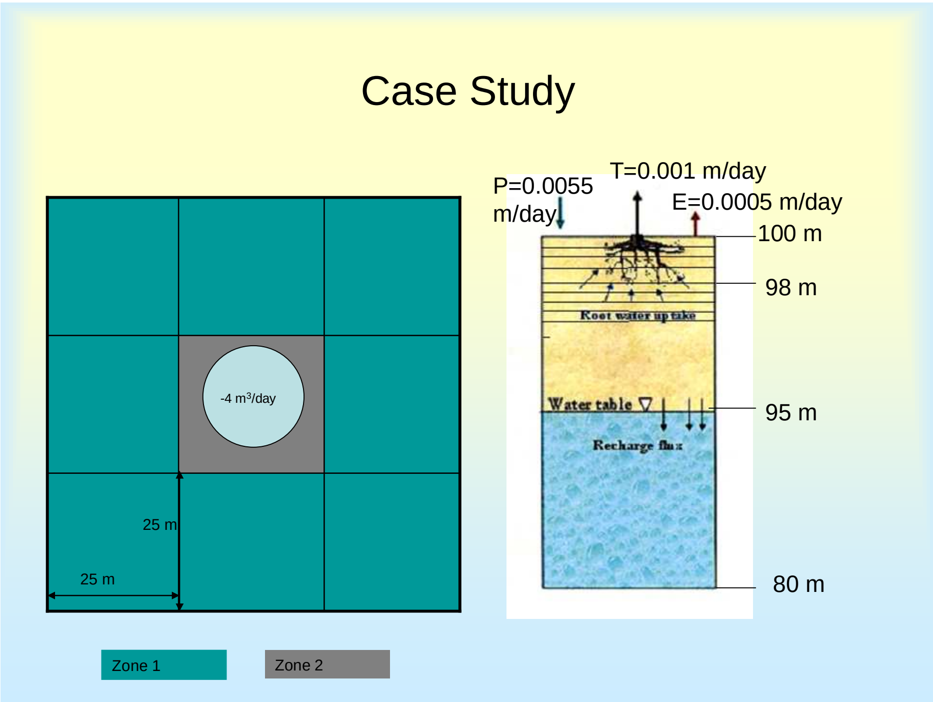
Kansas Geological Survey

Recent MODFLOW developments for groundwater modeling

Ashok KC and Marios Sophocleous



Kansas Geological Survey Open-file Report 2009-4
December 2008

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INTRODUCTION

The purpose of this report is to test and evaluate a number of recent improvements and additions that have been made to the standard U.S. Geological Survey MODFLOW ground-water flow model since 2000. Thus, two new streamflow packages, SFR1 and SFR2 were compared against the original streamflow package STR. The new ground-water evapotranspiration package ETS1 was compared against the original EVT package. The unsaturated flow packages UZF1, HYDRUS, and MODFLOW-HYDRUS were also evaluated. Finally, the conduit flow package (CFP) was also tested and evaluated. Major advantages and disadvantages of some of these packages were pointed out.

1.1 Example case description: A test case (figure 1.1) was simulated using three different versions of Modflow's stream package; STR, SFR1, and SFR2. The differences in inputs and the outputs are shown in the respective sections.

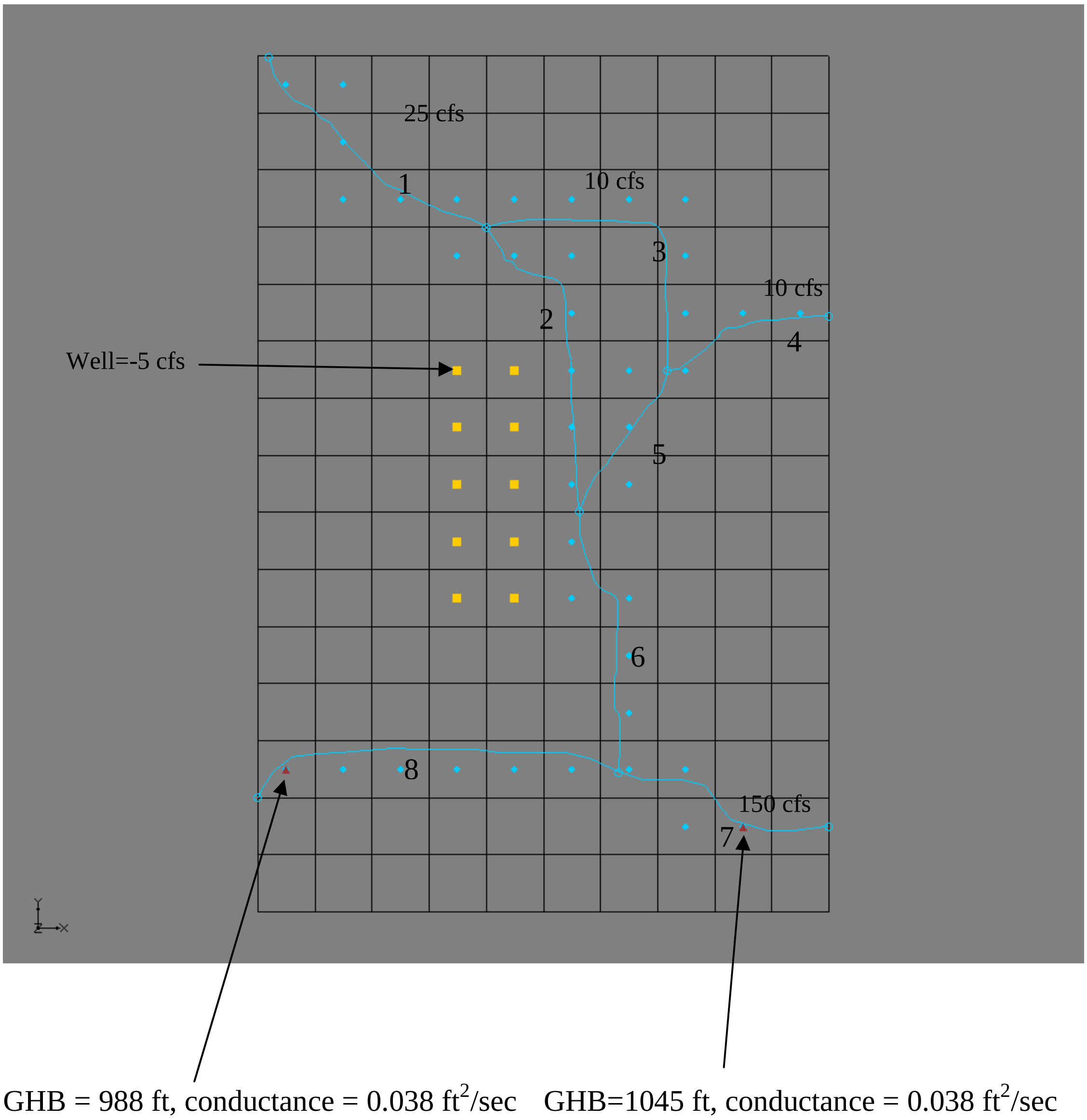


Figure 1.1

The total area was divided into 15 (rows)*10 (columns) cells, figure 1.2. The size of each cell was assigned as 5000 ft *5000 ft. Only one layer was considered in the simulation. The other common properties for the test case are as shown below:

<u>Boundary Condition</u>

1	2	3	4	5	6	7	8	9	10	
1	1	0	0	0	0	0	0	0	0	1
1	1	1	0	0	1	1	1	0	0	2
0	1	1	1	1	1	1	1	0	0	3
1	1	1	1	1	1	1	1	1	0	4
1	1	1	1	1	1	1	1	1	1	5
1	1	1	1	1	1	1	1	1	1	6
1	1	1	1	1	1	1	1	1	0	7
0	1	1	1	1	1	1	1	1	0	8
0	1	1	1	1	1	1	1	1	0	9
0	1	1	1	1	1	1	1	1	1	10
0	1	1	1	1	1	1	1	1	0	11
1	1	1	1	1	1	1	1	1	0	12
1	1	1	1	1	1	1	1	1	0	13
0	1	1	1	1	1	1	1	1	0	14
0	0	1	1	1	1	0	0	0	0	15

(0=Inactive cells, 1=active cells)

Figure 1.2

Initial Starting head (ft)

1090	1086.114	6999	6999	6999	6999	6999	6999	6999	6999
1089.9	1086.074	1081.4	6999	6999	1072.3	1071.5	1071.1	6999	6999
6999	1079.4	1077.5	1070	1069.984	1067.269	1064.554	1062.11	6999	6999
1069.1	1070.7	1070.2	1067	1065.5	1063.6	1063.9	1062.059	1066.1	6999
1064.9	1063.9	1062.9	1061.5	1060.8	1060.8	1060.2	1058.801	1065.7	1068.1
1059.8	1058.3	1057.2	1056.4	1056.3	1056.9	1051.043	1055	1061.9	1065.6
1056.1	1053	1051.7	1051.2	1051.3	1051.9	1050.881	1055.5	1056.5	6999
6999	1046.3	1045.7	1045.5	1045.8	1040	1045.935	1049.9	1050.4	6999
6999	1039.1	1039.1	1039.5	1040	1039.889	1041.6	1042.9	1044	6999
6999	1031.1	1031.8	1033.3	1034.3	1035.4	1035.455	1037.6	1039.3	1041.6
6999	1021.4	1023.1	1026.8	1028.7	1030.5	1030.909	1033.6	1035.7	6999
1001.2	1009.2	1014.5	1019.6	1023.1	1026.2	1026.364	1030.4	1034.3	6999
985	995	1001.25	1007.5	1013.65	1017.863	1020	1030.131	1036.1	6999
6999	1004	1009	1013.7	1018.9	1024	1029.5	1030.176	1035	6999
6999	6999	1011.9	1015.1	1019.1	1022.4	6999	6999	6999	6999

(Pink cells are the inactive cells, 6999 is the head assigned to them)

Figure 1.3.a

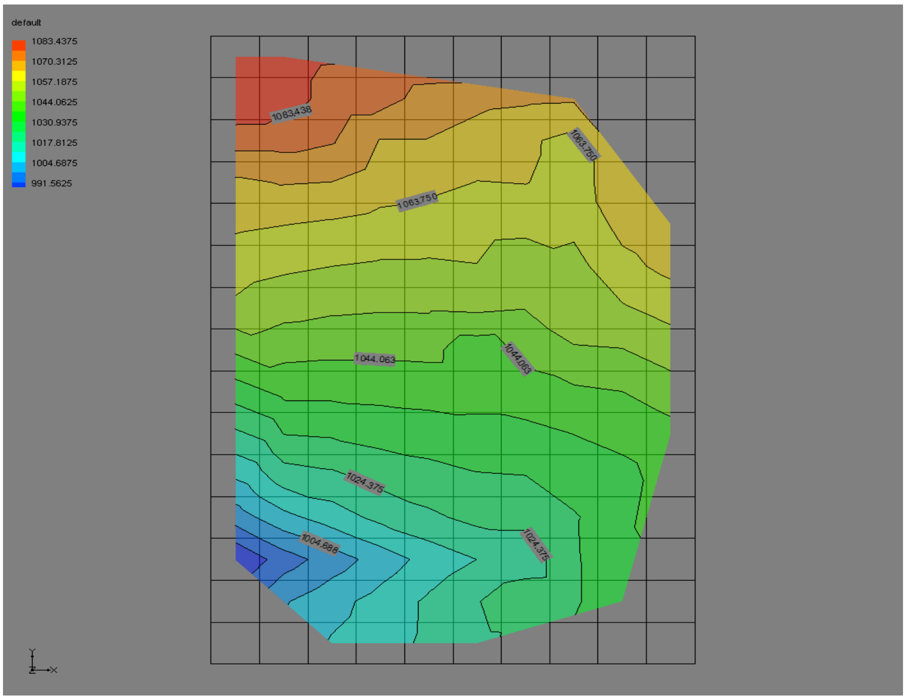


Figure 1.3.b. Contour of Initial Starting head

Top Elevations of Models cells (ft)

1105	1105	0	0	0	0	0	0	0	0
1105	1095	1105	0	0	1100	1100	1110	0	0
0	1100	1085	1080	1078	1076	1073	1090	0	0
1110	1100	1090	1085	1076	1080	1080	1070	1100	0
1110	1100	1085	1080	1078	1074	1077	1066	1075	1080
1105	1095	1080	1077	1073	1069	1070	1063	1085	1095
1105	1090	1075	1072	1070	1065	1065	1069	1090	0
0	1080	1070	1068	1063	1060	1063	1067	1090	0
0	1075	1065	1062	1058	1052	1055	1065	1090	0
0	1070	1060	1055	1046	1046	1044	1060	1088	1100
0	1055	1050	1045	1041	1042	1040	1050	1075	0
1027	1028	1028	1032	1032	1033	1032	1040	1060	0
997	1004	1008	1014	1020	1027	1032	1038	1050	0
0	1030	1040	1045	1050	1050	1050	1050	1044	0
0	0	1080	1080	1080	1080	0	0	0	0

Figure 1.4.a

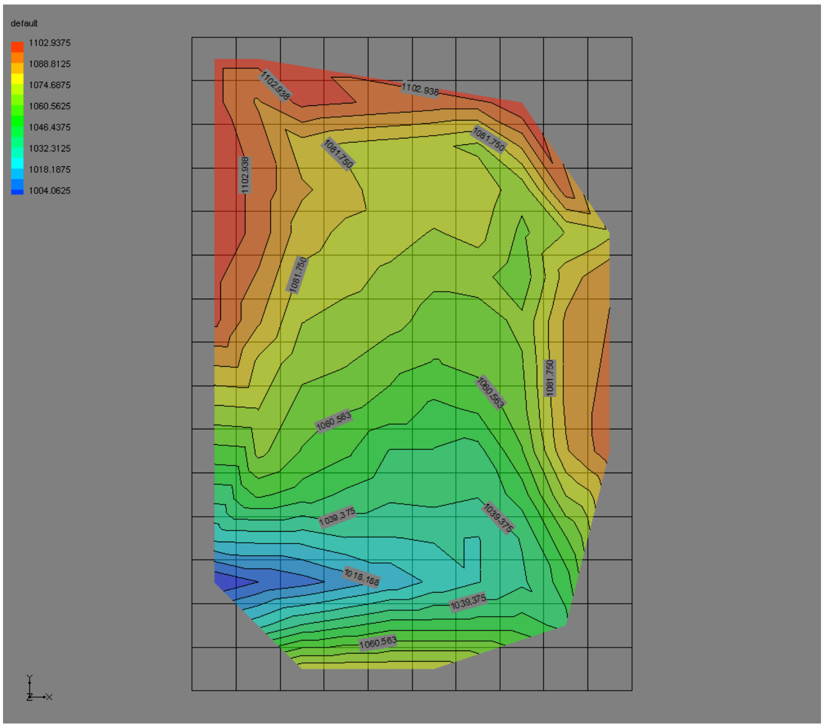


Figure 1.4.b. Contour of Top Elevations of Model cells

Bottom Elevations of Model cells (ft)

1000	1000	0	0	0	0	0	0	0	0
1000	900	900	0	0	950	950	950	0	0
0	850	670	680	680	770	770	890	0	0
925	850	650	650	650	680	740	850	950	0
925	800	650	600	600	600	650	720	850	950
925	800	650	600	550	600	650	720	850	970
925	800	650	600	550	600	650	720	950	0
0	850	700	650	570	600	700	850	950	0
0	850	700	650	540	580	700	850	950	0
0	850	700	630	530	580	650	800	900	950
0	850	700	620	580	620	700	800	900	0
900	830	710	640	600	650	700	800	900	0
900	810	750	700	650	700	750	800	900	0
0	950	850	850	850	850	850	850	850	0
0	0	950	950	950	950	0	0	0	0

Figure 1.5

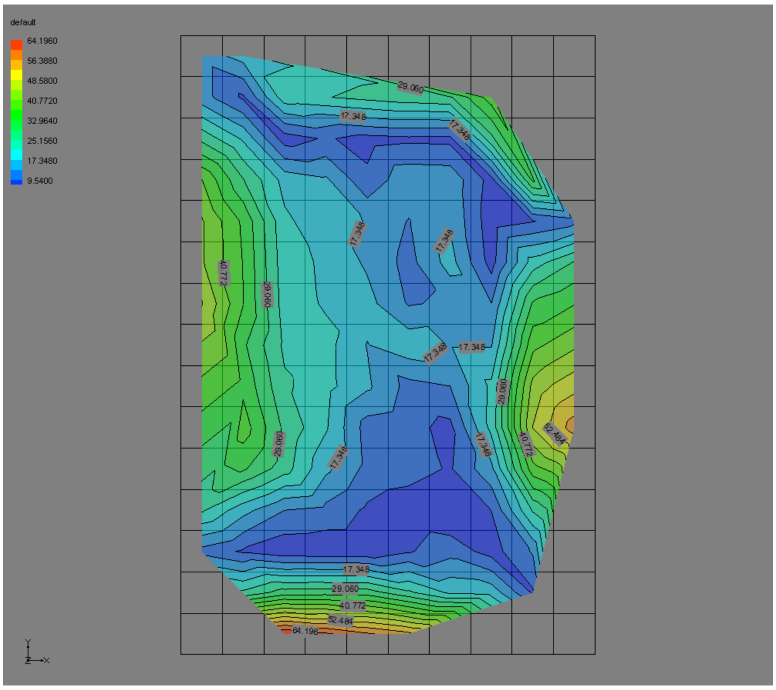


Figure 1.6. Contour of thickness of Unsaturated zone (Difference of top elevations and Initial Heads)

Evapotranspiration Surface Elevations for Model cells

1110	1110	0	0	0	0	0	0	0	0
1110	1105	1110	0	0	1100	1100	1110	0	0
0	1100	1095	1088	1085	1085	1085	1090	0	0
1105	1100	1090	1083	1078	1075	1080	1085	1100	0
1105	1090	1080	1077	1074	1073	1074	1078	1080	1085
1100	1080	1075	1072	1071	1069	1070	1075	1080	1100
1100	1080	1070	1065	1065	1065	1065	1070	1090	0
0	1075	1065	1059	1059	1058	1063	1070	1090	0
0	1065	1055	1053	1053	1052	1055	1065	1090	0
0	1060	1046	1046	1046	1046	1044	1060	1088	1100
0	1045	1039	1040	1041	1042	1040	1050	1075	0
1027	1028	1028	1032	1032	1033	1032	1040	1060	0
997	1004	1008	1014	1020	1027	1032	1038	1050	0
0	1030	1040	1045	1050	1050	1050	1050	1044	0
0	0	1080	1080	1080	1080	0	0	0	0

Figure 1.7

(Note: The ET surface used in USGS example case is slightly different than the top surface elevation shown previously)

Evapotranspiration rate=9.5e-08 ft/sec

Extinction depth=15 feet

Recharge rate (ft/sec)

2.50E-10	1.00E-09	0	0	0	0	0	0	0	0
1.00E-09	2.50E-10	1.00E-09	0	0	4.00E-09	4.00E-09	4.00E-09	0	0
0	1.00E-09	2.50E-10	1.00E-09	1.00E-09	2.50E-10	2.50E-10	2.50E-10	0	0
4.00E-09	2.50E-10	2.50E-10	2.50E-10	2.50E-10	2.50E-10	2.50E-10	2.50E-10	1.00E-09	0
4.00E-09	2.50E-10	2.50E-10	2.50E-10	2.50E-10	2.50E-10	2.50E-10	2.50E-10	2.50E-10	2.50E-10
1.00E-09	2.50E-10	2.50E-10	2.50E-10	2.50E-10	2.50E-10	2.50E-10	2.50E-10	2.50E-10	1.00E-09
1.00E-09	2.50E-10	2.50E-10	2.50E-10	2.50E-10	2.50E-10	2.50E-10	2.50E-10	1.00E-09	0
0	1.00E-09	2.50E-10	2.50E-10	2.50E-10	2.50E-10	2.50E-10	2.50E-10	1.00E-09	0
0	1.00E-09	2.50E-10	2.50E-10	2.50E-10	2.50E-10	2.50E-10	2.50E-10	1.00E-09	0
0	1.00E-09	2.50E-10	2.50E-10	2.50E-10	2.50E-10	2.50E-10	2.50E-10	2.50E-10	4.00E-09
0	1.00E-09	2.50E-10	2.50E-10	2.50E-10	2.50E-10	2.50E-10	2.50E-10	1.00E-09	0
1.00E-09	2.50E-10	2.50E-10	2.50E-10	2.50E-10	2.50E-10	2.50E-10	2.50E-10	1.00E-09	0
2.50E-10	2.50E-10	2.50E-10	2.50E-10	2.50E-10	2.50E-10	2.50E-10	2.50E-10	1.00E-09	0
0	2.50E-10	2.50E-10	2.50E-10	2.50E-10	2.50E-10	1.00E-09	1.00E-09	2.50E-10	0
0	0	1.00E-09	1.00E-09	1.00E-09	1.00E-09	0	0	0	0

Figure 1.8

(2.5E-10ft/sec=0.095 inches/year, 1.0E-9ft/sec=0.38 inches/year, 4.0E-09 ft/sec=1.5 inches/year)

Pumping

10 wells pumping at -5.0 cfs for the first stress period as shown in figure 1.1. Pumping was shut down in the second stress period.

