.4	17239.4	17239.4	17239.4	17239.4	17239.4
19	SOUTHEND	14	139	725	6722.4	6722.4	6722.4	6722.4	6722.4	6722.4	6722.4
20	LINKWOOD	15	171	424	1023.3	1023.3	1023.3	1023.3	1023.3	1023.3	1023.3
21	BRIARWICK	16	187	266	1235.1	1235.1	1235.1	1235.1	1235.1	1235.1	1235.1
22	RIDGEMONT	17	188	222	1016.3	1016.3	1016.3	1016.3	1016.3	1016.3	1016.3
23	CHASEWOOD	18	201	257	4198.9	4198.9	4198.9	4198.9	4198.9	4198.9	4198.9
24	DISTRICT 41-2	19	203	335	2344.3	2344.3	2344.3	2344.3	2344.3	2344.3	2344.3
25	SIMS BAYOU	20	204	128	11048.8	11048.8	11048.8	11048.8	11048.8	11048.8	11048.8
26	WESTBURY-1	21	211	238	1054.2	1054.2	1054.2	1054.2	1054.2	1054.2	1054.2
27	WILLOW BEND	22	217	190	323.9	323.9	323.9	323.9	323.9	323.9	323.9
28	BRAESWOOD	23	228	135	1985.8	1985.8	1985.8	1985.8	1985.8	1985.8	1985.8
29	GLENSHIRE-2	24	245	147	725.6	725.6	725.6	725.6	725.6	725.6	725.6
30	GLENSHIRE-1	25	246	144	760.8	760.8	760.8	760.8	760.8	760.8	760.8
31	BRAEBURN WEST	26	247	223	729.0	729.0	729.0	729.0	729.0	729.0	729.0
32	WESTBURY-2	27	257	159	1758.3	1758.3	1758.3	1758.3	1758.3	1758.3	1758.3
33	MEYERLAND-1	28	261	308	941.0	941.0	941.0	941.0	941.0	941.0	941.0
34	SHARPSTOWN-2	29	270	267	2127.8	2127.8	2127.8	2127.8	2127.8	2127.8	2127.8
35	DISTRICT 94	30	271	390	1871.1	1871.1	1871.1	1871.1	1871.1	1871.1	1871.1
36	SHARPSTOWN-1	31	273	179	3054.0	3054.0	3054.0	3054.0	3054.0	3054.0	3054.0
37	DISTRICT 139	32	291	270	509.0	509.0	509.0	509.0	509.0	509.0	509.0
38	PARKGLEN-1	33	292	335	479.2	479.2	479.2	479.2	479.2	479.2	479.2
39	PARKGLEN WEST	34	295	169	693.9	693.9	693.9	693.9	693.9	693.9	693.9
40	DISTRICT 111-2	35	297	192	894.1	894.1	894.1	894.1	894.1	894.1	894.1
41	DISTRICT 111-1	36	298	168	745.2	745.2	745.2	745.2	745.2	745.2	745.2
42	DISTRICT 90-2	37	299	187	587.5	587.5	587.5	587.5	587.5	587.5	587.5
43	DISTRICT 184	38	302	204	1758.7	1758.7	1758.7	1758.7	1758.7	1758.7	1758.7
44	BOONE ROAD	39	303	205	281.3	281.3	281.3	281.3	281.3	281.3	281.3
45	MANNING	40	304	171	899.5	899.5	899.5	899.5	899.5	899.5	899.5
46	Internal Demand in Pumps				11381.0	11381.0	11381.0	11381.0	11381.0	11381.0	11381.0
47	Groundwater				103690.9	103690.9	103690.9	103690.9	103690.9	103690.9	103690.9
48											
49	Inflow1				1296.9	1553.7	1663.0	1557.3	1267.3	1606.9	1451.4
50	Inflow2				1945.4	2330.6	2494.5	2336.0	1900.9	2410.3	2177.1
51	Internal Demand in Inflow				5000.0	5000.0	5000.0	5000.0	5000.0	5000.0	5000.0
52	Surface Water				8242.4	8884.3	9157.5	8893.3	8168.1	9017.1	8628.4
53											
54	Total Water				111933.2	112575.2	112848.4	112584.2	111859.0	112708.0	112319.3
55											
56	Ratio GW/TW				92.64%	92.11%	91.89%	92.10%	92.70%	92.00%	92.32%