Hydraulic Conductivity of the model cells (ft/sec)

0.002	0.002	0	0	0	0	0	0	0	0
0.0004	0.002	0.002	0	0	0.0004	0.0004	0.0004	0	0
0	0.0004	0.002	0.002	0.0004	0.0004	0.0004	0.0004	0	0
0.0004	0.0004	0.0004	0.002	0.002	0.002	0.0004	0.0004	0.0004	0
0.0004	0.0004	0.0004	0.002	0.002	0.002	0.002	0.002	0.002	0.002
0.0004	0.0004	0.0004	0.002	0.002	0.002	0.002	0.002	0.0004	0.0004
0.0004	0.0004	0.0004	0.002	0.002	0.002	0.002	0.002	0.0004	0
0	0.0004	0.0004	0.002	0.002	0.002	0.002	0.0004	0.0004	0
0	0.0004	0.0004	0.002	0.002	0.002	0.002	0.0004	0.0004	0
0	0.0004	0.0004	0.002	0.002	0.002	0.002	0.0004	0.0004	0.0004
0	0.0004	0.0004	0.002	0.002	0.002	0.002	0.0004	0.0004	0
0.0004	0.0004	0.002	0.002	0.002	0.002	0.002	0.0004	0.0004	0
0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0
0	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.002	0
0	0	0.0004	0.0004	0.0004	0.0004	0	0	0	0

Figure 1.9

(0.002 ft/sec=172.8 ft/day, 0.0004 ft/sec=34.56 ft/day)

Specific yield of the model cells

0.2	0.2	0	0	0	0	0	0	0	0
0.1	0.2	0.2	0	0	0.1	0.1	0.1	0	0
0	0.1	0.2	0.2	0.1	0.1	0.1	0.1	0	0
0.1	0.1	0.1	0.2	0.2	0.2	0.1	0.1	0.1	0
0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2
0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.1	0.1
0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.1	0
0	0.1	0.1	0.2	0.2	0.2	0.2	0.1	0.1	0
0	0.1	0.1	0.2	0.2	0.2	0.2	0.1	0.1	0
0	0.1	0.1	0.2	0.2	0.2	0.2	0.1	0.1	0.1
0	0.1	0.1	0.2	0.2	0.2	0.2	0.1	0.1	0
0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0
0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0
0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0
0	0	0.1	0.1	0.1	0.1	0	0	0	0

Figure 1.10

No of stress periods=2

Length of each stress period=1577880000 sec=50 years

No of time steps=50

Δt=1 year

1.2 STR package: This version of stream flow routing package simulates streams with rectangular cross sections only. Input to Stream flow-Routing (STR) package is read from the file that has file type 'STR' in the MODFLOW Name file (Figure 1.11). The data required in this package in order to simulate STR with MODFLOW 2000 are: number of stream segments, number of stream reaches, number of stream tributaries that can connect to one segment, constant value (1.486 for flow in cfs, 1.0 for flow in m3/sec, and constant must be multiplied by 86400 if using time units of days in the simulation), stream bed hydraulic conductance (stream bed hydraulic conductivity*reach length/thickness of stream bed), elevations of top and bottom of stream bed, stream width, slope, Manning' s roughness coefficients and flow in the stream segments.

The model calculates stream depth at the beginning of each reach. The stream bed top and bottom elevations are specified for each reach. This STR version does not account for addition of water along the reach due to precipitation and overland runoff and removal of water from evapotranspiration along the reach. This version also does not simulate unsaturated flow either beneath the stream or between land surface and water table.

1.2.1 Stream properties

seg	reach	Q inflow cfs	bot elevn, ft	top elevn, ft	Width, ft	slope	rough	bed thickness, ft	reach length, ft	segment length, ft	K, ft/sec	reach conductance, ft^2/sec
1	1	25	1092	1095	13	0.000863	0.03	3	4500	23162	0.00003	0.585
1	2	25	1088.114	1091.114	13	0.000863	0.03	3	47		0.00003	0.00611
1	3	25	1088.074	1091.074	13	0.000863	0.03	3	7000		0.00003	0.91
1	4	25	1082.029	1085.029	13	0.000863	0.03	3	65		0.00003	0.00845
1	5	25	1081.973	1084.973	13	0.000863	0.03	3	6000		0.00003	0.78
1	6	25	1072	1075	13	0.000863	0.03	3	5550		0.00003	0.7215
2	1	-	1072	1075	12	0.000941	0.03	3	12	26554	0.00003	0.00144
2	2	-	1071.989	1074.989	12	0.000941	0.03	3	42		0.00003	0.00504
2	3	-	1071.949	1074.949	12	0.000941	0.03	3	4760		0.00003	0.5712
2	4	-	1067.468	1070.468	12	0.000941	0.03	3	1740		0.00003	0.2088
2	5	-	1065.83	1068.83	12	0.000941	0.03	3	5000		0.00003	0.6
2	6	-	1061.122	1064.122	12	0.000941	0.03	3	5000		0.00003	0.6
2	7	-	1056.415	1059.415	12	0.000941	0.03	3	5000		0.00003	0.6
2	8	-	1047	1050	12	0.000941	0.03	3	5000		0.00003	0.6
3	1	-10	1072	1075	10	0.000543	0.03	3	30	27624	0.00003	0.003
3	2	-10	1071.984	1074.984	10	0.000543	0.03	3	5000		0.00003	0.5
3	3	-10	1069.269	1072.269	10	0.000543	0.03	3	5000		0.00003	0.5
3	4	-10	1066.554	1069.554	10	0.000543	0.03	3	4500		0.00003	0.45
3	5	-10	1064.11	1067.11	10	0.000543	0.03	3	94		0.00003	0.0094
3	6	-10	1064.059	1067.059	10	0.000543	0.03	3	6000		0.00003	0.6
3	7	-10	1060.801	1063.801	10	0.000543	0.03	3	5000		0.00003	0.5
3	8	-10	1057	1060	10	0.000543	0.03	3	2000		0.00003	0.2
4	1	10	1077	1080	10	0.001805	0.03	3	2500	11083.4	0.00003	0.25
4	2	10	1072.489	1075.489	10	0.001805	0.03	3	5000		0.00003	0.5
4	3	10	1063.466	1066.466	10	0.001805	0.03	3	83.4		0.00003	0.00834
4	4	10	1057	1060	10	0.001805	0.03	3	3500		0.00003	0.35
5	1	-	1057	1060	10	0.000989	0.03	3	4000	15164	0.00003	0.4
5	2	-	1053.043	1056.043	10	0.000989	0.03	3	164		0.00003	0.0164
5	3	-	1052.881	1055.881	10	0.000989	0.03	3	5000		0.00003	0.5
5	4	-	1047.935	1050.935	10	0.000989	0.03	3	3500		0.00003	0.35
5	5	-	1042	1045	10	0.000989	0.03	3	2500		0.00003	0.25
6	1	-	1042	1045	12	0.000909	0.03	3	122	22000	0.00003	0.01464
6	2	-	1041.889	1044.889	12	0.000909	0.03	3	3040		0.00003	0.3648
6	3	-	1039.125	1042.125	12	0.000909	0.03	3	1838		0.00003	0.22056
6	4	-	1037.455	1040.455	12	0.000909	0.03	3	5000		0.00003	0.6
6	5	-	1032.909	1035.909	12	0.000909	0.03	3	5000		0.00003	0.6
6	6	-	1028.364	1031.364	12	0.000909	0.03	3	5000		0.00003	0.6
6	7	-	1022	1025	12	0.000909	0.03	3	2000		0.00003	0.24
7	1	150	1037	1040	50	0.000965	0.025	3	5000	15546	0.00006	5

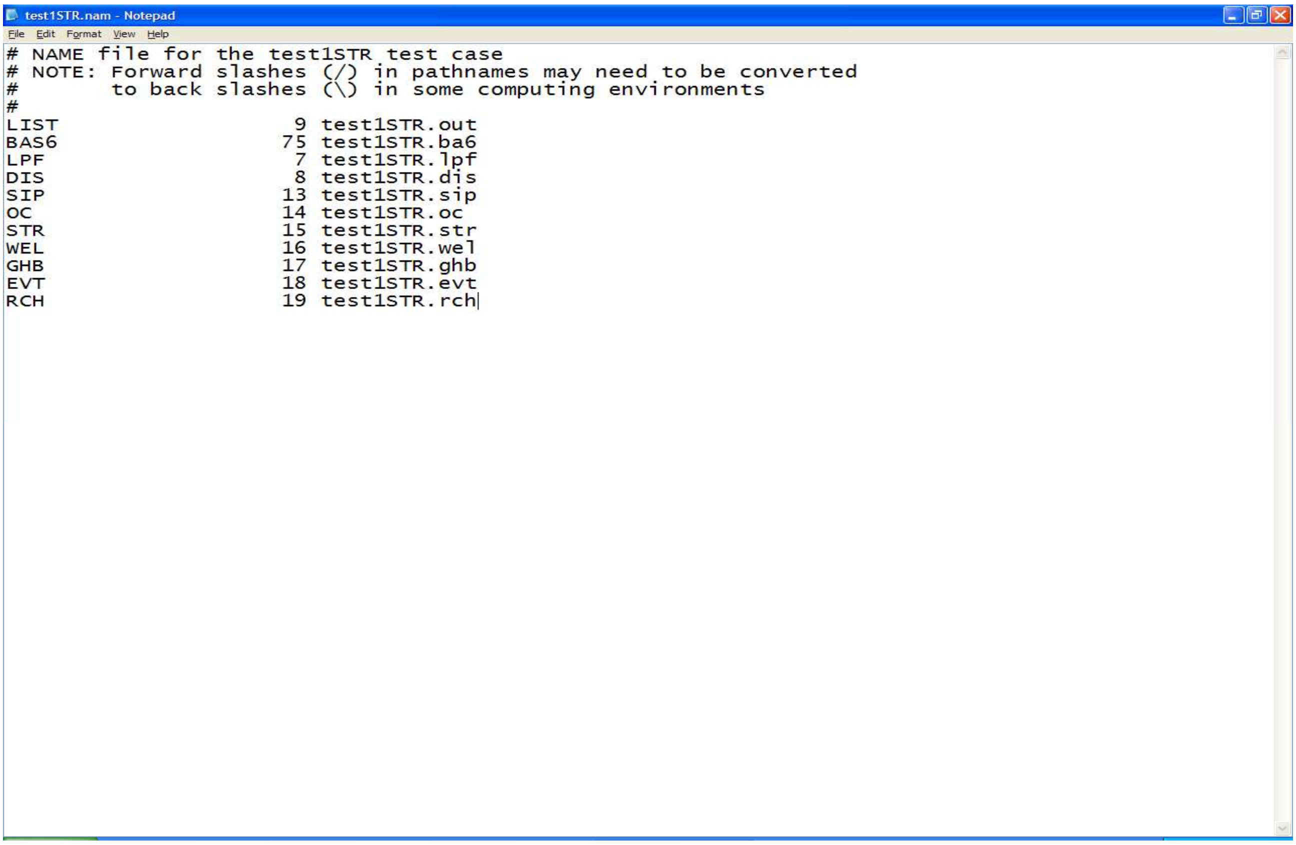
7	2	150	1032.176	1035.176	50	0.000965	0.025	3	46		0.00006	0.046
7	3	150	1032.131	1035.131	50	0.000965	0.025	3	5500		0.00006	5.5
7	4	150	1022	1025	50	0.000965	0.025	3	5000		0.00006	5
8	1	-	1022	1025	50	0.00125	0.025	3	1710	28000	0.00006	1.71
8	2	-	1019.863	1022.863	50	0.00125	0.025	3	3290		0.00006	3.29
8	3	-	1015.75	1018.75	50	0.00125	0.025	3	5000		0.00006	5
8	4	-	1009.5	1012.5	50	0.00125	0.025	3	5000		0.00006	5
8	5	-	1003.25	1006.25	50	0.00125	0.025	3	5000		0.00006	5
8	6	-	997	1000	50	0.00125	0.025	3	5000		0.00006	5
8	7	-	987	990	50	0.00125	0.025	3	3000		0.00006	3

(-10 cfs in segment 3 is the flow diverted from segment 1)

Table 1.1

1.2.2 MODFLOW Execution:

A name file was created listing all of the input files and output file as shown in Figure 1.11. This version ran successfully using both MODFLOW 2000 and MODFLOW 2005 executable programs.




```
# NAME file for the test1STR test case
# NOTE: Forward slashes (/) in pathnames may need to be converted
#        to back slashes (\) in some computing environments
#
LIST                     9 test1STR.out
BAS6                    75 test1STR.ba6
LPF                      7 test1STR.lpf
DIS                      8 test1STR.dis
SIP                     13 test1STR.sip
OC                      14 test1STR.oc
STR                     15 test1STR.str
WEL                     16 test1STR.wel
GHB                     17 test1STR.ghb
EVT                     18 test1STR.evt
RCH                     19 test1STR.rch
```

Figure 1.11

1.2.3 Output from simulation

An output file will be created after the simulation with the name of output file as specified in the Name file. Depending upon the options specified in the output control file, the volumetric budget of the entire model, heads, and drawdown will be printed at desired time steps and stress periods in this output file. A sample of output file is as shown below.

HEAD IN LAYER 1 AT END OF TIME STEP 50 IN STRESS PERIOD 1

	1	2	3	4	5	6	7	8	9	10
1	1091	1080	6999	6999	6999	6999	6999	6999	6999	6999
2	1081	1071	1058	6999	6999	1044	1046	1046	6999	6999
3	6999	1055	1049	1042	1040	1041	1045	1044	6999	6999
4	1036	1039	1037	1032	1030	1029	1033	1041	1038	6999
5	1029	1028	1025	1022	1022	1024	1027	1031	1036	1039
6	1022	1019	1016	1013	1014	1019	1023	1028	1031	1036
7	1017	1013	1009	1006	1009	1014	1019	1023	1026	6999
8	6999	1008	1005	1002	1005	1011	1015	1019	1021	6999
9	6999	1005	1003	1001	1004	1009	1012	1015	1019	6999
10	6999	1005	1004	1003	1005	1010	1012	1016	1019	1022
11	6999	1006	1007	1008	1010	1013	1015	1019	1023	6999
12	997.1	1004	1008	1011	1014	1017	1019	1026	1030	6999
13	991.4	1001	1007	1013	1018	1022	1026	1035	1037	6999
14	6999	1005	1009	1014	1018	1023	1028	1036	1041	6999
15	6999	6999	1012	1015	1019	1021	6999	6999	6999	6999

DRAWDOWN IN LAYER 1 AT END OF TIME STEP 50 IN STRESS PERIOD 1

	1	2	3	4	5	6	7	8	9	10
1	-0.8636	6.369	6999	6999	6999	6999	6999	6999	6999	6999
2	9.174	15.31	23.27	6999	6999	28.03	25.75	25.02	6999	6999
3	6999	24.53	28.76	28.28	29.93	25.93	19.93	18.05	6999	6999
4	33.31	31.85	33.14	35.36	35.87	34.24	30.8	20.74	27.62	6999
5	35.59	36.21	37.67	39.08	38.36	36.49	33.67	27.69	29.85	29.01
6	37.79	38.99	41.26	43.73	42.15	38.08	28.12	27.42	30.55	29.67
7	38.87	39.91	42.28	44.97	42.75	37.62	31.57	32.52	30.97	6999
8	6999	38.32	40.61	43.34	40.82	29.02	30.94	31.34	29.41	6999
9	6999	33.68	35.78	38.61	36.22	30.57	29.28	27.51	25.38	6999
10	6999	25.98	27.6	30.64	29.15	25.64	22.99	21.93	19.83	19.25
11	6999	15.8	16.1	19.06	18.91	17.81	15.89	14.81	13.15	6999
12	4.094	5.319	6.048	8.789	9.2	9.354	7.005	4.765	4.645	6999
13	-6.44	-5.89	-5.928	-5.471	-4.846	-4.402	-5.85	-4.941	-0.4052	6999
14	6999	-0.6706	-0.2795	3.36E-2	0.5333	1.472	1.812	-5.332	-5.608	6999
15	6999	6999	-0.1415	0.1626	0.5783	1.143	6999	6999	6999	6999

```
 VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP 50 IN STRESS PERIOD   1
  ---------------------------------------------------------------------------

     CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
     ------------------                 ------------------------

           IN:                                      IN:
           ---                                      ---
             STORAGE =  9930354688.0000               STORAGE =          0.7220
       CONSTANT HEAD =           0.0000         CONSTANT HEAD =          0.0000
               WELLS =           0.0000                 WELLS =          0.0000
                  ET =           0.0000                    ET =          0.0000
     HEAD DEP BOUNDS =   263135568.0000       HEAD DEP BOUNDS =          0.1669
            RECHARGE =  2830322944.0000              RECHARGE =          1.7937
      STREAM LEAKAGE = 97924923392.0000        STREAM LEAKAGE =         66.2679

            TOTAL IN =110948737024.0000              TOTAL IN =         68.9505

          OUT:                                     OUT:
          ----                                     ----
             STORAGE =   438921344.0000               STORAGE =          0.0000
       CONSTANT HEAD =           0.0000         CONSTANT HEAD =          0.0000
               WELLS = 78894014464.0000                 WELLS =         50.0000
                  ET = 28980064256.0000                    ET =         17.5396
     HEAD DEP BOUNDS =   208015184.0000       HEAD DEP BOUNDS =          0.1307
            RECHARGE =           0.0000              RECHARGE =          0.0000
      STREAM LEAKAGE =  2433737984.0000        STREAM LEAKAGE =          1.2847

           TOTAL OUT =110954749952.0000             TOTAL OUT =         68.9550

            IN - OUT =    -6012928.0000              IN - OUT =     -4.5166E-03

 PERCENT DISCREPANCY =          -0.01     PERCENT DISCREPANCY =          -0.01
```

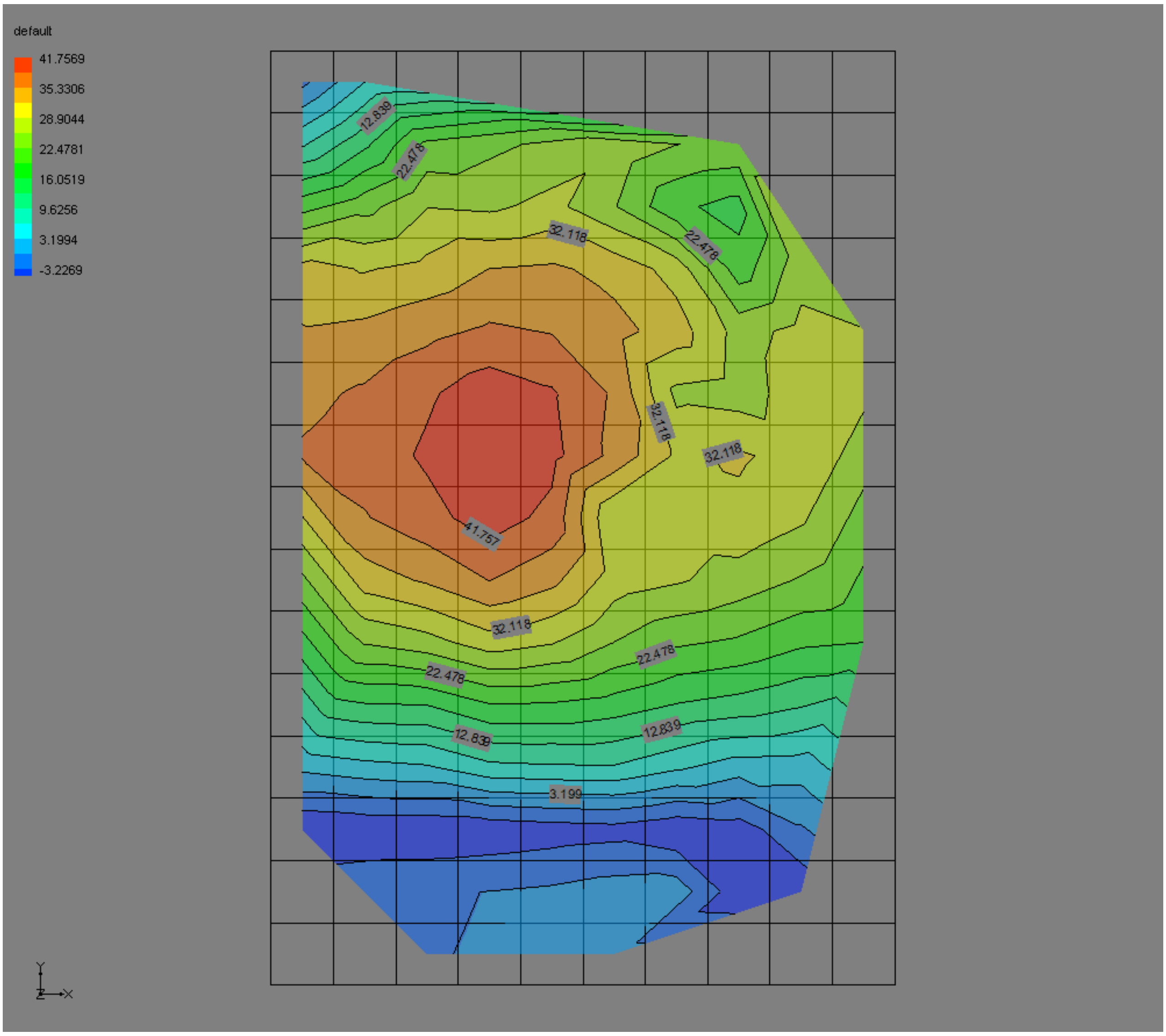


Figure 1.12 Contours of drawdown (ft) at time step 50, stress period 1

1.3 SFR1 Package: The SFR1 package simulates stream aquifer interaction with MODFLOW 2000. Detailed description of this package can be found in USGS open file report 2004-1042-‘ A New Streamflow-Routing (SFR1) package to simulate Stream-Aquifer Interaction with MODFLOW 2000’ by Prudic and others. Stream flow routing is activated by including a record in the Modflow Name file (Figure 1.13) using file type (Ftype) ‘SFR’ to indicate that relevant calculations are to be made in the model, and to specify the related input data files (Prudic and others, 2004).