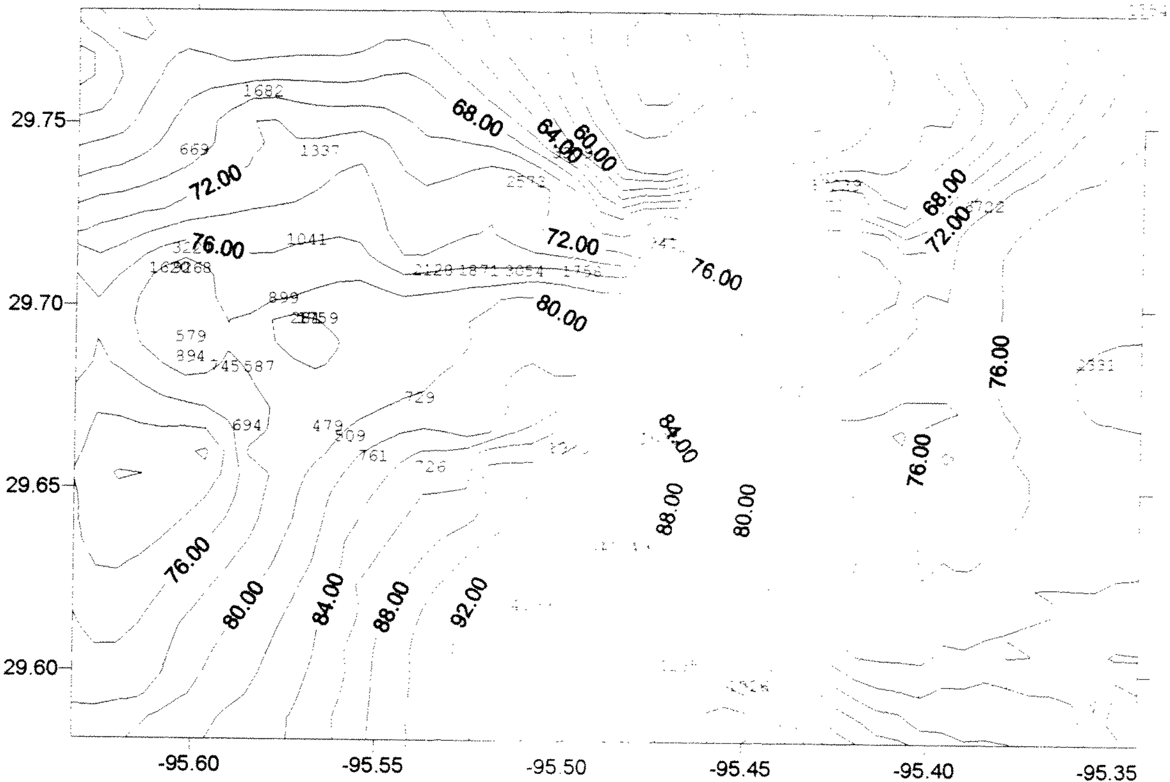


Figure 6.23 Pressure Distribution for Region 1 20% Demand Increase

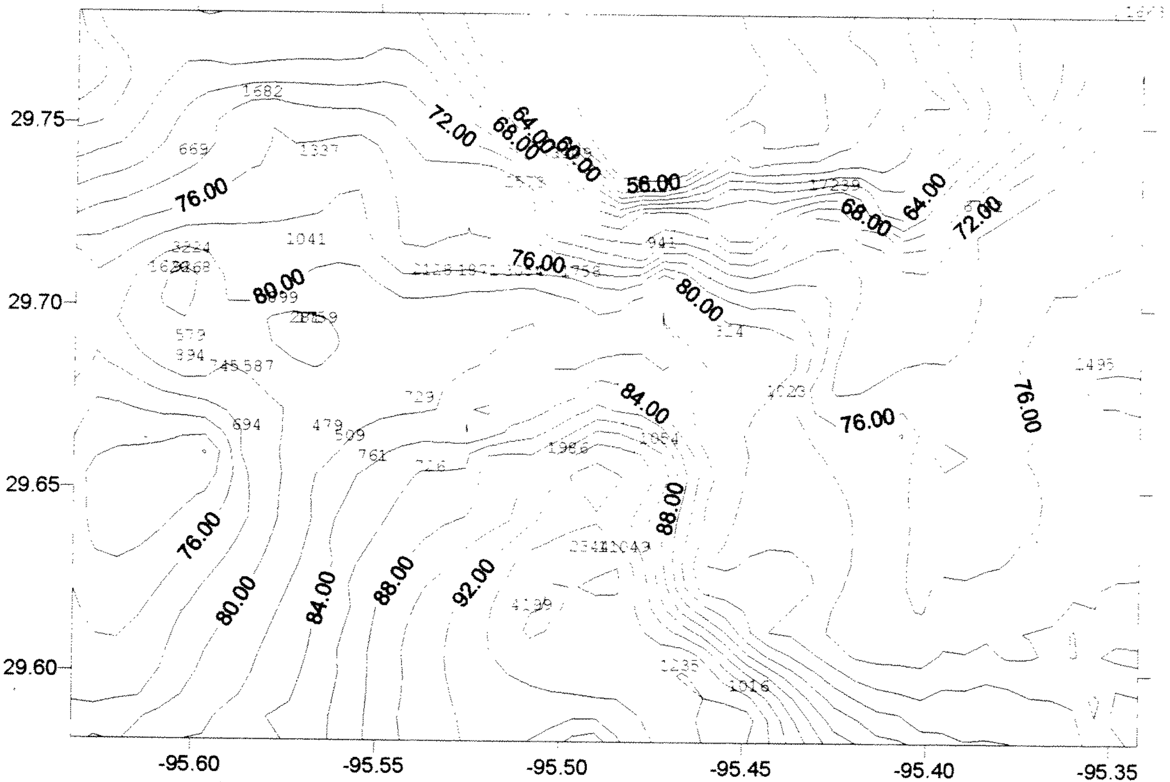


Figure 6.24 Pressure Distribution for Region 2 20% Demand Increase

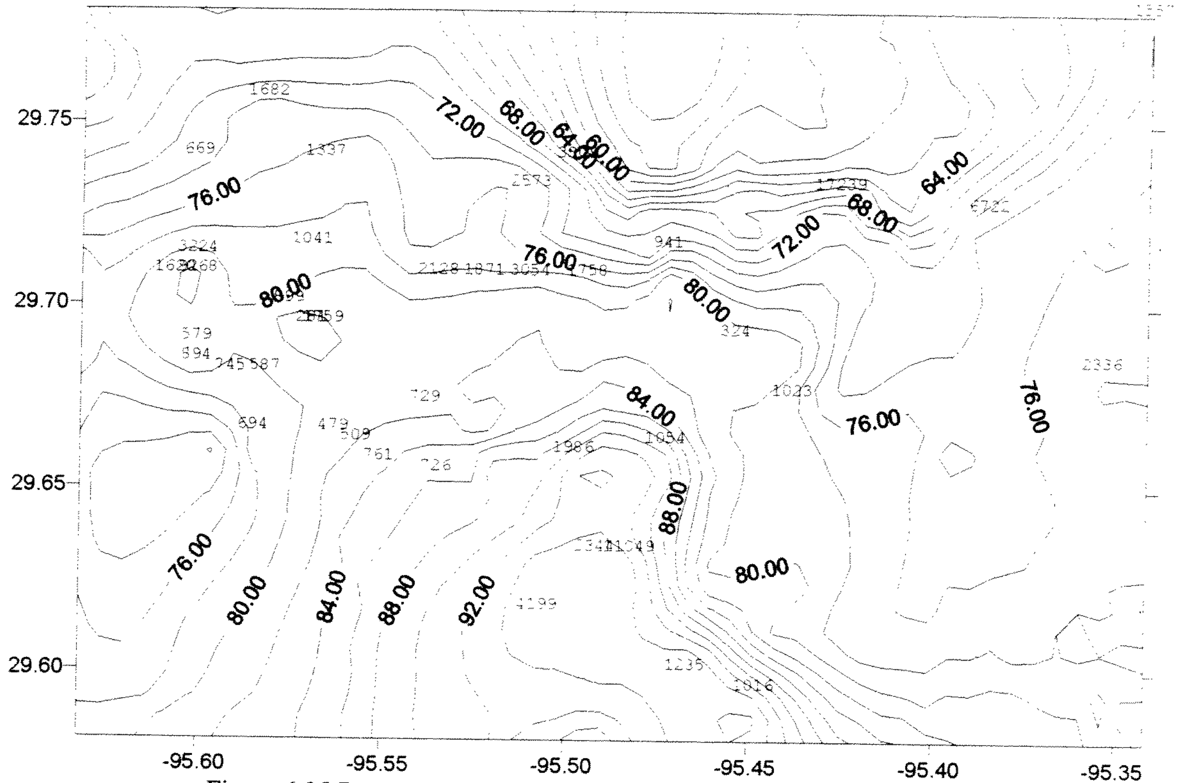


Figure 6.25 Pressure Distribution for Region 3 20% Demand Increase

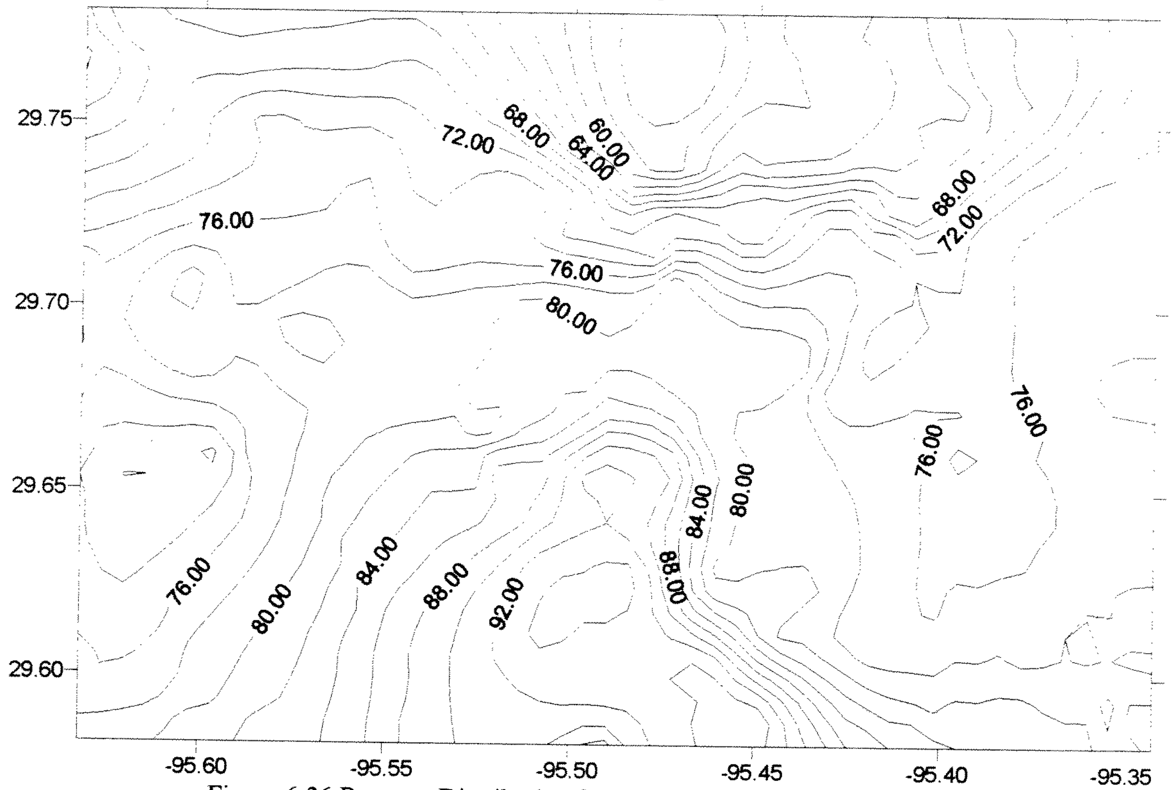


Figure 6.26 Pressure Distribution for Region 4 20% Demand Increase

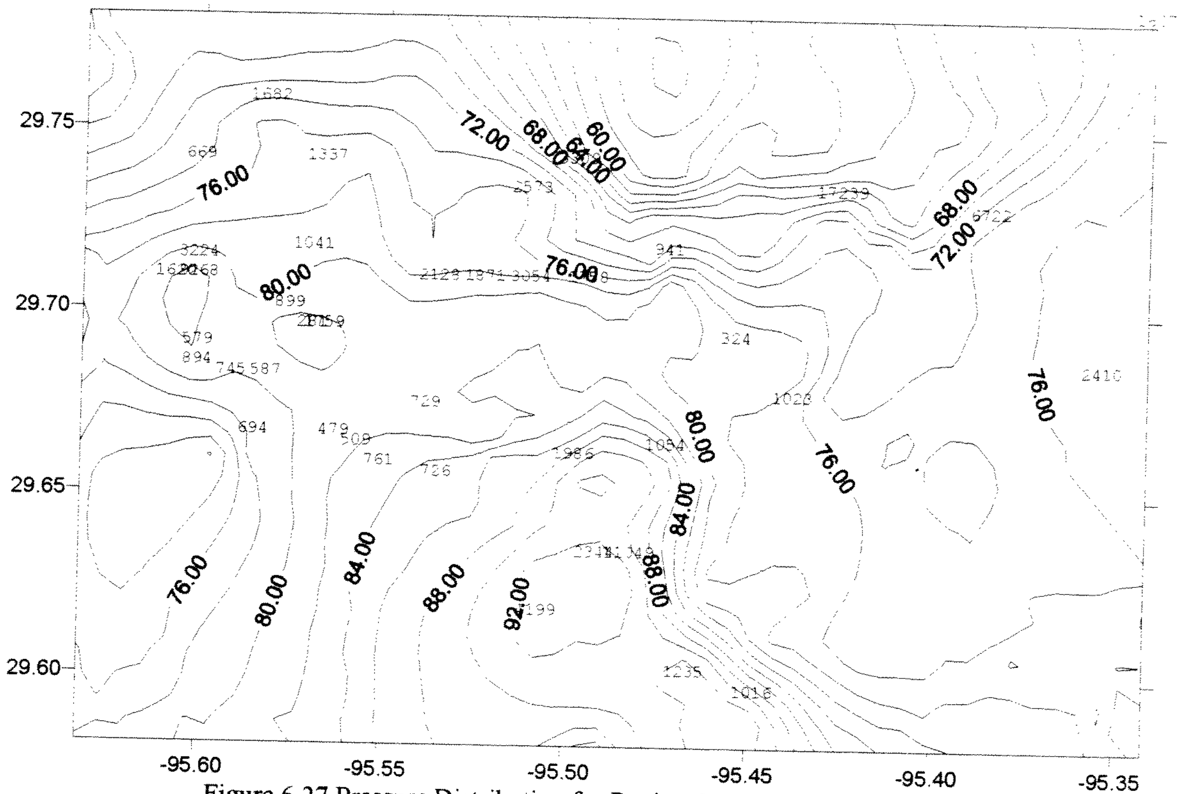


Figure 6.27 Pressure Distribution for Region 5 20% Demand Increase

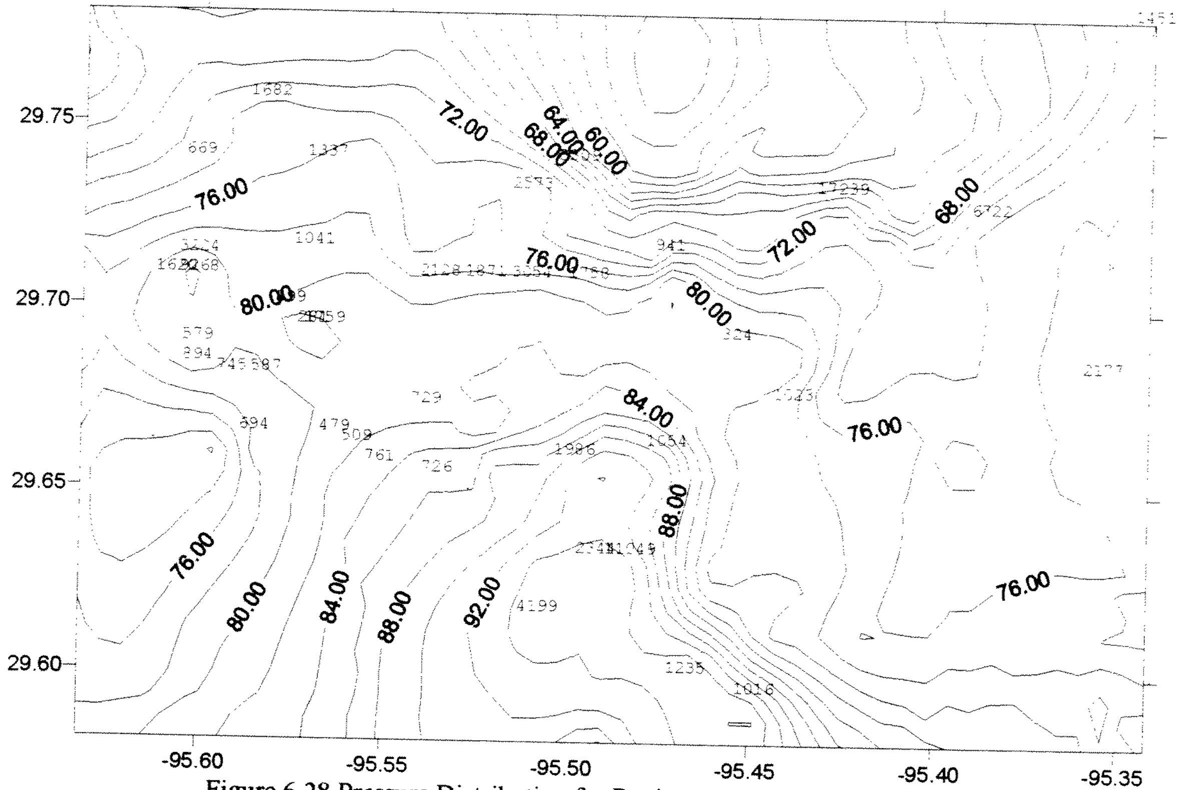