SFR1 package replaces STR1 package by computing stream depth in the middle of each reach instead at the beginning of each reach as is done in the STR1 package. Contrary to STR1 package, which uses only rectangular cross section to calculate stream depth, SFR1 package uses five options to calculate stream depth. The methods are specified by using ICALC=0, 1, 2, 3, 4. The description using each of the methods can be found in the USGS Open File Report 2004-1042 by Prudic and others. Eventually, different sets of input data are required if using different values of ICALC to calculate stream depths. The other difference of SFR1 with STR1 is that in SFR1 package elevation of top of stream bed is specified for the first reach and last reach of each segment whereas in STR1 package top and bottom elevation of stream bed is specified for each reach of a segment. One of the advantages using SFR1 over STR1 is that, SFR1 allows for addition of water along the reach from precipitation and overland flow and removal of water from evapotranspiration along the reach. The data required in this package in order to simulate SFR1 with MODFLOW 2000 are: number of stream segments, number of stream reaches, constant Value (1.486, 1 or 0: 1.486 for flow in cfs and if using Manning's equation, 1 for flow in m^3/sec and if using Manning's equation, 0 if Manning's equation is not used, i.e. if ICALC is not equal to 1 or 2), length of stream reach, flow, roughness constant, thickness of stream bed material, width of stream, elevation of top of stream bed. Also depending upon the method used to calculate stream depth (ICALC=0,1,2,3,4), other input data are required. This package does not simulate unsaturated flow either beneath the stream or between land surface and water table. Cells of model grid can be assigned as 'stream gaging station' locations. At each such cell or (stream reach), the time, stage, streamflow out of that reach will be written to a separate output file to facilitate model output evaluation and graphical post processing of the calculated data. The input file for specifying gaging station location is read if file type (Ftype) "GAGE" is included in the MODFLOW name file. If the LAK3 package is also active, a gaging station may be placed on a lake (Prudic and others, 2004).

The stream used in our example (Figure 1.1) was assumed to have a rectangular cross section. So ICALC was set equal to 1.

1.3.1 Stream Properties: The required stream properties input data and flow patterns of the stream are as shown in Table 1.1 of section 1.2.1, and Figure 1.1, respectively.

<u>1.3.2 MODFLOW Execution:</u> A Name file (Figure 1.13) was created listing all of the input files and output file. Also gaging stations were set in every stream segment following the procedure described in Open File Report 2004-1042, page 52, by Prudic and others. This version ran successfully using both MODFLOW 2000 and MODFLOW 2005 executable programs.

test1sfr1.nam - Notepad

File Edit Format View Help

```
# NAME file for the test1SFR1 test case
# NOTE: Forward slashes (/) in pathnames may need to be converted
#       to back slashes (\) in some computing environments
#
LIST                     9 test1sfr1.out          OUTPUT FILE
BAS6                    75 test1sfr1.ba6          INPUT  FILE
LPF                      7 test1sfr1.lpf          INPUT  FILE
DIS                      8 test1sfr1.dis          INPUT  FILE
SIP                     13 test1sfr1.sip          INPUT  FILE
OC                      14 test1sfr1.oc           INPUT  FILE
SFR                     15 test1sfr1.sfr          INPUT  FILE
WEL                     16 test1sfr1.wel          INPUT  FILE
GHB                     17 test1sfr1.ghb          INPUT  FILE
EVT                     18 test1sfr1.evt          INPUT  FILE
RCH                     19 test1sfr1.rch          INPUT  FILE
GAGE                    32 test1sfr1.gag          INPUT  FILE
DATA                    83 test1sfr1.sg1          OUTPUT FILE
DATA                    84 test1sfr1.sg2          OUTPUT FILE
DATA                    85 test1sfr1.sg3          OUTPUT FILE
DATA                    86 test1sfr1.sg4          OUTPUT FILE
DATA                    87 test1sfr1.sg5          OUTPUT FILE
DATA                    88 test1sfr1.sg6          OUTPUT FILE
DATA                    89 test1sfr1.sg7          OUTPUT FILE
DATA                    90 test1sfr1.sg8          OUTPUT FILE
DATA                    91 test1sfr1.dvsg3        OUTPUT FILE
```

Figure 1.13

*(For output files *.sg1, sg2, dvsge e.t.c file type should be listed as 'DATA' type, so that they could be readable when they are created, otherwise they will be printed in Binary format)*

<u>1.3.3 Output From Simulation</u>: A MODFLOW output file will be created after the simulation with the name of output file as specified in name file. Depending upon the options specified in the output control file, the volumetric budget of entire model, heads, and drawdown will be printed at desired time steps and stress periods in this output file. A sample of output file is as shown below. Also gage output files are created for each segment.

STREAM LISTING PERIOD 1 STEP 50

LAYER	ROW	COL.	STREAM SEG.NO.	RCH. NO.	FLOW INTO STRM. RCH.	FLOW TO AQUIFER	FLOW OUT OF STRM. RCH.	OVRLND. RUNOFF	DIRECT PRECIP	STREAM ET	STREAM HEAD	STREAM DEPTH	STREAM WIDTH	STREAMBED CONDCTNC.	STREAMBED GRADIENT
1	1	1	1	1	25.000	2.426	22.574	0.000	0.000	0.000	1094.200	1.147	13.000	0.585	1.382
1	1	2	1	2	22.574	0.025	22.549	0.000	0.000	0.000	1092.210	1.111	13.000	0.006	1.370
1	2	2	1	3	22.549	3.690	18.858	0.000	0.000	0.000	1089.110	1.055	13.000	0.910	1.352
1	3	2	1	4	18.858	0.034	18.825	0.000	0.000	0.000	1086.000	0.997	13.000	0.008	1.332
1	3	3	1	5	18.825	3.079	15.746	0.000	0.000	0.000	1083.330	0.947	13.000	0.780	1.316
1	3	4	1	6	15.746	2.776	12.970	0.000	0.000	0.000	1078.240	0.847	13.000	0.722	1.282
1	3	4	2	1	2.970	0.005	2.965	0.000	0.000	0.000	1075.330	0.336	12.000	0.001	1.112
1	4	4	2	2	2.965	0.017	2.948	0.000	0.000	0.000	1075.300	0.336	12.000	0.005	1.112
1	4	5	2	3	2.948	1.866	1.082	0.000	0.000	0.000	1072.980	0.267	12.000	0.571	1.089
1	4	6	2	4	1.082	0.657	0.425	0.000	0.000	0.000	1069.800	0.148	12.000	0.209	1.049
1	5	6	2	5	0.425	0.425	0.000	0.000	0.000	0.000	1066.500	0.000	12.000	0.600	1.008
1	6	6	2	6	0.000	0.000	0.000	0.000	0.000	0.000	1061.770	0.000	12.000	0.600	1.000
1	7	6	2	7	0.000	0.000	0.000	0.000	0.000	0.000	1057.060	0.000	12.000	0.600	1.000
1	8	6	2	8	0.000	0.000	0.000	0.000	0.000	0.000	1052.350	0.000	12.000	0.600	1.000
1	3	4	3	1	10.000	0.012	9.988	0.000	0.000	0.000	1075.910	0.917	10.000	0.003	1.306
1	3	5	3	2	9.988	1.931	8.057	0.000	0.000	0.000	1074.490	0.863	10.000	0.500	1.288
1	3	6	3	3	8.057	1.874	6.183	0.000	0.000	0.000	1071.660	0.748	10.000	0.500	1.249
1	3	7	3	4	6.183	1.634	4.549	0.000	0.000	0.000	1068.960	0.632	10.000	0.450	1.211
1	3	8	3	5	4.549	0.034	4.515	0.000	0.000	0.000	1067.660	0.571	10.000	0.009	1.190
1	4	8	3	6	4.515	2.092	2.423	0.000	0.000	0.000	1065.920	0.486	10.000	0.600	1.162
1	5	8	3	7	2.423	1.653	0.771	0.000	0.000	0.000	1062.750	0.305	10.000	0.500	1.102
1	6	8	3	8	0.771	0.629	0.142	0.000	0.000	0.000	1060.690	0.144	10.000	0.200	1.048

1	5	10	4	1	10.000	0.906	9.094	0.000	0.000	0.000	1078.370	0.622	10.000	0.250	1.207
1	5	9	4	2	9.094	1.784	7.310	0.000	0.000	0.000	1071.550	0.568	10.000	0.500	1.189
1	5	8	4	3	7.310	0.029	7.281	0.000	0.000	0.000	1066.920	0.530	10.000	0.008	1.177
1	6	8	4	4	7.281	1.226	6.055	0.000	0.000	0.000	1063.660	0.502	10.000	0.350	1.167
1	6	8	5	1	6.197	1.414	4.783	0.000	0.000	0.000	1058.560	0.535	10.000	0.400	1.178
1	6	7	5	2	4.783	0.057	4.726	0.000	0.000	0.000	1056.450	0.491	10.000	0.016	1.164
1	7	7	5	3	4.726	1.717	3.009	0.000	0.000	0.000	1053.840	0.434	10.000	0.500	1.144
1	8	7	5	4	3.009	1.165	1.845	0.000	0.000	0.000	1049.530	0.328	10.000	0.350	1.109
1	8	6	5	5	1.845	0.810	1.035	0.000	0.000	0.000	1046.480	0.240	10.000	0.250	1.080
1	8	6	6	1	1.035	0.047	0.988	0.000	0.000	0.000	1045.120	0.178	12.000	0.015	1.059
1	9	6	6	2	0.988	0.988	0.000	0.000	0.000	0.000	1043.550	0.000	12.000	0.365	1.013
1	10	6	6	3	0.000	0.000	0.000	0.000	0.000	0.000	1041.290	0.000	12.000	0.221	1.000
1	10	7	6	4	0.000	0.000	0.000	0.000	0.000	0.000	1038.180	0.000	12.000	0.600	1.000
1	11	7	6	5	0.000	0.000	0.000	0.000	0.000	0.000	1033.640	0.000	12.000	0.600	1.000
1	12	7	6	6	0.000	0.000	0.000	0.000	0.000	0.000	1029.090	0.000	12.000	0.600	1.000
1	13	7	6	7	0.000	-0.194	0.194	0.000	0.000	0.000	1025.910	0.000	12.000	0.240	-0.270
1	14	9	7	1	150.000	2.896	147.100	0.000	0.000	0.000	1038.920	1.330	50.000	5.000	0.193
1	14	8	7	2	147.100	0.108	147.000	0.000	0.000	0.000	1036.480	1.322	50.000	0.046	0.786
1	13	8	7	3	147.000	5.151	141.840	0.000	0.000	0.000	1033.790	1.308	50.000	5.500	0.312
1	13	7	7	4	141.840	9.801	132.040	0.000	0.000	0.000	1028.680	1.267	50.000	5.000	0.653
1	13	7	8	1	132.240	-2.792	135.030	0.000	0.000	0.000	1025.090	1.155	50.000	1.710	-0.544
1	13	6	8	2	135.030	4.599	130.430	0.000	0.000	0.000	1021.960	1.150	50.000	3.290	0.466
1	13	5	8	3	130.430	5.253	125.180	0.000	0.000	0.000	1016.750	1.125	50.000	5.000	0.350
1	13	4	8	4	125.180	2.225	122.950	0.000	0.000	0.000	1010.480	1.105	50.000	5.000	0.148
1	13	3	8	5	122.950	0.036	122.920	0.000	0.000	0.000	1004.220	1.099	50.000	5.000	0.002
1	13	2	8	6	122.920	-0.489	123.410	0.000	0.000	0.000	997.975	1.100	50.000	5.000	-0.033
1	13	1	8	7	123.410	0.343	123.060	0.000	0.000	0.000	992.975	1.100	50.000	3.000	0.038

HEAD IN LAYER 1 AT END OF TIME STEP 50 IN STRESS PERIOD 1

	1	2	3	4	5	6	7	8	9	10
1	1090	1079	6999	6999	6999	6999	6999	6999	6999	6999
2	1080	1069	1057	6999	6999	1043	1044	1045	6999	6999
3	6999	1053	1047	1040	1038	1040	1043	1042	6999	6999
4	1034	1037	1035	1030	1028	1028	1031	1040	1037	6999
5	1028	1026	1024	1021	1021	1023	1025	1029	1034	1037
6	1020	1018	1014	1011	1012	1017	1021	1026	1030	1034
7	1015	1011	1008	1004	1007	1012	1018	1021	1024	6999
8	6999	1006	1003	1000	1003	1009	1013	1017	1019	6999
9	6999	1003	1001	998.9	1002	1008	1011	1014	1017	6999
10	6999	1003	1002	1001	1003	1008	1011	1014	1018	1021
11	6999	1003	1005	1006	1008	1011	1014	1017	1021	6999
12	996.9	1002	1006	1008	1012	1015	1019	1024	1028	6999
13	992.9	998.1	1004	1010	1016	1021	1027	1033	1035	6999
14	6999	1002	1006	1011	1016	1021	1027	1034	1038	6999
15	6999	6999	1009	1012	1016	1019	6999	6999	6999	6999

DRAWDOWN IN LAYER 1 AT END OF TIME STEP 50 IN STRESS PERIOD 1

	1	2	3	4	5	6	7	8	9	10
1	0.2211	7.598	6999	6999	6999	6999	6999	6999	6999	6999
2	10.39	16.64	24.69	6999	6999	29.61	27.32	26.58	6999	6999
3	6999	25.96	30.23	29.74	31.5	27.55	21.53	19.65	6999	6999
4	34.88	33.41	34.72	36.98	37.56	35.96	32.5	22.36	29.26	6999
5	37.22	37.87	39.36	40.8	40.11	38.29	35.43	29.41	31.52	30.62
6	39.5	40.74	43.03	45.53	43.95	39.87	29.89	29.15	32.24	31.31
7	40.63	41.73	44.12	46.82	44.59	39.42	33.34	34.27	32.67	6999
8	6999	40.21	42.52	45.24	42.69	30.83	32.71	33.08	31.09	6999
9	6999	35.67	37.76	40.57	38.11	32.38	31.02	29.2	27.01	6999
10	6999	28.08	29.7	32.68	31.08	27.42	24.63	23.52	21.39	20.74
11	6999	18.03	18.41	21.24	20.92	19.52	17.27	16.22	14.66	6999
12	4.305	7.596	8.652	11.25	11.42	10.97	7.745	6.024	6.219	6999
13	-7.861	-3.073	-2.967	-2.535	-2.049	-2.696	-6.719	-2.718	1.445	6999
14	6999	2.142	2.568	2.791	2.969	3.043	2.188	-3.943	-3.339	6999
15	6999	6999	2.593	2.76	2.867	2.987	6999	6999	6999	6999

```
 VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP 50 IN STRESS PERIOD   1
  ------------------------------------------------------------------------------

     CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
     ------------------                 ------------------------

           IN:                                      IN:
           ---                                      ---
             STORAGE = 10550845440.0000               STORAGE =           0.7553
       CONSTANT HEAD =           0.0000         CONSTANT HEAD =           0.0000
               WELLS =           0.0000                 WELLS =           0.0000
                  ET =           0.0000                    ET =           0.0000
     HEAD DEP BOUNDS =   398894912.0000       HEAD DEP BOUNDS =           0.2531
            RECHARGE =  2830322944.0000              RECHARGE =           1.7937
      STREAM LEAKAGE = 97114357760.0000        STREAM LEAKAGE =          65.4129

            TOTAL IN =110894424064.0000              TOTAL IN =          68.2150

          OUT:                                     OUT:
          ----                                     ----
             STORAGE =   303353824.0000               STORAGE =           0.0000
       CONSTANT HEAD =           0.0000         CONSTANT HEAD =           0.0000
               WELLS = 78894014464.0000                 WELLS =          50.0000
                  ET = 24106188800.0000                    ET =          14.5617
     HEAD DEP BOUNDS =   293321440.0000       HEAD DEP BOUNDS =           0.1847
            RECHARGE =           0.0000              RECHARGE =           0.0000
      STREAM LEAKAGE =  7305799168.0000        STREAM LEAKAGE =           3.4754

           TOTAL OUT =110902681600.0000             TOTAL OUT =          68.2219

            IN - OUT =    -8257536.0000              IN - OUT =     -6.8741E-03

 PERCENT DISCREPANCY =          -0.01     PERCENT DISCREPANCY =          -0.01
```

Gage output file for segment 6 Reach 7.

Time	Stage	Flow	Depth	Width	M-P Flow	Cond.	HeadDiff	Hyd.Grad
31558000	1025.900	0.310	0.000	12.000	0.000	0.240	-1.290	-0.430
63115000	1025.900	0.326	0.000	12.000	0.000	0.240	-1.357	-0.452
94673000	1025.900	0.311	0.000	12.000	0.000	0.240	-1.294	-0.431
126230000	1025.900	0.298	0.000	12.000	0.000	0.240	-1.241	-0.414
157790000	1025.900	0.287	0.000	12.000	0.000	0.240	-1.195	-0.398
189350000	1025.900	0.278	0.000	12.000	0.000	0.240	-1.156	-0.385
220900000	1025.900	0.270	0.000	12.000	0.000	0.240	-1.124	-0.375
252460000	1025.900	0.263	0.000	12.000	0.000	0.240	-1.097	-0.366
284020000	1025.900	0.258	0.000	12.000	0.000	0.240	-1.074	-0.358
315580000	1025.900	0.253	0.000	12.000	0.000	0.240	-1.054	-0.351
347130000	1025.900	0.249	0.000	12.000	0.000	0.240	-1.036	-0.345
378690000	1025.900	0.245	0.000	12.000	0.000	0.240	-1.020	-0.340
410250000	1025.900	0.241	0.000	12.000	0.000	0.240	-1.005	-0.335
441810000	1025.900	0.238	0.000	12.000	0.000	0.240	-0.990	-0.330
473360000	1025.900	0.234	0.000	12.000	0.000	0.240	-0.977	-0.326
504920000	1025.900	0.232	0.000	12.000	0.000	0.240	-0.965	-0.322
536480000	1025.900	0.229	0.000	12.000	0.000	0.240	-0.953	-0.318
568040000	1025.900	0.226	0.000	12.000	0.000	0.240	-0.943	-0.314
599590000	1025.900	0.224	0.000	12.000	0.000	0.240	-0.933	-0.311
631150000	1025.900	0.222	0.000	12.000	0.000	0.240	-0.924	-0.308
662710000	1025.900	0.220	0.000	12.000	0.000	0.240	-0.915	-0.305
694270000	1025.900	0.218	0.000	12.000	0.000	0.240	-0.907	-0.302
725830000	1025.900	0.216	0.000	12.000	0.000	0.240	-0.900	-0.300
757380000	1025.900	0.214	0.000	12.000	0.000	0.240	-0.893	-0.298
788940000	1025.900	0.213	0.000	12.000	0.000	0.240	-0.887	-0.296
820500000	1025.900	0.211	0.000	12.000	0.000	0.240	-0.881	-0.294
852060000	1025.900	0.210	0.000	12.000	0.000	0.240	-0.875	-0.292
883610000	1025.900	0.209	0.000	12.000	0.000	0.240	-0.870	-0.290
915170000	1025.900	0.208	0.000	12.000	0.000	0.240	-0.865	-0.288
946730000	1025.900	0.206	0.000	12.000	0.000	0.240	-0.860	-0.287
978290000	1025.900	0.205	0.000	12.000	0.000	0.240	-0.856	-0.285
1009800000	1025.900	0.204	0.000	12.000	0.000	0.240	-0.852	-0.284
1041400000	1025.900	0.203	0.000	12.000	0.000	0.240	-0.848	-0.283
1073000000	1025.900	0.203	0.000	12.000	0.000	0.240	-0.844	-0.281
1104500000	1025.900	0.202	0.000	12.000	0.000	0.240	-0.841	-0.280

1136100000	1025.900	0.201	0.000	12.000	0.000	0.240	-0.838	-0.279
1167600000	1025.900	0.200	0.000	12.000	0.000	0.240	-0.835	-0.278
1199200000	1025.900	0.200	0.000	12.000	0.000	0.240	-0.832	-0.277
1230700000	1025.900	0.199	0.000	12.000	0.000	0.240	-0.829	-0.276
1262300000	1025.900	0.198	0.000	12.000	0.000	0.240	-0.827	-0.276
1293900000	1025.900	0.198	0.000	12.000	0.000	0.240	-0.825	-0.275
1325400000	1025.900	0.197	0.000	12.000	0.000	0.240	-0.823	-0.274
1357000000	1025.900	0.197	0.000	12.000	0.000	0.240	-0.821	-0.274
1388500000	1025.900	0.196	0.000	12.000	0.000	0.240	-0.819	-0.273
1420100000	1025.900	0.196	0.000	12.000	0.000	0.240	-0.817	-0.272
1451700000	1025.900	0.196	0.000	12.000	0.000	0.240	-0.815	-0.272
1483200000	1025.900	0.195	0.000	12.000	0.000	0.240	-0.814	-0.271
1514800000	1025.900	0.195	0.000	12.000	0.000	0.240	-0.812	-0.271
1546300000	1025.900	0.195	0.000	12.000	0.000	0.240	-0.811	-0.270
1577900000	1025.900	0.194	0.000	12.000	0.000	0.240	-0.810	-0.270
1609400000	1025.900	0.219	0.000	12.000	0.000	0.240	-0.912	-0.304
1641000000	1025.900	0.245	0.000	12.000	0.000	0.240	-1.022	-0.341
1672600000	1025.900	0.267	0.000	12.000	0.000	0.240	-1.111	-0.370
1704100000	1025.900	0.284	0.000	12.000	0.000	0.240	-1.182	-0.394
1735700000	1025.900	0.298	0.000	12.000	0.000	0.240	-1.241	-0.414
1767200000	1025.900	0.309	0.000	12.000	0.000	0.240	-1.289	-0.430
1798800000	1025.900	0.319	0.000	12.000	0.000	0.240	-1.329	-0.443
1830300000	1025.900	0.327	0.000	12.000	0.000	0.240	-1.363	-0.454
1861900000	1025.900	0.334	0.000	12.000	0.000	0.240	-1.393	-0.464
1893500000	1025.900	0.342	0.000	12.000	0.000	0.240	-1.423	-0.474
1925000000	1025.900	0.350	0.000	12.000	0.000	0.240	-1.458	-0.486
1956600000	1025.900	0.365	0.000	12.000	0.000	0.240	-1.521	-0.507
1988100000	1026.100	1.601	0.220	12.000	1.278	0.240	-1.337	-0.446
2019700000	1026.200	2.530	0.298	12.000	2.224	0.240	-1.271	-0.424
2051200000	1026.200	3.121	0.340	12.000	2.823	0.240	-1.234	-0.411
2082800000	1026.300	3.478	0.364	12.000	3.186	0.240	-1.213	-0.404
2114400000	1026.300	3.702	0.379	12.000	3.413	0.240	-1.201	-0.400
2145900000	1026.300	3.847	0.388	12.000	3.560	0.240	-1.193	-0.398
2177500000	1026.300	3.943	0.394	12.000	3.658	0.240	-1.188	-0.396
2209000000	1026.300	4.008	0.398	12.000	3.724	0.240	-1.184	-0.395
2240600000	1026.300	4.053	0.401	12.000	3.767	0.240	-1.182	-0.394
2272100000	1026.300	4.083	0.403	12.000	3.799	0.240	-1.180	-0.393
2303700000	1026.300	4.105	0.404	12.000	3.821	0.240	-1.179	-0.393
2335300000	1026.300	4.120	0.405	12.000	3.837	0.240	-1.178	-0.393

2366800000	1026.300	4.131	0.406	12.000	3.847	0.240	-1.178	-0.393
2398400000	1026.300	4.138	0.406	12.000	3.855	0.240	-1.177	-0.392
2429900000	1026.300	4.144	0.407	12.000	3.861	0.240	-1.177	-0.392
2461500000	1026.300	4.148	0.407	12.000	3.865	0.240	-1.177	-0.392
2493100000	1026.300	4.151	0.407	12.000	3.868	0.240	-1.177	-0.392
2524600000	1026.300	4.153	0.407	12.000	3.870	0.240	-1.177	-0.392
2556200000	1026.300	4.155	0.407	12.000	3.872	0.240	-1.177	-0.392
2587700000	1026.300	4.156	0.407	12.000	3.873	0.240	-1.177	-0.392
2619300000	1026.300	4.157	0.408	12.000	3.874	0.240	-1.176	-0.392
2650800000	1026.300	4.157	0.408	12.000	3.874	0.240	-1.176	-0.392
2682400000	1026.300	4.157	0.408	12.000	3.875	0.240	-1.176	-0.392
2714000000	1026.300	4.158	0.408	12.000	3.875	0.240	-1.176	-0.392
2745500000	1026.300	4.158	0.408	12.000	3.876	0.240	-1.176	-0.392
2777100000	1026.300	4.158	0.408	12.000	3.876	0.240	-1.176	-0.392
2808600000	1026.300	4.158	0.408	12.000	3.876	0.240	-1.176	-0.392
2840200000	1026.300	4.158	0.408	12.000	3.876	0.240	-1.176	-0.392
2871700000	1026.300	4.158	0.408	12.000	3.876	0.240	-1.176	-0.392
2903300000	1026.300	4.159	0.408	12.000	3.876	0.240	-1.176	-0.392
2934900000	1026.300	4.159	0.408	12.000	3.876	0.240	-1.176	-0.392
2966400000	1026.300	4.159	0.408	12.000	3.876	0.240	-1.176	-0.392
2998000000	1026.300	4.159	0.408	12.000	3.876	0.240	-1.176	-0.392
3029500000	1026.300	4.159	0.408	12.000	3.876	0.240	-1.176	-0.392
3061100000	1026.300	4.159	0.408	12.000	3.876	0.240	-1.176	-0.392
3092600000	1026.300	4.159	0.408	12.000	3.876	0.240	-1.176	-0.392
3124200000	1026.300	4.159	0.408	12.000	3.876	0.240	-1.176	-0.392
3155800000	1026.300	4.159	0.408	12.000	3.876	0.240	-1.176	-0.392

Gage Output file for Segment 3 Reach 1

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STREAM SEGMENT   3 IS DIVERTED FROM SEGMENT   1 DIVERSION TYPE IS IPRIOR OF   0

      Time           Stage       Max. Rate       Rate Diverted   Upstream Flow"
     3.1558E+07   1.0759E+03    1.0000E+01        1.0000E+01     1.5163E+01
     6.3115E+07   1.0759E+03    1.0000E+01        1.0000E+01     1.5288E+01
     9.4673E+07   1.0759E+03    1.0000E+01        1.0000E+01     1.5087E+01
     1.2623E+08   1.0759E+03    1.0000E+01        1.0000E+01     1.4796E+01
     1.5779E+08   1.0759E+03    1.0000E+01        1.0000E+01     1.4493E+01
     1.8935E+08   1.0759E+03    1.0000E+01        1.0000E+01     1.4314E+01
     2.2090E+08   1.0759E+03    1.0000E+01        1.0000E+01     1.4255E+01
     2.5246E+08   1.0759E+03    1.0000E+01        1.0000E+01     1.4183E+01
     2.8402E+08   1.0759E+03    1.0000E+01        1.0000E+01     1.4106E+01
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3.1558E+08	1.0759E+03	1.0000E+01	1.0000E+01	1.4028E+01
3.4713E+08	1.0759E+03	1.0000E+01	1.0000E+01	1.3953E+01
3.7869E+08	1.0759E+03	1.0000E+01	1.0000E+01	1.3880E+01
4.1025E+08	1.0759E+03	1.0000E+01	1.0000E+01	1.3812E+01
4.4181E+08	1.0759E+03	1.0000E+01	1.0000E+01	1.3747E+01
4.7336E+08	1.0759E+03	1.0000E+01	1.0000E+01	1.3687E+01
5.0492E+08	1.0759E+03	1.0000E+01	1.0000E+01	1.3631E+01
5.3648E+08	1.0759E+03	1.0000E+01	1.0000E+01	1.3579E+01
5.6804E+08	1.0759E+03	1.0000E+01	1.0000E+01	1.3531E+01
5.9959E+08	1.0759E+03	1.0000E+01	1.0000E+01	1.3485E+01
6.3115E+08	1.0759E+03	1.0000E+01	1.0000E+01	1.3443E+01
6.6271E+08	1.0759E+03	1.0000E+01	1.0000E+01	1.3404E+01
6.9427E+08	1.0759E+03	1.0000E+01	1.0000E+01	1.3368E+01
7.2583E+08	1.0759E+03	1.0000E+01	1.0000E+01	1.3334E+01
7.5738E+08	1.0759E+03	1.0000E+01	1.0000E+01	1.3303E+01
7.8894E+08	1.0759E+03	1.0000E+01	1.0000E+01	1.3274E+01
8.2050E+08	1.0759E+03	1.0000E+01	1.0000E+01	1.3246E+01
8.5206E+08	1.0759E+03	1.0000E+01	1.0000E+01	1.3221E+01
8.8361E+08	1.0759E+03	1.0000E+01	1.0000E+01	1.3197E+01
9.1517E+08	1.0759E+03	1.0000E+01	1.0000E+01	1.3175E+01
9.4673E+08	1.0759E+03	1.0000E+01	1.0000E+01	1.3154E+01
9.7829E+08	1.0759E+03	1.0000E+01	1.0000E+01	1.3135E+01
1.0098E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.3117E+01
1.0414E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.3101E+01
1.0730E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.3085E+01
1.1045E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.3070E+01
1.1361E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.3057E+01
1.1676E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.3044E+01
1.1992E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.3032E+01
1.2307E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.3021E+01
1.2623E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.3011E+01
1.2939E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.3001E+01
1.3254E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.2992E+01
1.3570E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.2983E+01
1.3885E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.2976E+01
1.4201E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.2970E+01
1.4517E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.2970E+01
1.4832E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.2970E+01
1.5148E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.2970E+01
1.5463E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.2970E+01
1.5779E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.2970E+01

1.6094E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.2970E+01
1.6410E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.2995E+01
1.6726E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.3113E+01
1.7041E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.3251E+01
1.7357E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.3407E+01
1.7672E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.3574E+01
1.7988E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.3744E+01
1.8303E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.3913E+01
1.8619E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.4078E+01
1.8935E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.4343E+01
1.9250E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.4914E+01
1.9566E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.5279E+01
1.9881E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.5525E+01
2.0197E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.5691E+01
2.0512E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.5801E+01
2.0828E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.5873E+01
2.1144E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.5920E+01
2.1459E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.5952E+01
2.1775E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.5974E+01
2.2090E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.5989E+01
2.2406E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.6000E+01
2.2721E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.6007E+01
2.3037E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.6012E+01
2.3353E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.6016E+01
2.3668E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.6019E+01
2.3984E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.6021E+01
2.4299E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.6022E+01
2.4615E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.6023E+01
2.4931E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.6024E+01
2.5246E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.6024E+01
2.5562E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.6025E+01
2.5877E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.6025E+01
2.6193E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.6025E+01
2.6508E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.6025E+01
2.6824E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.6026E+01
2.7140E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.6026E+01
2.7455E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.6026E+01
2.7771E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.6026E+01
2.8086E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.6026E+01
2.8402E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.6026E+01
2.8717E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.6026E+01

2.9033E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.6026E+01
2.9349E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.6026E+01
2.9664E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.6026E+01
2.9980E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.6026E+01
3.0295E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.6026E+01
3.0611E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.6026E+01
3.0926E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.6026E+01
3.1242E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.6026E+01
3.1558E+09	1.0759E+03	1.0000E+01	1.0000E+01	1.6026E+01

Contour of drawdown at time step 50 stress period 1

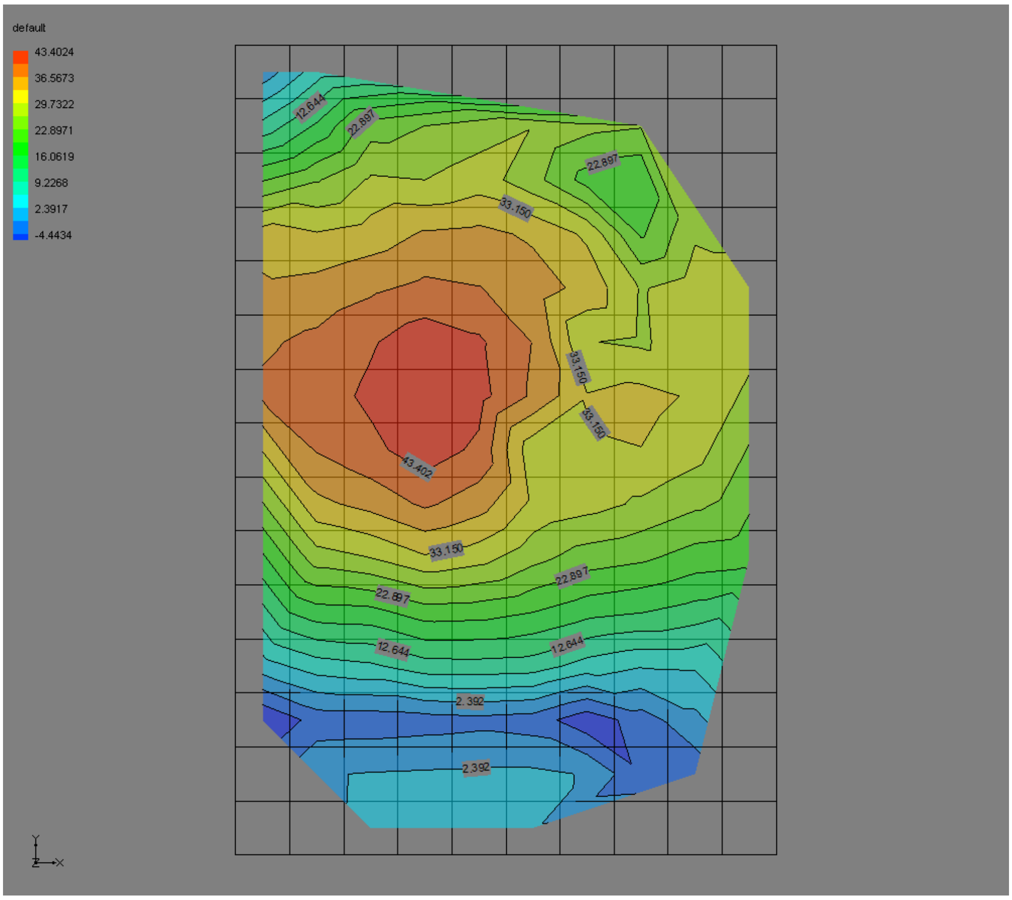


Figure 1.14

1.3.3 Results: In the output file, if we look at the volumetric budget of the entire model at time step 50 and stress period 1, the inflow from storage is equal to .7553 cfs which is almost equal to the inflow from storage in STR1 package 0.7220 cfs. (Section 1.2.3). Inflow due to head dependent boundaries in SFR1 package is 0.2531 cfs whereas in STR 1 package it is 0.1669 cfs. Inflow due to stream leakage in SFR1 package is 65.4129 cfs whereas in STR1 package it is 66.2679. Similarly outflow due to evapotranspiration in SFR1 package is 15.5617 cfs, and it is 17.5396 cfs in STR1 package. Outflow due to head dependent boundaries in SFR1 package is 0.1847 cfs and 0.1347 cfs in STR1 package. Outflow due to stream leakage in SFR1 package is 3.4754 cfs and 1.2847 cfs in STR1 package. The differences in the output in these two packages (SFR1 and STR1 package) may be due to the way these packages calculate stream depth differently even though we used rectangular channel in both the cases. SFR1 package calculates flow across the streambed on the basis of stream depth calculated at the midpoint of a reach, whereas STR1 package calculates flow across the streambed on the basis of stream depth calculated at the beginning of a reach (Prudic and others, 2004). Thus, the simulated exchange across the streambed using the same data in both packages will likely differ between the SFR1 package and STR1 package (Prudic and others, 2004).

1.4 SFR2 Package: This package simulates unsaturated zone beneath the stream only with MODFLOW 2000. Detailed description of this package can be found in the USGS report 'Documentation of the Streamflow-Routing (SFR2) Package to Include Unsaturated Flow Beneath Streams – A modifications to SFR1' by Niswonger and Prudic, 2006. The streamflow-routing package is activated by including a record in the MODFLOW file using the file type (Ftype) 'SFR' to indicate that relevant calculations are to be made in the model and to specify the related input data file (Niswonger and Prudic, 2006). So both SFR1 and SFR2 have file type 'SFR'. SFR2 is distinguished from SFR1 by changing the integer 'NSTRM' (in SFR file) to negative; additional variables ISFROPT, NSTRAIL, ISUZN, and NSFRSETS are read by MODFLOW to simulate the unsaturated zone beneath the stream which are also in SFR file.

The modifications in SFR2 do not require any changes to the data input for SFR1 (Niswonger and Prudic, 2006). With all of the data as required in SFR1 package, this package requires additional unsaturated flow variables including saturated and initial water contents, Brooks and Corey exponent, and vertical saturated hydraulic conductivity of unsaturated zone beneath the stream (this variable is necessary when using the BCF package, but optional when using the LPF package). These variables are defined independently for each stream reach (Niswonger and Prudic, 2006). Unlike SFR1, seepage loss from the stream may be restricted by the hydraulic conductivity of the unsaturated zone (Niswonger and Prudic, 2006). Also SFR2 package can use five options to calculate stream depth as in SFR1 package but the option to simulate unsaturated flow beneath the stream is not available when using ICALC=0,3,4. The unsaturated flow is simulated independently of saturated flow within each model cell corresponding to a stream reach whenever the water table is below the elevation of stream bed (Niswonger and Prudic, 2006). This package also allows additions of water along stream reach from precipitation and overland flow and removal of water from evapotranspiration. Unlike the other unsaturated versions of MODFLOW (UZF package, MODFLOW Hydrus), separate evapotranspiration package (EVT) and recharge package (RCH) can be included in the simulation if desired.

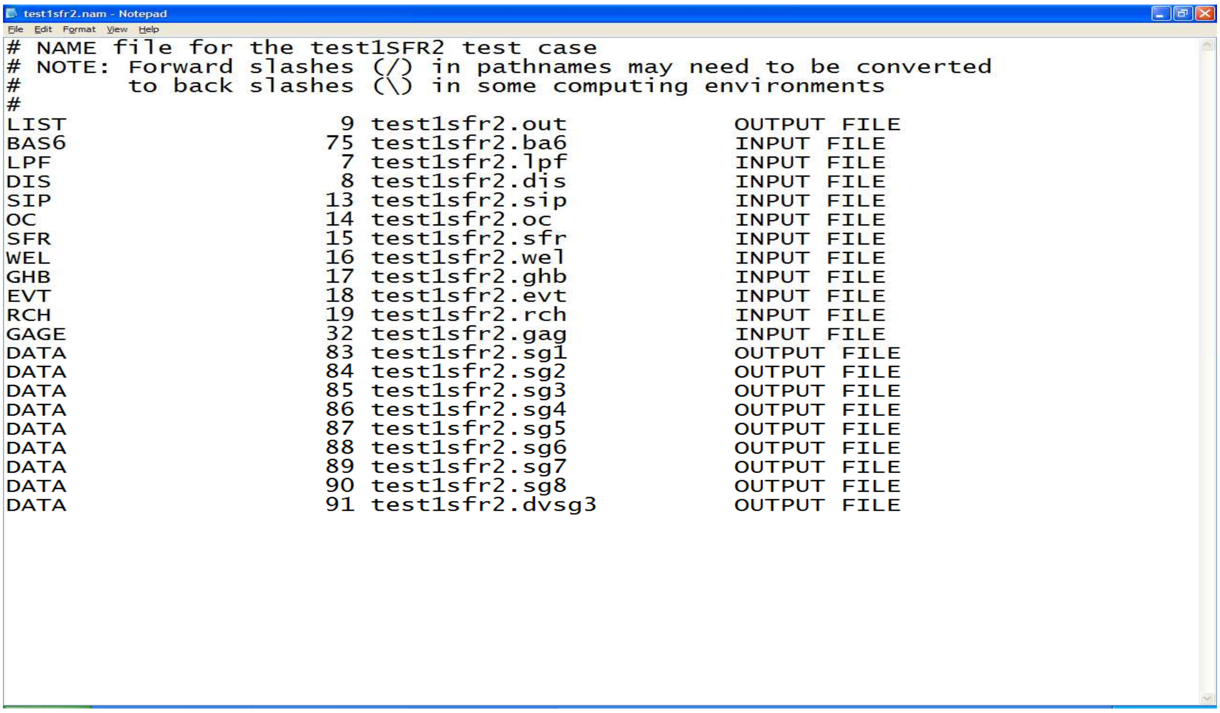
The present form of the SFR2 package does not simulate the unsaturated flow through multiple layers of varying hydraulic conductivity (Niswonger and Prudic, 2006).