Figure 6.28 Pressure Distribution for Region 6 20% Demand Increase

Conclusions

The results of the uncertainty analysis as performed showed that uncertainty in several of the driving parameters (unit production cost, and demand) had little effect on the overall supply allocation.

A cost variation analysis was performed for two sets of conditions: 60% and 90% groundwater derived supply. In the case where 60% of the water supplied is groundwater derived, pump stations with a unit cost of greater than $187 or less than $168 did not change their pumpage in all simulation-optimization trials. Pump stations with unit costs between these ranges were sensitive to the changes in unit costs. In the cases where 90% of the water supplied is groundwater derived, none of the pump stations were sensitive to changes in costs. At this level of groundwater derived supply, system hydraulics completely dominates the solution and little optimization appears to be possible.

A demand variation analysis was performed for the same two sets of conditions where the demand in siz different regions was varied to determine what changes in supply allocations might occur under different demands. In all these cases, the supply allocation was completely unchanged with demand variations up to 20% for the base demand within a region. We infer from this result that demand in this model at these levels is less important that either unit cost or hydraulics in selecting good allocations.

Overall, the model was relatively insensitive to variations in the inputs of cost or demand at the base case input levels. A high groundwater derived supply, hydraulics seems to dictate the supply allocation, while at lower groundwater derived supply, unit cost becomes more important. We recomend that future efforts be directed at determining production costs and system hydraulics carefully, while demand estimation is less critical (at least the the scale we used).

Research into Production Cost Reduction by Energy Management of Houston's Surface and Groundwater Systems

Part XII

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by

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Final Report

Prepared for

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City of Houston Project # 33100
University of Houston Project # 1558893

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