1.4.1 Stream Properties: The required stream properties input data and flow patterns of the stream are as shown in Table 1.1 of section 1.2.1 and Figure 1.1, respectively. For simulating the unsaturated zone beneath the stream the required hydraulic properties are as shown below:

Saturated water content=0.35 for all segments
Initial water content=0.25 for all segments
Brooks and Corey exponent=3.5 for all segments
Vertical saturated hydraulic conductivity of the unsaturated zone beneath the stream=2.0E-06 ft/sec for all segments. The unsaturated zone lies in the area below the stream bed, so they exist in the cells where the stream segments are located as shown Figure 1.1. The thickness of the unsaturated zones is as shown in the table below:

Segment	Upstream Bed Top Elevation	Initial Starting Head	Thickness of Unsaturated zone	Downstream Bed Top Elevation	Initial Starting Head	Thickness of Unsaturated zone
1	1095	1090	5	1075	1070	5
2	1075	1070	5	1050	1040	10
3	1075	1070	5	1060	1055	5
4	1080	1068.1	11.9	1060	1055	5
5	1060	1055	5	1045	1040	5
6	1045	1040	5	1025	1020	5
7	1040	1035	5	1025	1020	5
8	1025	1020	5	990	985	5

1.4.2 MODFLOW Execution: A Name file (Figure 1.15) was created listing all of the input files and output file. Also gaging stations were set in every stream segment following the procedure described in USGS report 'Documentation of the Streamflow-Routing (SFR2) Package to Include Unsaturated Flow Beneath Streams-A Modification to SFR1', page 30, by Niswonger and Prudic, 2006. This version ran successfully using both MODFLOW 2000 and MODFLOW 2005 executable programs.




```
# NAME file for the test1SFR2 test case
# NOTE: Forward slashes (/) in pathnames may need to be converted
#       to back slashes (\) in some computing environments
#
LIST                    9 test1sfr2.out           OUTPUT FILE
BAS6                   75 test1sfr2.ba6           INPUT FILE
LPF                     7 test1sfr2.lpf           INPUT FILE
DIS                     8 test1sfr2.dis           INPUT FILE
SIP                    13 test1sfr2.sip           INPUT FILE
OC                     14 test1sfr2.oc            INPUT FILE
SFR                    15 test1sfr2.sfr           INPUT FILE
WEL                    16 test1sfr2.wel           INPUT FILE
GHB                    17 test1sfr2.ghb           INPUT FILE
EVT                    18 test1sfr2.evt           INPUT FILE
RCH                    19 test1sfr2.rch           INPUT FILE
GAGE                   32 test1sfr2.gag           INPUT FILE
DATA                   83 test1sfr2.sg1           OUTPUT FILE
DATA                   84 test1sfr2.sg2           OUTPUT FILE
DATA                   85 test1sfr2.sg3           OUTPUT FILE
DATA                   86 test1sfr2.sg4           OUTPUT FILE
DATA                   87 test1sfr2.sg5           OUTPUT FILE
DATA                   88 test1sfr2.sg6           OUTPUT FILE
DATA                   89 test1sfr2.sg7           OUTPUT FILE
DATA                   90 test1sfr2.sg8           OUTPUT FILE
DATA                   91 test1sfr2.dvsg3         OUTPUT FILE
```

Figure 1.15

1.4.3 Output From Simulation: A MODFLOW output file will be created after the simulation with the name of output file as specified in the name file. Depending upon the options specified in output control file, the volumetric budget of entire model and the volumetric budget for the unsaturated zone beneath the stream, heads, and drawdown will be printed at desired time steps and stress periods in this output file. A sample of output file is as shown below. Also gage output files are created for every segment.

STREAM LISTING PERIOD 1 STEP 50

LAYER	ROW	COL.	STREAM SEG.NO.	RCH. NO.	FLOW INTO STRM. RCH.	STREAM LOSS	FLOW OUT OF STRM. RCH.	OVRLND. RUNOFF	DIRECT PRECIP	STREAM ET	STREAM HEAD	STREAM DEPTH	STREAM WIDTH	STREAMBED CONDCTNC.	FLOW TO WAT. TAB.	CHNG. UNSAT. STORAGE
1	1	1	1	1	25.000	0.117	24.883	0.000	0.000	0.000	1094.240	1.180	13.000	0.585	0.117	0.000
1	1	2	1	2	24.883	0.001	24.882	0.000	0.000	0.000	1092.270	1.179	13.000	0.006	0.001	0.000
1	2	2	1	3	24.882	0.182	24.700	0.000	0.000	0.000	1089.230	1.176	13.000	0.910	0.182	0.000
1	3	2	1	4	24.700	0.002	24.698	0.000	0.000	0.000	1086.170	1.173	13.000	0.008	0.002	0.000
1	3	3	1	5	24.698	0.156	24.542	0.000	0.000	0.000	1083.550	1.171	13.000	0.780	0.156	0.000
1	3	4	1	6	24.542	0.144	24.398	0.000	0.000	0.000	1078.560	1.167	13.000	0.722	0.144	0.000
1	3	4	2	1	14.398	0.000	14.397	0.000	0.000	0.000	1075.860	0.868	12.000	0.001	0.000	0.000
1	4	4	2	2	14.397	0.001	14.396	0.000	0.000	0.000	1075.840	0.868	12.000	0.005	0.001	0.000
1	4	5	2	3	14.396	0.114	14.282	0.000	0.000	0.000	1073.570	0.866	12.000	0.571	0.114	0.000
1	4	6	2	4	14.282	0.042	14.240	0.000	0.000	0.000	1070.510	0.863	12.000	0.209	0.042	0.000
1	5	6	2	5	14.240	0.120	14.120	0.000	0.000	0.000	1067.340	0.860	12.000	0.600	0.120	0.000
1	6	6	2	6	14.120	0.120	14.000	0.000	0.000	0.000	1062.620	0.856	12.000	0.600	0.120	0.000
1	7	6	2	7	14.000	0.120	13.880	0.000	0.000	0.000	1057.910	0.851	12.000	0.600	0.120	0.000
1	8	6	2	8	13.880	0.120	13.760	0.000	0.000	0.000	1053.200	0.847	12.000	0.600	0.120	0.000
1	3	4	3	1	10.000	0.001	9.999	0.000	0.000	0.000	1075.910	0.918	10.000	0.003	0.001	0.000
1	3	5	3	2	9.999	0.100	9.899	0.000	0.000	0.000	1074.540	0.915	10.000	0.500	0.100	0.000
1	3	6	3	3	9.899	0.100	9.799	0.000	0.000	0.000	1071.820	0.909	10.000	0.500	0.100	0.000
1	3	7	3	4	9.799	0.090	9.709	0.000	0.000	0.000	1069.240	0.904	10.000	0.450	0.090	0.000
1	3	8	3	5	9.709	0.002	9.708	0.000	0.000	0.000	1067.990	0.901	10.000	0.009	0.002	0.000
1	4	8	3	6	9.708	0.120	9.588	0.000	0.000	0.000	1066.330	0.898	10.000	0.600	0.120	0.000
1	5	8	3	7	9.588	0.100	9.488	0.000	0.000	0.000	1063.340	0.892	10.000	0.500	0.100	0.000
1	6	8	3	8	9.488	0.040	9.448	0.000	0.000	0.000	1061.430	0.888	10.000	0.200	0.040	0.000

1	5	10	4	1	10.000	0.050	9.950	0.000	0.000	0.000	1078.380	0.639	10.000	0.250	0.050	0.000
1	5	9	4	2	9.950	0.100	9.850	0.000	0.000	0.000	1071.610	0.636	10.000	0.500	0.100	0.000
1	5	8	4	3	9.850	0.002	9.848	0.000	0.000	0.000	1067.030	0.634	10.000	0.008	0.002	0.000
1	6	8	4	4	9.848	0.070	9.778	0.000	0.000	0.000	1063.790	0.633	10.000	0.350	0.070	0.000
1	6	8	5	1	19.226	0.080	19.146	0.000	0.000	0.000	1059.150	1.133	10.000	0.400	0.080	0.000
1	6	7	5	2	19.146	0.003	19.143	0.000	0.000	0.000	1057.090	1.132	10.000	0.016	0.003	0.000
1	7	7	5	3	19.143	0.100	19.043	0.000	0.000	0.000	1054.540	1.130	10.000	0.500	0.100	0.000
1	8	7	5	4	19.043	0.070	18.973	0.000	0.000	0.000	1050.330	1.127	10.000	0.350	0.070	0.000
1	8	6	5	5	18.973	0.050	18.923	0.000	0.000	0.000	1047.360	1.125	10.000	0.250	0.050	0.000
1	8	6	6	1	32.683	0.003	32.680	0.000	0.000	0.000	1046.380	1.434	12.000	0.015	0.003	0.000
1	9	6	6	2	32.680	0.073	32.607	0.000	0.000	0.000	1044.940	1.433	12.000	0.365	0.073	0.000
1	10	6	6	3	32.607	0.044	32.563	0.000	0.000	0.000	1042.720	1.431	12.000	0.221	0.044	0.000
1	10	7	6	4	32.563	0.120	32.443	0.000	0.000	0.000	1039.610	1.429	12.000	0.600	0.120	0.000
1	11	7	6	5	32.443	0.120	32.323	0.000	0.000	0.000	1035.060	1.426	12.000	0.600	0.120	0.000
1	12	7	6	6	32.323	0.120	32.203	0.000	0.000	0.000	1030.510	1.423	12.000	0.600	0.120	0.000
1	13	7	6	7	32.203	0.313	31.890	0.000	0.000	0.000	1027.330	1.417	12.000	0.240	0.000	0.000
1	14	9	7	1	150.000	3.147	146.850	0.000	0.000	0.000	1038.920	1.330	50.000	5.000	0.000	0.000
1	14	8	7	2	146.850	0.119	146.730	0.000	0.000	0.000	1036.470	1.321	50.000	0.046	0.000	0.000
1	13	8	7	3	146.730	6.551	140.180	0.000	0.000	0.000	1033.780	1.303	50.000	5.500	0.000	0.000
1	13	7	7	4	140.180	13.199	126.980	0.000	0.000	0.000	1028.660	1.248	50.000	5.000	0.000	0.000
1	13	7	8	1	-158.870	1.376	160.250	0.000	0.000	0.000	1025.220	1.285	50.000	1.710	0.000	0.000
1	13	6	8	2	160.250	9.734	150.520	0.000	0.000	0.000	1022.070	1.265	50.000	3.290	0.000	0.000
1	13	5	8	3	150.520	11.887	138.630	0.000	0.000	0.000	1016.840	1.211	50.000	5.000	0.000	0.000
1	13	4	8	4	138.630	7.579	131.050	0.000	0.000	0.000	1010.540	1.161	50.000	5.000	0.000	0.000
1	13	3	8	5	131.050	3.300	127.750	0.000	0.000	0.000	1004.260	1.133	50.000	5.000	0.000	0.000
1	13	2	8	6	127.750	0.304	127.450	0.000	0.000	0.000	997.999	1.124	50.000	5.000	0.000	0.000
1	13	1	8	7	127.450	0.515	126.930	0.000	0.000	0.000	992.996	1.121	50.000	3.000	0.000	0.000

```
VOLUMETRIC BUDGET FOR UNSATURATED ZONE BENEATH STREAMS AT END OF TIME STEP  50 STRESS PERIOD   1
------------------------------------------------------------------------------------------------

  CUMULATIVE VOLUMES             L**3    RATES FOR THIS TIME STEP         L**3/T
  ------------------                     ------------------------


        STREAM LOSS =   4399932928.0000           STREAM LOSS =           2.7969
  CHANGE IN STORAGE =     23809614.0000      CHANGE IN STORAGE =       2.8433E-03
     RECHARGE TO GW =   4376103424.0000         RECHARGE TO GW =           2.7941

           TOTAL IN =   4399932928.0000               TOTAL IN =           2.7969

          TOTAL OUT =   4399912960.0000              TOTAL OUT =           2.7969

           IN - OUT =        19968.0000               IN - OUT =      -7.1526E-07

PERCENT DISCREPANCY =            0.00      PERCENT DISCREPANCY =            0.00
```

HEAD IN LAYER 1 AT END OF TIME STEP 50 IN STRESS PERIOD 1

	1	2	3	4	5	6	7	8	9	10
1	1021.7	1000.34	6999	6999	6999	6999	6999	6999	6999	6999
2	1001.55	959.27	957.11	6999	6999	967.69	969.04	970.84	6999	6999
3	6999	957.17	955.2	954.3	954.65	956.57	958.95	961.32	6999	6999
4	961.71	956.11	953.93	952.87	953.21	954.31	956.53	959.16	962.39	6999
5	960.26	954.54	952.1	950.83	951.85	954.12	956.15	957.72	958.99	962.29
6	957.96	953.6	950.43	947.43	949.39	954.05	956.75	958.08	959.28	972.13
7	957.73	954.61	951.38	948.11	950.69	956.15	958.93	959.18	964.48	6999
8	6999	958.88	955.78	952.46	955.5	961.16	964.01	965.44	972.57	6999
9	6999	966.75	963.9	960.8	963.65	968.95	972.17	975.98	983.18	6999
10	6999	976.89	974.98	972.26	974.33	979.03	982.28	987.28	994.43	998.9
11	6999	987.96	988.76	986.82	988.29	991.33	994.42	999.87	1005.59	6999
12	994.49	996.11	999.08	998.9	1001.41	1004.79	1008.84	1016.81	1021.67	6999
13	992.82	997.94	1003.6	1009.02	1014.46	1019.11	1026.02	1032.59	1033.83	6999
14	6999	1001.48	1005.73	1009.95	1014.8	1019.81	1026.63	1033.88	1038.29	6999
15	6999	6999	1008.52	1011.41	1015.18	1018.32	6999	6999	6999	6999

DRAWDOWN IN LAYER 1 AT END OF TIME STEP 50 IN STRESS PERIOD 1

	1	2	3	4	5	6	7	8	9	10
1	68.3	85.77	6999	6999	6999	6999	6999	6999	6999	6999
2	88.35	126.8	124.3	6999	6999	104.6	102.5	100.3	6999	6999
3	6999	122.2	122.3	115.7	115.3	110.7	105.6	100.8	6999	6999
4	107.4	114.6	116.3	114.1	112.3	109.3	107.4	102.9	103.7	6999
5	104.6	109.4	110.8	110.7	108.9	106.7	104	101.1	106.7	105.8
6	101.8	104.7	106.8	109	106.9	102.8	94.3	96.92	102.6	93.47
7	98.37	98.39	100.3	103.1	100.6	95.75	91.95	96.32	92.02	6999
8	6999	87.42	89.92	93.04	90.3	78.84	81.93	84.46	77.83	6999
9	6999	72.35	75.2	78.7	76.35	70.94	69.43	66.92	60.82	6999
10	6999	54.21	56.82	61.04	59.97	56.37	53.17	50.32	44.87	42.7
11	6999	33.44	34.34	39.98	40.41	39.17	36.49	33.73	30.11	6999
12	6.711	13.09	15.42	20.7	21.69	21.41	17.53	13.59	12.63	6999
13	-7.825	-2.938	-2.348	-1.521	-0.8085	-1.249	-6.021	-2.458	2.273	6999
14	6999	2.523	3.271	3.752	4.1	4.189	2.872	-3.705	-3.288	6999
15	6999	6999	3.382	3.692	3.92	4.078	6999	6999	6999	6999

```
VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP 50 IN STRESS PERIOD   1
  ------------------------------------------------------------------------------

     CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
     ------------------                 ------------------------

           IN:                                      IN:
           ---                                      ---
             STORAGE = 29082671104.0000              STORAGE =          3.5675
       CONSTANT HEAD =           0.0000        CONSTANT HEAD =          0.0000
               WELLS =           0.0000                WELLS =          0.0000
                  ET =           0.0000                   ET =          0.0000
     HEAD DEP BOUNDS =   400886208.0000      HEAD DEP BOUNDS =          0.2551
            RECHARGE =  2830322944.0000             RECHARGE =          1.7937
      STREAM LEAKAGE = 73628254208.0000       STREAM LEAKAGE =         59.4424

            TOTAL IN =105942130688.0000             TOTAL IN =         65.0586

          OUT:                                     OUT:
          ----                                     ----
             STORAGE =   248198192.0000              STORAGE =      7.0237E-02
       CONSTANT HEAD =           0.0000        CONSTANT HEAD =          0.0000
               WELLS = 78894014464.0000                WELLS =         50.0000
                  ET = 22488731648.0000                   ET =         13.4346
     HEAD DEP BOUNDS =   294776608.0000      HEAD DEP BOUNDS =          0.1833
            RECHARGE =           0.0000             RECHARGE =          0.0000
      STREAM LEAKAGE =  4022330112.0000       STREAM LEAKAGE =          1.3757

           TOTAL OUT =105948053504.0000            TOTAL OUT =         65.0639

            IN - OUT =    -5922816.0000             IN - OUT =     -5.2338E-03

 PERCENT DISCREPANCY =           -0.01     PERCENT DISCREPANCY =           -0.01
```

Gage output file for segment 6 Reach 7

Time	Stage	Flow	Depth	Width	M-P Flow	Cond.	HeadDiff	Hyd.Grad
31558000	1027.2	26.848	1.274	12	26.817	0.24	-0.13069	-0.04356
63115000	1027.3	29.743	1.3548	12	29.712	0.24	-0.13124	-0.04375
94673000	1027.3	32.177	1.421	12	32.203	0.24	0.10896	0.036321
126230000	1027.3	32.154	1.4207	12	32.203	0.24	0.20461	0.068202
157790000	1027.3	32.136	1.4205	12	32.203	0.24	0.28021	0.093405
189350000	1027.3	32.12	1.4203	12	32.203	0.24	0.34675	0.11558
220900000	1027.3	32.105	1.4201	12	32.203	0.24	0.40768	0.13589
252460000	1027.3	32.092	1.4199	12	32.203	0.24	0.46341	0.15447
284020000	1027.3	32.079	1.4197	12	32.203	0.24	0.51491	0.17164
315580000	1027.3	32.068	1.4196	12	32.203	0.24	0.56303	0.18768

347130000	1027.3	32.057	1.4194	12	32.203	0.24	0.60787	0.20262
378690000	1027.3	32.047	1.4193	12	32.203	0.24	0.64965	0.21655
410250000	1027.3	32.037	1.4192	12	32.203	0.24	0.69087	0.23029
441810000	1027.3	32.028	1.4191	12	32.203	0.24	0.73051	0.2435
473360000	1027.3	32.019	1.4189	12	32.203	0.24	0.76788	0.25596
504920000	1027.3	32.01	1.4188	12	32.203	0.24	0.80292	0.26764
536480000	1027.3	32.002	1.4187	12	32.203	0.24	0.83572	0.27857
568040000	1027.3	31.995	1.4186	12	32.203	0.24	0.86657	0.28886
599590000	1027.3	31.988	1.4185	12	32.203	0.24	0.89563	0.29854
631150000	1027.3	31.982	1.4184	12	32.203	0.24	0.92285	0.30762
662710000	1027.3	31.975	1.4184	12	32.203	0.24	0.94841	0.31614
694270000	1027.3	31.97	1.4183	12	32.203	0.24	0.9726	0.3242
725830000	1027.3	31.964	1.4182	12	32.203	0.24	0.99527	0.33176
757380000	1027.3	31.959	1.4181	12	32.203	0.24	1.0167	0.3389
788940000	1027.3	31.954	1.4181	12	32.203	0.24	1.037	0.34566
820500000	1027.3	31.95	1.418	12	32.203	0.24	1.0561	0.35202
852060000	1027.3	31.945	1.418	12	32.203	0.24	1.0741	0.35804
883610000	1027.3	31.941	1.4179	12	32.203	0.24	1.0911	0.36371
915170000	1027.3	31.937	1.4179	12	32.203	0.24	1.1074	0.36912
946730000	1027.3	31.934	1.4178	12	32.203	0.24	1.1227	0.37423
978290000	1027.3	31.93	1.4178	12	32.203	0.24	1.1371	0.37903
1009800000	1027.3	31.927	1.4177	12	32.203	0.24	1.1508	0.38361
1041400000	1027.3	31.924	1.4177	12	32.203	0.24	1.1639	0.38796
1073000000	1027.3	31.921	1.4176	12	32.203	0.24	1.1761	0.39204
1104500000	1027.3	31.918	1.4176	12	32.203	0.24	1.1878	0.39595
1136100000	1027.3	31.915	1.4176	12	32.203	0.24	1.1989	0.39965
1167600000	1027.3	31.913	1.4175	12	32.203	0.24	1.2094	0.40313
1199200000	1027.3	31.91	1.4175	12	32.203	0.24	1.2194	0.40645
1230700000	1027.3	31.908	1.4175	12	32.203	0.24	1.2289	0.40963
1262300000	1027.3	31.906	1.4174	12	32.203	0.24	1.2379	0.41264
1293900000	1027.3	31.904	1.4174	12	32.203	0.24	1.2463	0.41543
1325400000	1027.3	31.902	1.4174	12	32.203	0.24	1.2544	0.41813
1357000000	1027.3	31.9	1.4174	12	32.203	0.24	1.262	0.42068
1388500000	1027.3	31.898	1.4173	12	32.203	0.24	1.2693	0.42311
1420100000	1027.3	31.897	1.4173	12	32.203	0.24	1.2762	0.42541
1451700000	1027.3	31.895	1.4173	12	32.203	0.24	1.2827	0.42756
1483200000	1027.3	31.894	1.4173	12	32.203	0.24	1.2889	0.42963

1514800000	1027.3	31.892	1.4173	12	32.203	0.24	1.2948	0.4316
1546300000	1027.3	31.891	1.4172	12	32.203	0.24	1.3003	0.43344
1577900000	1027.3	31.89	1.4172	12	32.203	0.24	1.3056	0.4352
1609400000	1027.3	31.913	1.4175	12	32.203	0.24	1.2085	0.40283
1641000000	1027.3	31.94	1.4179	12	32.203	0.24	1.0974	0.36579
1672600000	1027.3	31.963	1.4182	12	32.203	0.24	1.0018	0.33393
1704100000	1027.3	31.981	1.4184	12	32.203	0.24	0.92334	0.30778
1735700000	1027.3	31.997	1.4186	12	32.203	0.24	0.85824	0.28608
1767200000	1027.3	32.01	1.4188	12	32.203	0.24	0.80282	0.26761
1798800000	1027.3	32.022	1.419	12	32.203	0.24	0.75454	0.25151
1830300000	1027.3	32.032	1.4191	12	32.203	0.24	0.71175	0.23725
1861900000	1027.3	32.041	1.4192	12	32.203	0.24	0.6732	0.2244
1893500000	1027.3	32.05	1.4193	12	32.203	0.24	0.63977	0.21326
1925000000	1027.3	32.057	1.4194	12	32.203	0.24	0.61031	0.20344
1956600000	1027.3	32.063	1.4195	12	32.203	0.24	0.58327	0.19442
1988100000	1027.3	32.069	1.4196	12	32.203	0.24	0.55809	0.18603
2019700000	1027.3	32.075	1.4197	12	32.203	0.24	0.53463	0.17821
2051200000	1027.3	32.08	1.4197	12	32.203	0.24	0.51271	0.1709
2082800000	1027.3	32.085	1.4198	12	32.203	0.24	0.49201	0.164
2114400000	1027.3	32.09	1.4199	12	32.203	0.24	0.47271	0.15757
2145900000	1027.3	32.094	1.4199	12	32.203	0.24	0.45435	0.15145
2177500000	1027.3	32.098	1.42	12	32.203	0.24	0.43716	0.14572
2209000000	1027.3	32.102	1.42	12	32.203	0.24	0.42076	0.14025
2240600000	1027.3	32.106	1.4201	12	32.203	0.24	0.40547	0.13516
2272100000	1027.3	32.109	1.4201	12	32.203	0.24	0.39141	0.13047
2303700000	1027.3	32.112	1.4202	12	32.203	0.24	0.37804	0.12601
2335300000	1027.3	32.115	1.4202	12	32.203	0.24	0.36547	0.12182
2366800000	1027.3	32.118	1.4203	12	32.203	0.24	0.35391	0.11797
2398400000	1027.3	32.121	1.4203	12	32.203	0.24	0.34316	0.11439
2429900000	1027.3	32.123	1.4203	12	32.203	0.24	0.33313	0.11104
2461500000	1027.3	32.125	1.4203	12	32.203	0.24	0.32362	0.10787
2493100000	1027.3	32.127	1.4204	12	32.203	0.24	0.31491	0.10497
2524600000	1027.3	32.129	1.4204	12	32.203	0.24	0.30657	0.10219
2556200000	1027.3	32.131	1.4204	12	32.203	0.24	0.29873	0.099577
2587700000	1027.3	32.133	1.4204	12	32.203	0.24	0.2914	0.097132
2619300000	1027.3	32.135	1.4205	12	32.203	0.24	0.2845	0.094832
2650800000	1027.3	32.136	1.4205	12	32.203	0.24	0.27812	0.092706

2682400000	1027.3	32.138	1.4205	12	32.203	0.24	0.27199	0.090665
2714000000	1027.3	32.139	1.4205	12	32.203	0.24	0.26634	0.088781
2745500000	1027.3	32.14	1.4205	12	32.203	0.24	0.26093	0.086975
2777100000	1027.3	32.142	1.4206	12	32.203	0.24	0.25587	0.08529
2808600000	1027.3	32.143	1.4206	12	32.203	0.24	0.25117	0.083723
2840200000	1027.3	32.144	1.4206	12	32.203	0.24	0.24674	0.082246
2871700000	1027.3	32.145	1.4206	12	32.203	0.24	0.24263	0.080878
2903300000	1027.3	32.146	1.4206	12	32.203	0.24	0.23876	0.079586
2934900000	1027.3	32.147	1.4206	12	32.203	0.24	0.235	0.078333
2966400000	1027.3	32.147	1.4206	12	32.203	0.24	0.23156	0.077188
2998000000	1027.3	32.148	1.4206	12	32.203	0.24	0.22833	0.076109
3029500000	1027.3	32.149	1.4207	12	32.203	0.24	0.22528	0.075092
3061100000	1027.3	32.15	1.4207	12	32.203	0.24	0.2224	0.074132
3092600000	1027.3	32.15	1.4207	12	32.203	0.24	0.21964	0.073215
3124200000	1027.3	32.151	1.4207	12	32.203	0.24	0.21717	0.072392
3155800000	1027.3	32.152	1.4207	12	32.203	0.24	0.21481	0.071602

Gage Output file for Segment 3 Reach 1

```
 STREAM SEGMENT   3 IS DIVERTED FROM SEGMENT   1 DIVERSION TYPE IS IPRIOR OF   0
       Time        Stage         Max. Rate        Rate Diverted   Upstream Flow
    3.1558E+07   1.0759E+03    1.0000E+01        1.0000E+01     2.0981E+01
    6.3115E+07   1.0759E+03    1.0000E+01        1.0000E+01     2.4398E+01
    9.4673E+07   1.0759E+03    1.0000E+01        1.0000E+01     2.4398E+01
    1.2623E+08   1.0759E+03    1.0000E+01        1.0000E+01     2.4398E+01
    1.5779E+08   1.0759E+03    1.0000E+01        1.0000E+01     2.4398E+01
    1.8935E+08   1.0759E+03    1.0000E+01        1.0000E+01     2.4398E+01
    2.2090E+08   1.0759E+03    1.0000E+01        1.0000E+01     2.4398E+01
    2.5246E+08   1.0759E+03    1.0000E+01        1.0000E+01     2.4398E+01
    2.8402E+08   1.0759E+03    1.0000E+01        1.0000E+01     2.4398E+01
    3.1558E+08   1.0759E+03    1.0000E+01        1.0000E+01     2.4398E+01
    3.4713E+08   1.0759E+03    1.0000E+01        1.0000E+01     2.4398E+01
    3.7869E+08   1.0759E+03    1.0000E+01        1.0000E+01     2.4398E+01
    4.1025E+08   1.0759E+03    1.0000E+01        1.0000E+01     2.4398E+01
    4.4181E+08   1.0759E+03    1.0000E+01        1.0000E+01     2.4398E+01
    4.7336E+08   1.0759E+03    1.0000E+01        1.0000E+01     2.4398E+01
    5.0492E+08   1.0759E+03    1.0000E+01        1.0000E+01     2.4398E+01
```

5.3648E+08	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
5.6804E+08	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
5.9959E+08	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
6.3115E+08	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
6.6271E+08	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
6.9427E+08	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
7.2583E+08	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
7.5738E+08	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
7.8894E+08	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
8.2050E+08	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
8.5206E+08	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
8.8361E+08	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
9.1517E+08	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
9.4673E+08	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
9.7829E+08	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
1.0098E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
1.0414E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
1.0730E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
1.1045E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
1.1361E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
1.1676E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
1.1992E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
1.2307E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
1.2623E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
1.2939E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
1.3254E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
1.3570E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
1.3885E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
1.4201E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
1.4517E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
1.4832E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
1.5148E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
1.5463E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
1.5779E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
1.6094E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
1.6410E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
1.6726E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
1.7041E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
1.7357E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01

1.7672E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
1.7988E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
1.8303E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
1.8619E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
1.8935E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
1.9250E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
1.9566E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
1.9881E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
2.0197E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
2.0512E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
2.0828E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
2.1144E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
2.1459E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
2.1775E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
2.2090E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
2.2406E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
2.2721E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
2.3037E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
2.3353E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
2.3668E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
2.3984E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
2.4299E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
2.4615E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
2.4931E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
2.5246E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
2.5562E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
2.5877E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
2.6193E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
2.6508E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
2.6824E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
2.7140E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
2.7455E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
2.7771E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
2.8086E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
2.8402E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
2.8717E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
2.9033E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
2.9349E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
2.9664E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01

2.9980E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
3.0295E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
3.0611E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
3.0926E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
3.1242E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01
3.1558E+09	1.0759E+03	1.0000E+01	1.0000E+01	2.4398E+01

Contour of drawdown at time step 50 stress period 1

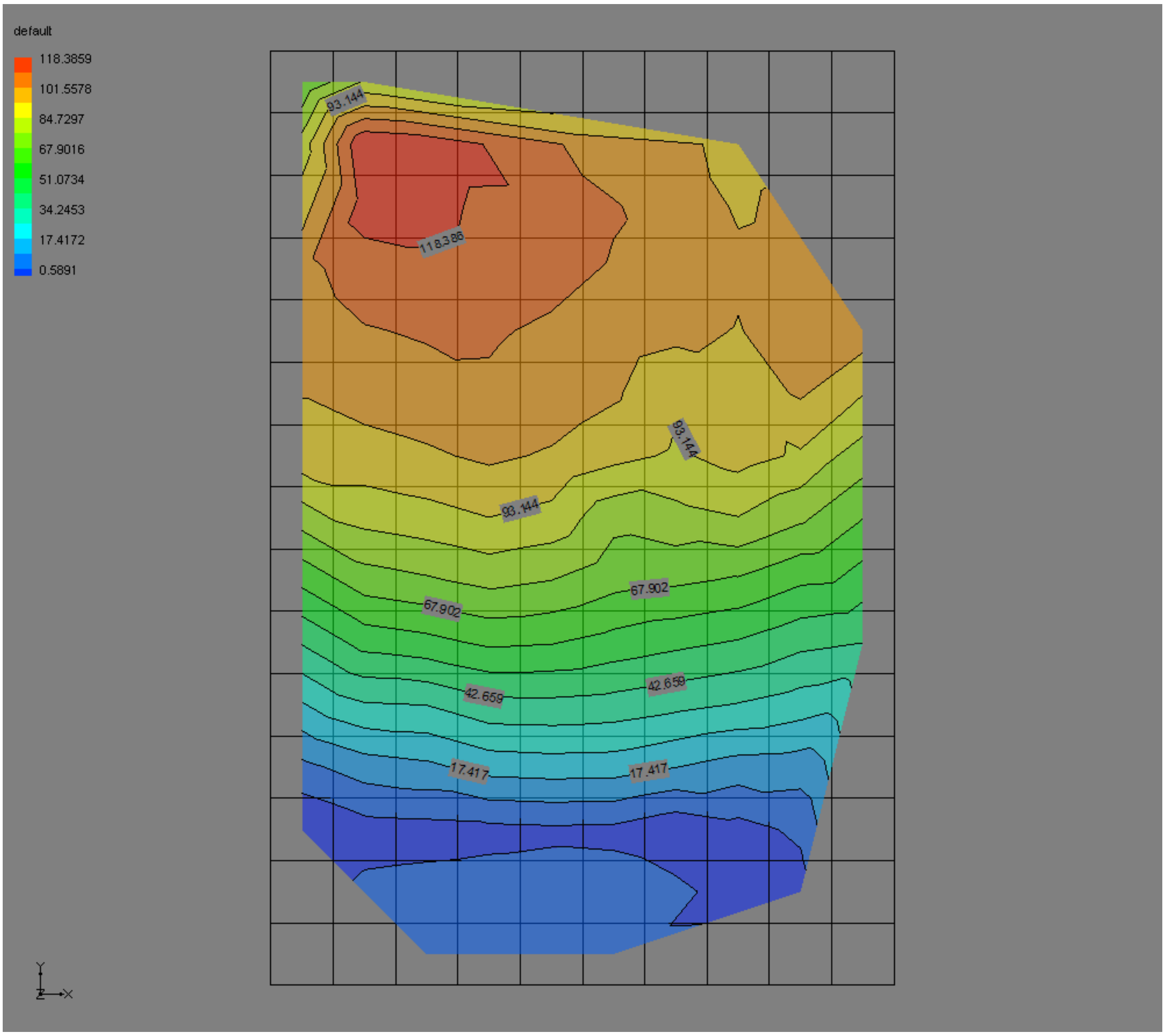


Figure 1.16

1.5 Results: In the output file created, besides the volumetric budget for the entire model, the volumetric budget for the unsaturated zone is also created in SFR2 package. The biggest difference in the volumetric budget in SFR2 package is that the inflow to aquifer and outflow from aquifer due to stream leakage is smaller in SFR2 package than in SFR1 package. This is because, unlike SFR1 package, seepage loss from the stream may be restricted by the hydraulic conductivity of the unsaturated zone (Niswonger and Prudic, 2006). The contour of drawdown (Figure 1.16) shows that drawdown is maximum in the vicinity of first segment instead of being maximum at the vicinity of the wells (as in SFR1 package, Figure 1.14). As in SFR1 package, the contours of drawdown in SFR2 were expected to be centralized around the locations of well, but this was not achieved. Therefore, a sensitivity analysis was done to see what could have possibly caused the drawdown to occur more in the vicinity of first segment than near the vicinity of the wells. The sensitivity analysis was done by keeping the Saturated Hydraulic conductivity (in LPF package) and specific yield constant all over the cells, and changing saturated water content (Ɵs), Brooks and Corey exponent, and unsaturated hydraulic conductivity of the unsaturated beneath the stream.

1.5.1 Sensitivity analysis:

Case 1: As a first test, the saturated hydraulic conductivity, Ks (in the LPF package) was kept equal to $2*10^{-3}$ ft/sec and Specific yield (Sy) was kept equal to 0.2 for all of the cells. The unsaturated hydraulic conductivity of the unsaturated zone (K) was also kept equal to $2*10^{-3}$ ft/sec as well. The saturated water content (Ɵs) was kept equal to 0.35, initial water content (Ɵi) to 0.25, and Brooks and Corey exponent was kept equal to 3.5. The output form the simulation is as shown below (only volumetric budget and drawdown are shown):

```
  VOLUMETRIC  BUDGET  FOR  UNSATURATED  ZONE  BENEATH  STREAMS  AT  END  OF  TIME  STEP   50  STRESS
PERIOD   1

    CUMULATIVE VOLUMES             L**3    RATES FOR THIS TIME STEP         L**3/T
    ------------------                     ------------------------


          STREAM LOSS =  54599241728.0000           STREAM LOSS =           35.0000
    CHANGE IN STORAGE =      1904264.0000     CHANGE IN STORAGE =        2.2276E-04
       RECHARGE TO GW =  54586896384.0000        RECHARGE TO GW =           34.9930

             TOTAL IN =  54599241728.0000              TOTAL IN =           35.0000

            TOTAL OUT =  54588801024.0000             TOTAL OUT =           34.9932

             IN - OUT =     10440704.0000              IN - OUT =        6.7558E-03

  PERCENT DISCREPANCY =             0.00     PERCENT DISCREPANCY =             0.00
```

DRAWDOWN IN LAYER 1 AT END OF TIME STEP 50 IN STRESS PERIOD 1

	1	2	3	4	5	6	7	8	9	10
1	25.35	31.8	6999	6999	6999	6999	6999	6999	6999	6999
2	35.67	39.89	43.44	6999	6999	42.26	41.16	40.56	6999	6999
3	6999	45.33	45.48	40.17	41	37.92	34.64	31.99	6999	6999
4	45.65	45.03	44.87	42.43	40.38	37.86	36.81	32.17	35.96	6999
5	44.97	44.17	43.67	43.05	41.61	39.32	36.11	31.15	35.5	35.61
6	43.87	43.47	43.75	45.28	43.98	39.96	30.07	29.74	34.93	36.08
7	43.01	42.13	42.69	44.91	43.4	38.53	32.73	34.62	33.74	6999
8	6999	38.96	39.92	42.44	40.66	28.99	30.61	32.06	30.95	6999
9	6999	33.89	34.99	37.65	35.76	30.01	28.07	26.69	25.94	6999
10	6999	26.69	27.72	30.44	28.95	25.01	21.43	20.75	20.48	22.16
11	6999	17.47	17.96	20.2	19.42	17.55	14.44	14.09	14.34	6999
12	3.083	7.341	9.137	10.85	10.6	9.767	5.908	6.047	8.265	6999
13	-8.084	-3.325	-3.058	-2.625	-2.151	-2.857	-6.799	-2.222	3.6	6999
14	6999	1.445	2.073	2.603	2.987	3.174	2.668	-2.434	-2.95	6999
15	6999	6999	2.801	3.129	3.377	3.572	6999	6999	6999	6999

```
  VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP 50 IN STRESS PERIOD   1
  ------------------------------------------------------------------------------

     CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
     ------------------                 ------------------------

           IN:                                      IN:
           ---                                      ---
             STORAGE = 15530801152.0000               STORAGE =          1.3237
       CONSTANT HEAD =           0.0000         CONSTANT HEAD =          0.0000
               WELLS =           0.0000                 WELLS =          0.0000
                  ET =           0.0000                    ET =          0.0000
     HEAD DEP BOUNDS =   420421568.0000       HEAD DEP BOUNDS =          0.2679
            RECHARGE =  2830322944.0000              RECHARGE =          1.7937
      STREAM LEAKAGE = 98706481152.0000        STREAM LEAKAGE =         67.4243

            TOTAL IN =117488025600.0000              TOTAL IN =         70.8097


          OUT:                                     OUT:
          ----                                     ----
             STORAGE =   318310816.0000               STORAGE =          0.0000
       CONSTANT HEAD =           0.0000         CONSTANT HEAD =          0.0000
               WELLS = 78894014464.0000                 WELLS =         50.0000
                  ET = 25113212928.0000                    ET =         14.8706
     HEAD DEP BOUNDS =   310513024.0000       HEAD DEP BOUNDS =          0.1932
            RECHARGE =           0.0000              RECHARGE =          0.0000
      STREAM LEAKAGE = 12861438976.0000        STREAM LEAKAGE =          5.7537
```

```
          TOTAL OUT =117497487360.0000              TOTAL OUT =          70.8175

           IN - OUT =     -9461760.0000              IN - OUT =      -7.7820E-03

 PERCENT DISCREPANCY =           -0.01     PERCENT DISCREPANCY =          -0.01
```

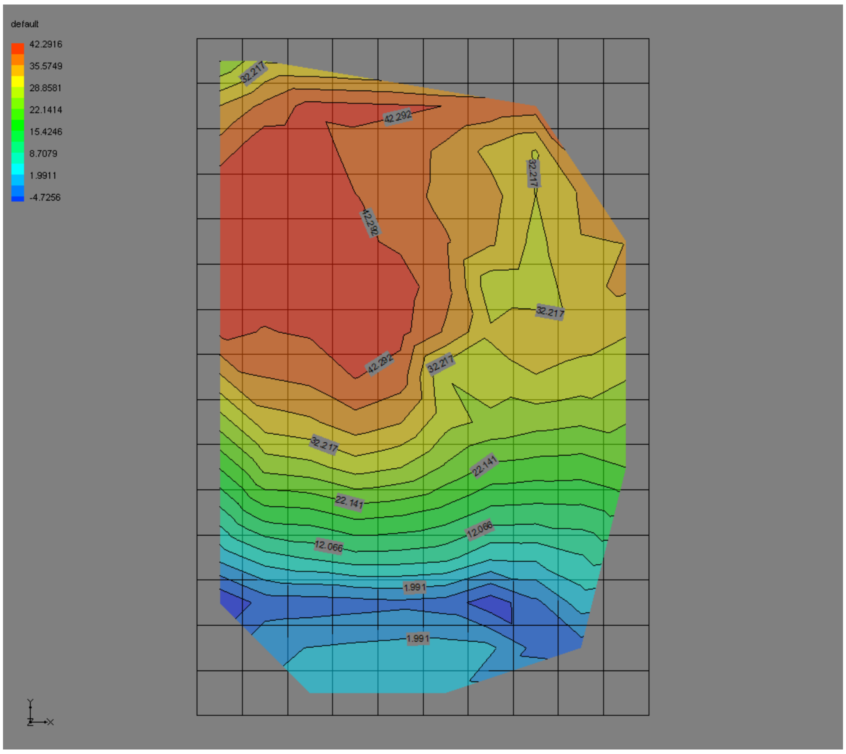


Figure 1.17: Contour of drawdown at time step 50 stress period 1 (Case 1)

Case 2: This case is similar to case 1 except that the Brooks and Corey exponent was changed to 7. Ks, K, S_y, Θ_s, Θ_i are as in case 1. There was not any significant change in the volumetric budgets and drawdown, as can be seen from the output from the simulation as shown below:

```
VOLUMETRIC BUDGET FOR UNSATURATED ZONE BENEATH STREAMS AT END OF TIME STEP  50 STRESS PERIOD
1
  ---------------------------------------------------------------------------------------------
-----

    CUMULATIVE VOLUMES            L**3    RATES FOR THIS TIME STEP         L**3/T
    ------------------                    ------------------------


          STREAM LOSS =  54599147520.0000          STREAM LOSS =           35.0000
    CHANGE IN STORAGE =      3799374.2500    CHANGE IN STORAGE =        3.9870E-04
       RECHARGE TO GW =  54584885248.0000       RECHARGE TO GW =           34.9929

             TOTAL IN =  54599147520.0000             TOTAL IN =           35.0000

            TOTAL OUT =  54588686336.0000            TOTAL OUT =           34.9933

             IN - OUT =     10461184.0000             IN - OUT =        6.7406E-03

  PERCENT DISCREPANCY =            0.00      PERCENT DISCREPANCY =            0.00
```

DRAWDOWN IN LAYER   1 AT END OF TIME STEP 50 IN STRESS PERIOD   1

	1	2	3	4	5	6	7	8	9	10
1	25.35	31.8	6999	6999	6999	6999	6999	6999	6999	6999
2	35.67	39.9	43.44	6999	6999	42.26	41.16	40.56	6999	6999
3	6999	45.33	45.49	40.18	41.01	37.92	34.64	31.99	6999	6999
4	45.65	45.03	44.87	42.43	40.38	37.86	36.81	32.18	35.96	6999
5	44.97	44.17	43.67	43.05	41.61	39.32	36.11	31.15	35.5	35.61
6	43.87	43.47	43.75	45.28	43.98	39.96	30.07	29.74	34.93	36.08
7	43.01	42.13	42.69	44.91	43.4	38.53	32.74	34.62	33.74	6999
8	6999	38.96	39.92	42.44	40.66	28.99	30.62	32.06	30.95	6999
9	6999	33.89	34.99	37.65	35.76	30.01	28.07	26.69	25.94	6999
10	6999	26.69	27.72	30.44	28.95	25.01	21.43	20.75	20.48	22.16
11	6999	17.47	17.96	20.2	19.42	17.55	14.44	14.09	14.34	6999
12	3.083	7.341	9.138	10.85	10.6	9.767	5.908	6.047	8.266	6999
13	-8.084	-3.325	-3.058	-2.625	-2.151	-2.857	-6.799	-2.222	3.6	6999
14	6999	1.445	2.073	2.603	2.987	3.174	2.668	-2.434	-2.95	6999
15	6999	6999	2.801	3.129	3.377	3.572	6999	6999	6999	6999

```
VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP 50 IN STRESS PERIOD   1
------------------------------------------------------------------------------

   CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
   ------------------                 ------------------------

         IN:                                   IN:
         ---                                   ---
           STORAGE = 15531058176.0000             STORAGE =          1.3232
     CONSTANT HEAD =            0.0000      CONSTANT HEAD =          0.0000
             WELLS =            0.0000              WELLS =          0.0000
                ET =            0.0000                 ET =          0.0000
   HEAD DEP BOUNDS =   420421888.0000     HEAD DEP BOUNDS =          0.2679
          RECHARGE =  2830322944.0000            RECHARGE =          1.7937
    STREAM LEAKAGE = 98705571840.0000      STREAM LEAKAGE =         67.4245

          TOTAL IN =117487378432.0000            TOTAL IN =         70.8094

        OUT:                                  OUT:
        ----                                  ----
           STORAGE =   318297248.0000             STORAGE =          0.0000
     CONSTANT HEAD =            0.0000      CONSTANT HEAD =          0.0000
             WELLS = 78894014464.0000               WELLS =         50.0000
                ET = 25113006080.0000                  ET =         14.8706
   HEAD DEP BOUNDS =   310512000.0000     HEAD DEP BOUNDS =          0.1932
          RECHARGE =            0.0000           RECHARGE =          0.0000
    STREAM LEAKAGE = 12861056000.0000      STREAM LEAKAGE =          5.7535

         TOTAL OUT =117496889344.0000           TOTAL OUT =         70.8173

          IN - OUT =    -9510912.0000            IN - OUT =     -7.8888E-03

PERCENT DISCREPANCY =          -0.01    PERCENT DISCREPANCY =         -0.01
```

Case 3: This case is also similar case 1 except that the Brooks and Corey exponent was changed to 1.75. Ks, K, Sy, ϴs, ϴi are as in case 1. There was not any significant change in the volumetric budgets and drawdown, as can be seen from output from the simulation as shown below:

```
  VOLUMETRIC BUDGET FOR UNSATURATED ZONE BENEATH STREAMS AT END OF TIME STEP   50 STRESS
PERIOD   1
  ---------------------------------------------------------------------------------------

    CUMULATIVE VOLUMES           L**3    RATES FOR THIS TIME STEP        L**3/T
    ------------------                   ------------------------


        STREAM LOSS =  54599217152.0000          STREAM LOSS =          35.0000
    CHANGE IN STORAGE =        291651.6562     CHANGE IN STORAGE =      6.9901E-05
       RECHARGE TO GW =  54588682240.0000        RECHARGE TO GW =         34.9932

             TOTAL IN =  54599217152.0000              TOTAL IN =         35.0000

            TOTAL OUT =  54588973056.0000             TOTAL OUT =         34.9932

             IN - OUT =     10244096.0000              IN - OUT =      6.7749E-03

  PERCENT DISCREPANCY =             0.00    PERCENT DISCREPANCY =           0.00
```

DRAWDOWN IN LAYER 1 AT END OF TIME STEP 50 IN STRESS PERIOD 1

	1	2	3	4	5	6	7	8	9	10
1	25.35	31.8	6999	6999	6999	6999	6999	6999	6999	6999
2	35.67	39.89	43.43	6999	6999	42.26	41.16	40.56	6999	6999
3	6999	45.33	45.48	40.17	41	37.92	34.64	31.99	6999	6999
4	45.65	45.03	44.87	42.43	40.37	37.86	36.81	32.17	35.96	6999
5	44.97	44.17	43.67	43.05	41.61	39.32	36.11	31.15	35.5	35.61
6	43.87	43.47	43.75	45.28	43.98	39.96	30.06	29.74	34.93	36.08
7	43.01	42.13	42.68	44.91	43.4	38.53	32.73	34.62	33.74	6999
8	6999	38.96	39.92	42.43	40.66	28.99	30.61	32.06	30.95	6999
9	6999	33.89	34.99	37.65	35.76	30.01	28.07	26.69	25.94	6999
10	6999	26.69	27.72	30.43	28.95	25.01	21.43	20.75	20.48	22.16
11	6999	17.47	17.96	20.2	19.42	17.55	14.44	14.09	14.34	6999
12	3.083	7.341	9.137	10.85	10.6	9.767	5.908	6.047	8.265	6999
13	-8.084	-3.325	-3.058	-2.625	-2.151	-2.857	-6.799	-2.222	3.6	6999
14	6999	1.445	2.073	2.603	2.987	3.174	2.668	-2.434	-2.95	6999
15	6999	6999	2.801	3.128	3.377	3.572	6999	6999	6999	6999

```
  VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP 50 IN STRESS PERIOD   1
  ------------------------------------------------------------------------------

     CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
     ------------------                 ------------------------
           IN:                                     IN:
           ---                                     ---
             STORAGE = 15530553344.0000               STORAGE =          1.3242
       CONSTANT HEAD =            0.0000         CONSTANT HEAD =          0.0000
               WELLS =            0.0000                 WELLS =          0.0000
                  ET =            0.0000                    ET =          0.0000
     HEAD DEP BOUNDS =   420421312.0000       HEAD DEP BOUNDS =          0.2679
            RECHARGE =  2830322944.0000              RECHARGE =          1.7937
      STREAM LEAKAGE = 98707202048.0000        STREAM LEAKAGE =         67.4244

            TOTAL IN =117488500736.0000              TOTAL IN =         70.8102
          OUT:                                    OUT:

          ----                                    ----
             STORAGE =   318320960.0000               STORAGE =          0.0000
       CONSTANT HEAD =            0.0000         CONSTANT HEAD =          0.0000
               WELLS = 78894014464.0000                 WELLS =         50.0000
                  ET = 25113391104.0000                    ET =         14.8707
     HEAD DEP BOUNDS =   310513568.0000       HEAD DEP BOUNDS =          0.1932
            RECHARGE =            0.0000              RECHARGE =          0.0000
      STREAM LEAKAGE = 12861798400.0000        STREAM LEAKAGE =          5.7538

           TOTAL OUT =117498036224.0000             TOTAL OUT =         70.8176
            IN - OUT =     -9535488.0000              IN - OUT =     -7.4234E-03
   PERCENT DISCREPANCY =           -0.01     PERCENT DISCREPANCY =           -0.01
```

Case 4: This case is also similar to case 1 except that the saturated water content (ϴs) was kept equal to 0.45. Ks, K, Sy, ϴi, Brooks and Corey exponent are as in case 1. There was not any significant change in the volumetric budgets and drawdown as can be seen from the output from the simulation as shown below:

```
  VOLUMETRIC  BUDGET  FOR  UNSATURATED  ZONE  BENEATH  STREAMS  AT  END  OF  TIME  STEP   50  STRESS
PERIOD   1
  ---------------------------------------------------------------------------------------------
-----

    CUMULATIVE VOLUMES             L**3    RATES FOR THIS TIME STEP         L**3/T
    ------------------                     ------------------------


          STREAM LOSS =  54599180288.0000           STREAM LOSS =           35.0000
    CHANGE IN STORAGE =      2348010.2500     CHANGE IN STORAGE =        2.2273E-04
       RECHARGE TO GW =  54586437632.0000        RECHARGE TO GW =           34.9930

             TOTAL IN =  54599180288.0000              TOTAL IN =           35.0000

            TOTAL OUT =  54588784640.0000             TOTAL OUT =           34.9933

             IN - OUT =     10395648.0000              IN - OUT =        6.7444E-03

  PERCENT DISCREPANCY =            0.00     PERCENT DISCREPANCY =             0.00


DRAWDOWN IN LAYER   1 AT END OF TIME STEP  50 IN STRESS PERIOD    1
```

	1	2	3	4	5	6	7	8	9	10
1	25.35	31.8	6999	6999	6999	6999	6999	6999	6999	6999
2	35.67	39.89	43.44	6999	6999	42.26	41.16	40.56	6999	6999
3	6999	45.33	45.48	40.17	41	37.92	34.64	31.99	6999	6999
4	45.65	45.03	44.87	42.43	40.38	37.86	36.81	32.17	35.96	6999
5	44.97	44.17	43.67	43.05	41.61	39.32	36.11	31.15	35.5	35.61
6	43.87	43.47	43.75	45.28	43.98	39.96	30.07	29.74	34.93	36.08
7	43.01	42.13	42.69	44.91	43.4	38.53	32.73	34.62	33.74	6999
8	6999	38.96	39.92	42.44	40.66	28.99	30.61	32.06	30.95	6999
9	6999	33.89	34.99	37.65	35.76	30.01	28.07	26.69	25.94	6999
10	6999	26.69	27.72	30.44	28.95	25.01	21.43	20.75	20.48	22.16
11	6999	17.47	17.96	20.2	19.42	17.55	14.44	14.09	14.34	6999
12	3.083	7.341	9.137	10.85	10.6	9.767	5.908	6.047	8.265	6999
13	-8.084	-3.325	-3.058	-2.625	-2.151	-2.857	-6.799	-2.222	3.6	6999
14	6999	1.445	2.073	2.603	2.987	3.174	2.668	-2.434	-2.95	6999
15	6999	6999	2.801	3.129	3.377	3.572	6999	6999	6999	6999

```
 VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP 50 IN STRESS PERIOD   1
  ------------------------------------------------------------------------------

     CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
     ------------------                 ------------------------

           IN:                                      IN:
           ---                                      ---
             STORAGE = 15530771456.0000               STORAGE =          1.3237
       CONSTANT HEAD =           0.0000         CONSTANT HEAD =          0.0000
               WELLS =           0.0000                 WELLS =          0.0000
                  ET =           0.0000                    ET =          0.0000
     HEAD DEP BOUNDS =   420421664.0000       HEAD DEP BOUNDS =          0.2679
            RECHARGE =  2830322944.0000              RECHARGE =          1.7937
      STREAM LEAKAGE = 98706268160.0000        STREAM LEAKAGE =         67.4243

            TOTAL IN =117487788032.0000              TOTAL IN =         70.8097

          OUT:                                     OUT:
          ----                                     ----
             STORAGE =   318284480.0000               STORAGE =          0.0000
       CONSTANT HEAD =           0.0000         CONSTANT HEAD =          0.0000
               WELLS = 78894014464.0000                 WELLS =         50.0000
                  ET = 25113137152.0000                    ET =         14.8706
     HEAD DEP BOUNDS =   310512288.0000       HEAD DEP BOUNDS =          0.1932
            RECHARGE =           0.0000              RECHARGE =          0.0000
      STREAM LEAKAGE = 12861330432.0000        STREAM LEAKAGE =          5.7537

           TOTAL OUT =117497282560.0000             TOTAL OUT =         70.8175

            IN - OUT =    -9494528.0000              IN - OUT =     -7.8049E-03

 PERCENT DISCREPANCY =           -0.01     PERCENT DISCREPANCY =           -0.01
```

Case 5: This case is similar to case 1 except that the unsaturated hydraulic conductivity (K) of the unsaturated zone beneath the stream was changed to $2.0*10^{-6}$ ft/ sec as in section 1.4.1. Ks, ϴs , Sy, ϴi, Brooks and Corey exponent are as in case 1. Now there was a significant difference in the volumetric budget, stream loss & gain, and drawdown in this case as can be seen from the output file as shown below:

```
  VOLUMETRIC  BUDGET  FOR  UNSATURATED  ZONE  BENEATH  STREAMS  AT  END  OF  TIME  STEP   50  STRESS
PERIOD   1
  -------------------------------------------------------------------------------------------
-----

    CUMULATIVE VOLUMES             L**3    RATES FOR THIS TIME STEP         L**3/T
    ------------------                     ------------------------


          STREAM LOSS =   4394316288.0000           STREAM LOSS =           2.7969
    CHANGE IN STORAGE =     22404116.0000     CHANGE IN STORAGE =       2.5321E-03
       RECHARGE TO GW =   4371885056.0000        RECHARGE TO GW =           2.7944

             TOTAL IN =   4394316288.0000              TOTAL IN =           2.7969

            TOTAL OUT =   4394289152.0000             TOTAL OUT =           2.7969

             IN - OUT =        27136.0000              IN - OUT =      -7.1526E-07

  PERCENT DISCREPANCY =             0.00      PERCENT DISCREPANCY =            0.00
```

DRAWDOWN IN LAYER   1 AT END OF TIME STEP 50 IN STRESS PERIOD   1

	1	2	3	4	5	6	7	8	9	10
1	73.51	85.59	6999	6999	6999	6999	6999	6999	6999	6999
2	89.4	114.4	110.5	6999	6999	98.7	97.26	96.18	6999	6999
3	6999	109.1	107.6	100.2	99.72	95.96	92.24	88.9	6999	6999
4	98.68	101.2	101.1	98.04	95.94	92.86	91.9	88.81	91.55	6999
5	94.99	95.14	94.88	94.1	92.62	90.54	88.11	85.2	90.91	91.69
6	90.38	89.91	90.18	91.91	90.63	86.94	78.35	80.58	86.68	88.21
7	86.47	83.81	84.02	86.45	84.98	80.49	76.31	79.34	78.57	6999
8	6999	74.22	75.14	77.93	76.17	64.94	67.48	69.2	66.77	6999
9	6999	61.96	63.27	66.23	64.47	59	56.76	54.75	52.36	6999
10	6999	47.6	48.97	51.99	50.8	46.79	42.65	40.98	39.28	40.67
11	6999	31.14	32.27	34.86	34.36	32.41	28.74	27.7	27.35	6999
12	6.776	13.7	16.65	18.77	18.65	17.72	13.17	13.06	15.41	6999
13	-7.879	-2.924	-2.386	-1.783	-1.195	-1.774	-6.255	-1.633	5.812	6999
14	6999	1.996	2.782	3.417	3.869	4.042	3.271	-2.006	-2.809	6999
15	6999	6999	3.548	3.932	4.225	4.426	6999	6999	6999	6999

```
 VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP 50 IN STRESS PERIOD   1
  ------------------------------------------------------------------------------

      CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
      ------------------                 ------------------------

            IN:                                      IN:
            ---                                      ---
              STORAGE = 33797984256.0000               STORAGE =          3.9455
        CONSTANT HEAD =            0.0000        CONSTANT HEAD =          0.0000
                WELLS =            0.0000                WELLS =          0.0000
                   ET =            0.0000                   ET =          0.0000
      HEAD DEP BOUNDS =   426072640.0000       HEAD DEP BOUNDS =          0.2733
             RECHARGE =  2830322944.0000              RECHARGE =          1.7937
       STREAM LEAKAGE = 72247271424.0000        STREAM LEAKAGE =         59.5106

             TOTAL IN =109301653504.0000              TOTAL IN =         65.5231

           OUT:                                     OUT:
           ----                                     ----
              STORAGE =   271186112.0000               STORAGE =      6.0046E-02
        CONSTANT HEAD =            0.0000        CONSTANT HEAD =          0.0000
                WELLS = 78894014464.0000                 WELLS =         50.0000
                   ET = 23097933824.0000                    ET =         13.4633
      HEAD DEP BOUNDS =   304983616.0000       HEAD DEP BOUNDS =          0.1854
             RECHARGE =            0.0000             RECHARGE =          0.0000
       STREAM LEAKAGE =  6740577280.0000        STREAM LEAKAGE =          1.8206

            TOTAL OUT =109308698624.0000             TOTAL OUT =         65.5294

             IN - OUT =    -7045120.0000              IN - OUT =     -6.2332E-03

  PERCENT DISCREPANCY =          -0.01     PERCENT DISCREPANCY =          -0.01
```

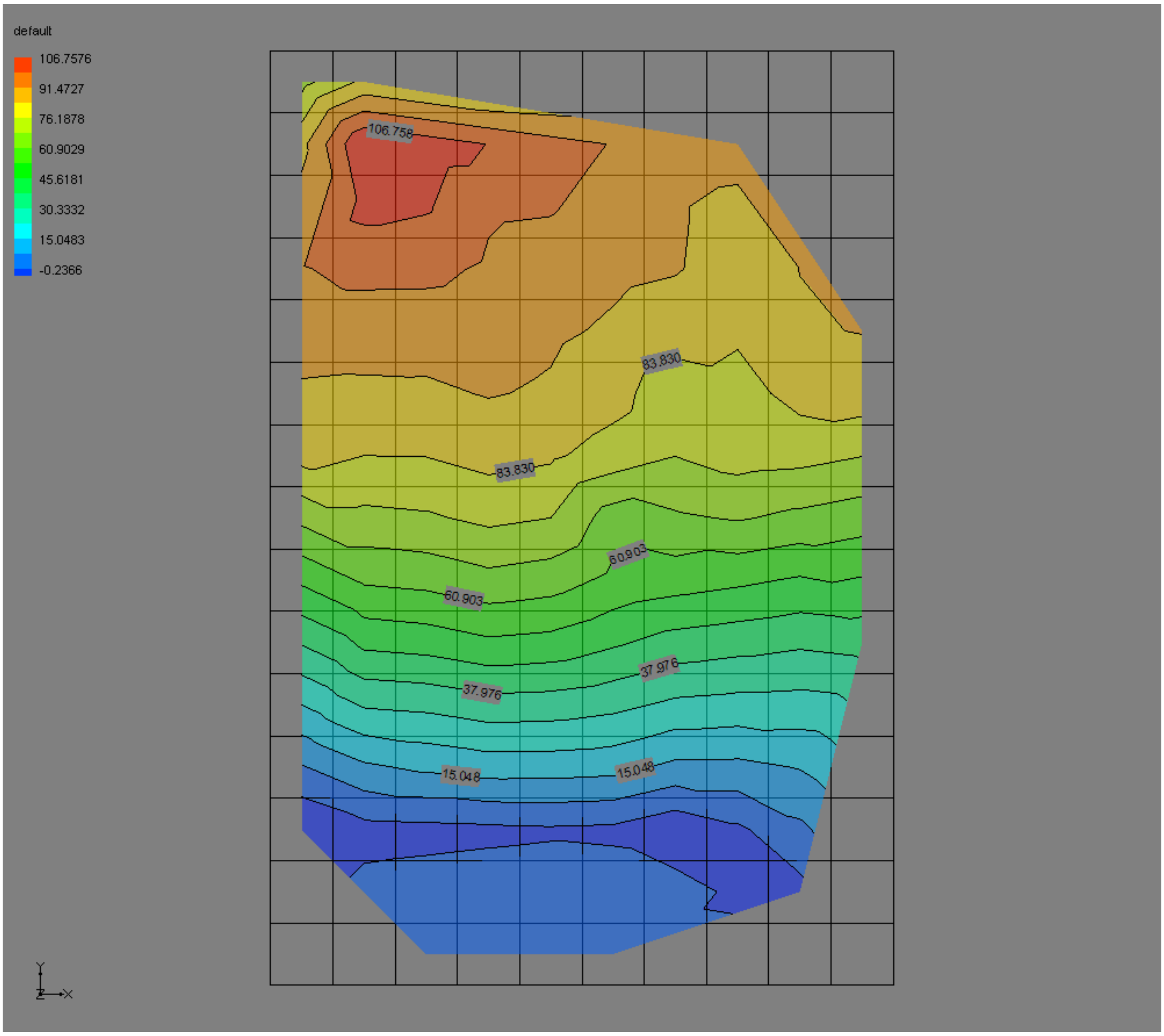


Figure 1.18: Contour of drawdown at time step 50, stress period 1 (case 5)

Case 6: From the above five cases, it was learned that the most important parameter affecting the volumetric budget and heads in the cell was the unsaturated hydraulic conductivity. In case 5, although it was seen that changing the unsaturated hydraulic conductivity makes a difference in the water budget and heads in the cell, the cone of depression (maximum drawdown) still could not be achieved near well locations. So it was tested wheather the stress caused due to pumping of the wells is not sufficient enough to create a cone of depression around them. Since drawdown in case 1 (Figure 1.17) shows a more realistic state, this case was again simulated, but this time doubling the pumping rate, i.e., pumping equal to -10 cfs for each of the wells. Since there are ten wells the total pumping equals to -100 cfs.

Finally this same case was simulated using the SFR1 package as well to compare how different the drawdown would be. The contours of drawdown and volumetric budget for the entire model are the same and there seem to be no significant difference (Figure 1.19 and 1.20).

<u>Outputs for Case 6 using SFR2 package</u>

```
 VOLUMETRIC BUDGET FOR UNSATURATED ZONE BENEATH STREAMS AT END OF TIME STEP  50 STRESS PERIOD
1
  ------------------------------------------------------------------------------------------
    CUMULATIVE VOLUMES             L**3    RATES FOR THIS TIME STEP         L**3/T
    ------------------                     ------------------------


         STREAM LOSS =  55075794944.0000           STREAM LOSS =           35.1982
    CHANGE IN STORAGE =      4992201.5000      CHANGE IN STORAGE =        6.7139E-04
       RECHARGE TO GW =  55058694144.0000         RECHARGE TO GW =           35.1894

            TOTAL IN =  55075794944.0000              TOTAL IN =           35.1982

           TOTAL OUT =  55063687168.0000             TOTAL OUT =           35.1901

            IN - OUT =     12107776.0000              IN - OUT =        8.0757E-03

  PERCENT DISCREPANCY =            0.01      PERCENT DISCREPANCY =            0.01
```

DRAWDOWN IN LAYER   1 AT END OF TIME STEP 50 IN STRESS PERIOD   1

	1	2	3	4	5	6	7	8	9	10
1	47.63	66.36	6999	6999	6999	6999	6999	6999	6999	6999
2	70.33	86.05	93.83	6999	6999	93.72	92	90.79	6999	6999
3	6999	96.95	98.77	94.07	94.8	90.85	86.59	83.09	6999	6999
4	99.21	99.09	99.8	97.8	95.29	91.72	89.3	82.82	85.16	6999
5	99.59	100	100.4	100.6	98.48	94.01	88.7	81.71	83.91	79.78
6	99.36	100.1	101.9	106.5	104	95.26	82.23	79.7	83.58	81.9
7	98.45	97.89	100.1	106	102.9	92.37	83.11	83.36	80.48	6999
8	6999	90.56	93.52	100	96.17	78.77	76.99	76.49	72.7	6999
9	6999	78.08	81.28	87.75	84.04	73.1	67.68	63.56	59.65	6999
10	6999	61.08	64.04	69.92	67.48	59.37	52.66	49.07	46.04	47.3
11	6999	40.33	42.5	45.93	45	41.42	36.23	33.83	32.62	6999
12	9.423	18.1	22.06	24.58	24.26	22.71	17.34	16.44	18.48	6999
13	-7.472	-2.385	-1.655	-0.9343	-0.3114	-0.8985	-5.822	-1.346	6.751	6999
14	6999	2.635	3.526	4.221	4.678	4.772	3.74	-1.738	-2.744	6999
15	6999	6999	4.31	4.717	5.007	5.172	6999	6999	6999	6999

```
 VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP 50 IN STRESS PERIOD   1
  ------------------------------------------------------------------------------

     CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
     ------------------                 ------------------------

           IN:                                      IN:
           ---                                      ---
             STORAGE = 35982270464.0000             STORAGE =          4.1155
       CONSTANT HEAD =           0.0000       CONSTANT HEAD =          0.0000
               WELLS =           0.0000               WELLS =          0.0000
                  ET =           0.0000                  ET =          0.0000
    HEAD DEP BOUNDS =   429597856.0000     HEAD DEP BOUNDS =          0.2757
            RECHARGE =  2830322944.0000            RECHARGE =          1.7937
      STREAM LEAKAGE =145079500800.0000      STREAM LEAKAGE =        108.0355

            TOTAL IN =184321687552.0000            TOTAL IN =        114.2205

          OUT:                                     OUT:
          ----                                     ----
             STORAGE =   255778752.0000             STORAGE =          0.0000
       CONSTANT HEAD =           0.0000       CONSTANT HEAD =          0.0000
               WELLS =157788028928.0000               WELLS =        100.0000
                  ET = 21415413760.0000                  ET =         12.6605
     HEAD DEP BOUNDS =   282252320.0000     HEAD DEP BOUNDS =          0.1699
            RECHARGE =           0.0000            RECHARGE =          0.0000
      STREAM LEAKAGE =  4587444736.0000      STREAM LEAKAGE =          1.3976

           TOTAL OUT =184328912896.0000           TOTAL OUT =        114.2280

            IN - OUT =    -7225344.0000            IN - OUT =     -7.5836E-03

 PERCENT DISCREPANCY =           0.00     PERCENT DISCREPANCY =          -0.01
```

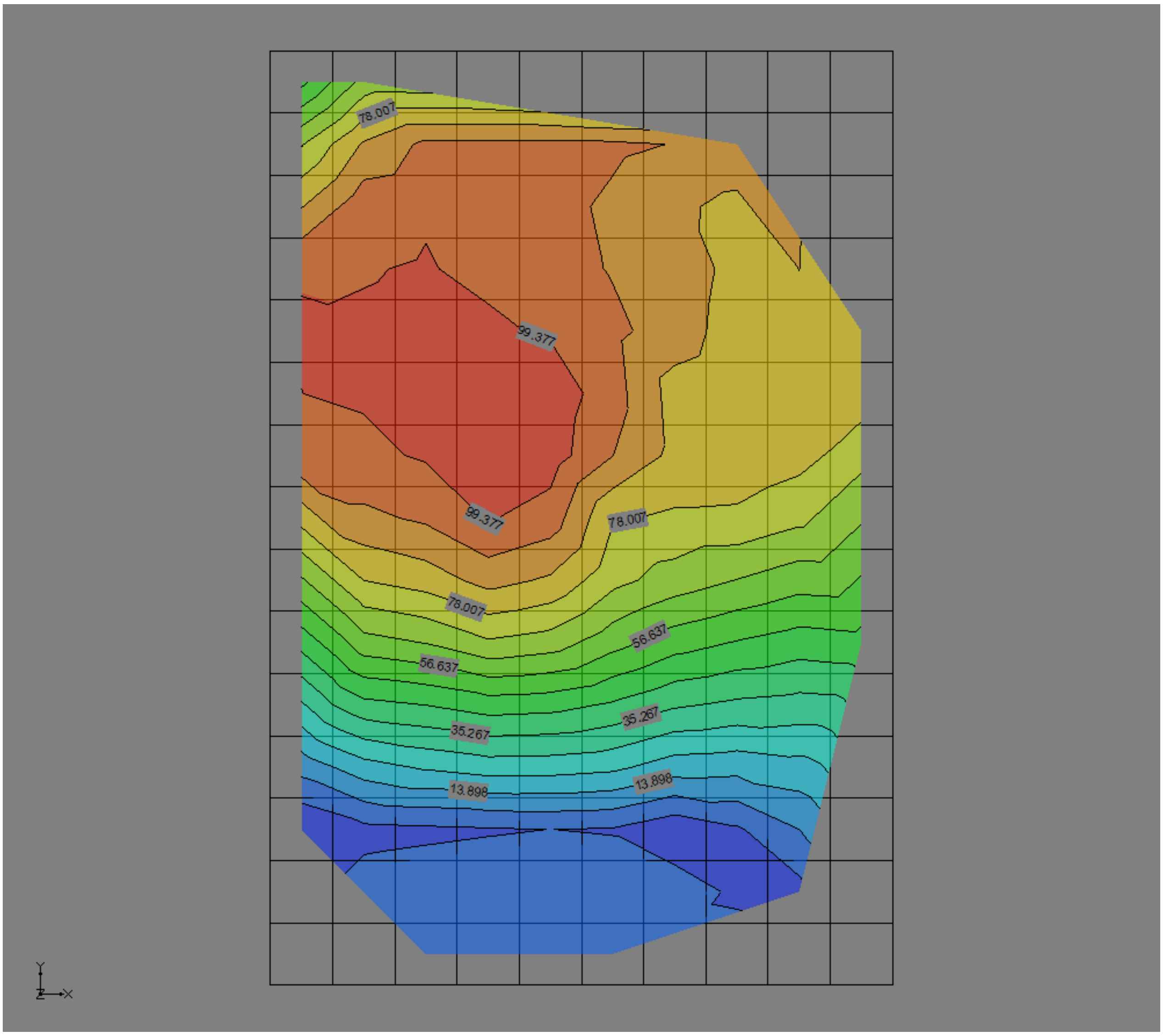


Figure 1.19: Contour of drawdown at time step 50, stress period 1 (Case 6, SFR2)

Outputs for case 6 using SFR1 package

DRAWDOWN IN LAYER 1 AT END OF TIME STEP 50 IN STRESS PERIOD 1

	1	2	3	4	5	6	7	8	9	10
1	47.63	66.35	6999	6999	6999	6999	6999	6999	6999	6999
2	70.33	86.04	93.82	6999	6999	93.7	91.98	90.78	6999	6999
3	6999	96.93	98.75	94.05	94.78	90.83	86.57	83.07	6999	6999
4	99.19	99.07	99.79	97.78	95.27	91.7	89.28	82.81	85.15	6999
5	99.58	100	100.3	100.6	98.47	93.99	88.68	81.69	83.9	79.77
6	99.34	100.1	101.9	106.5	104	95.24	82.21	79.69	83.56	81.89
7	98.43	97.88	100.1	106	102.8	92.36	83.09	83.35	80.46	6999
8	6999	90.55	93.5	100	96.16	78.76	76.98	76.47	72.69	6999
9	6999	78.07	81.27	87.74	84.03	73.09	67.67	63.55	59.64	6999
10	6999	61.08	64.04	69.92	67.47	59.36	52.65	49.07	46.03	47.3
11	6999	40.32	42.5	45.92	44.99	41.42	36.22	33.82	32.62	6999
12	9.422	18.1	22.05	24.58	24.26	22.7	17.34	16.43	18.47	6999
13	-7.472	-2.385	-1.655	-0.9346	-0.3117	-0.8988	-5.822	-1.346	6.751	6999
14	6999	2.635	3.525	4.22	4.678	4.772	3.74	-1.738	-2.744	6999
15	6999	6999	4.31	4.716	5.006	5.172	6999	6999	6999	6999

```
VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP 50 IN STRESS PERIOD   1
  ------------------------------------------------------------------------------

     CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
     ------------------                 ------------------------

           IN:                                      IN:
           ---                                      ---
             STORAGE = 35976613888.0000                STORAGE =          4.1158
       CONSTANT HEAD =            0.0000          CONSTANT HEAD =          0.0000
               WELLS =            0.0000                  WELLS =          0.0000
                  ET =            0.0000                     ET =          0.0000
     HEAD DEP BOUNDS =   429595808.0000        HEAD DEP BOUNDS =          0.2757
            RECHARGE =  2830322944.0000               RECHARGE =          1.7937
      STREAM LEAKAGE =145086038016.0000         STREAM LEAKAGE =        108.0367

            TOTAL IN =184322572288.0000               TOTAL IN =        114.2220

          OUT:                                     OUT:
          ----                                     ----
             STORAGE =   255778016.0000                STORAGE =          0.0000
       CONSTANT HEAD =            0.0000          CONSTANT HEAD =          0.0000
               WELLS =157788028928.0000                  WELLS =        100.0000
                  ET = 21415862272.0000                     ET =         12.6608
     HEAD DEP BOUNDS =   282257152.0000        HEAD DEP BOUNDS =          0.1699
            RECHARGE =            0.0000               RECHARGE =          0.0000
      STREAM LEAKAGE =  4588047872.0000         STREAM LEAKAGE =          1.3979

           TOTAL OUT =184329977856.0000              TOTAL OUT =        114.2287

            IN - OUT =    -7405568.0000               IN - OUT =     -6.7215E-03

 PERCENT DISCREPANCY =            0.00     PERCENT DISCREPANCY =          -0.01
```

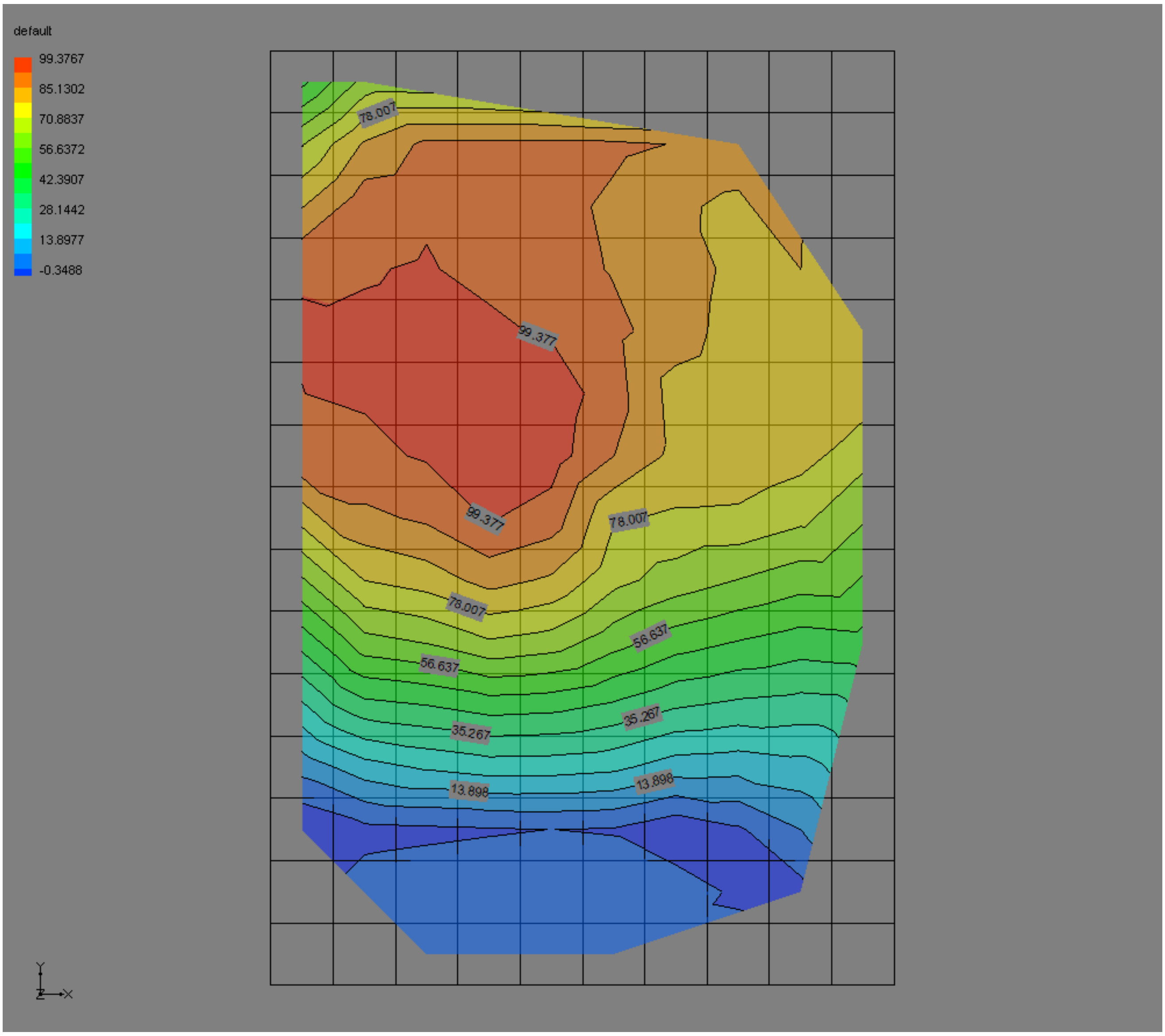


Figure 1.20: Contour of drawdown at time step 50, stress period 1 (Case 6, SFR1)

1.6 Conclusion: Unsaturated hydraulic conductivity is the most sensitive parameter for the SFR2 package. Random choice of the hydraulic parameters may not represent the true results after the model simulation. If applicable, it is best to put the value of the hydraulic properties that is representative of the aquifer of interest. It is because of the value of unsaturated hydraulic conductivity of the unsaturated zone beneath the stream and the stress caused due to pumping that causes the cone of depression to occur somewhere else rather near the well locations as is always expected.

CHAPTER 2: EVT and ETS1 packages

2.1 Introduction: The Evapotranspiration package is used to simulate a head-dependent flux, distributed over the top of the model, and specified in units of length/time. Within MODFLOW, these rates are multiplied by the horizontal area of the cells to which they are applied to calculate the volumetric flux rates (http://water.usgs.gov/nrp/gwsoftware/modflow2000/MFDOC/index.html?introduction). The EVT package to simulate evapotranspiration is available in MODFLOW since its early release. The Evapotranspiration package (EVT) by McDonald and Harbaugh, 1988, provides a useful method for simulating evapotranspiration that may be based on a more simplified conceptual model of evapotranspiration, than is warranted by knowledge of actual field conditions (Banta, 2000). The EVT package simulates evapotranspiration with a single linear function, Figure 2.1 (Banta, 2000).
The new Evapotranspiration Segments (ETS1) package allows simulation of evapotranspiration with a user defined relation between evapotranspiration rate and hydraulic head (Banta, 2000). This capability provides a degree of flexibility not supported by the EVT package (Banta, 2000). In the ETS1 package, the relation of evapotranspiration rate to hydraulic head is conceptualized as a segmented line between an evapotranspiration surface, defined as the elevation where the evapotranspiration rate reaches a maximum, and an elevation located at an extinction depth below the evapotranspiration surface, where the evapotranspiration rate reaches zero (Banta, 2000). The user supplies input to define as many intermediate segment endpoints as desired to define the relation of evapotranspiration rate to head between these two elevations, Figure 2.2 (Banta, 2000). The ETS1 package differs from the EVT package in that ETS1 package allows the user to specify a segmented function for the relation of evapotranspiration rate to depth of head below the ET surface in the variable interval (ET surface – Extinction Depth). The user can specify as many segments as desired to approximate a curve or other type of relation (Banta, 2000). The input data for EVT package include ET surface elevation, maximum ET flux rate, and extinction depth. In the EVT package, Figure 2.1, when the head is in the variable interval (ET surface – Extinction Depth), the evapotranspiration rate is a simple linear function of depth of the head below the ET surface, such that the evapotranspiration rate is the maximum evapotranspiration rate when the depth is zero, and the evapotranspiration rate is zero when the depth equals the extinction depth (Banta, 2000).

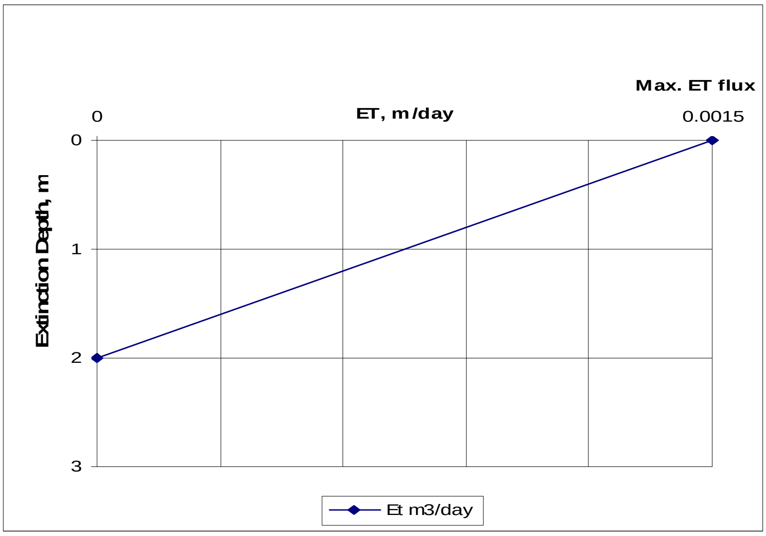


Figure 2.1: Typical graph for Evapotranspiration package

In the ETS1 package, the functional relation of evapotranspiration rate to head is conceptualized as a segmented line in the variable interval (Banta, 2000). The segments that determine the shape of the function in the variable interval are defined by intermediate points where adjacent segments join; Figure 2.2 (Banta, 2000). The ends of the segments at the top and bottom of the variable interval are defined by the ET surface, the maximum evapotranspiration rate, and the extinction depth respectively (Banta, 2000). For each intermediate point, two values, PXDP and PETM, are entered to define the point (Banta, 2000). PXDP is a proportion (between zero and one) of the extinction depth, and PETM is a proportion of the maximum evapotranspiration rate (Banta, 2000). PXDP is 0.0 at the ET surface and is 1.0 at the bottom of the variable interval. PETM is 1.0 at the ET surface and is 0.0 at the bottom of the variable interval (Banta, 2000). The input data for ETS1 package include ET surface, Maximum ET flux, Extinction depth, PXDP (ratio of depth of intermediate point in the variable interval to total extinction depth), and PETM (ratio of ET rate of intermediate point in the variable interval to maximum ET flux).

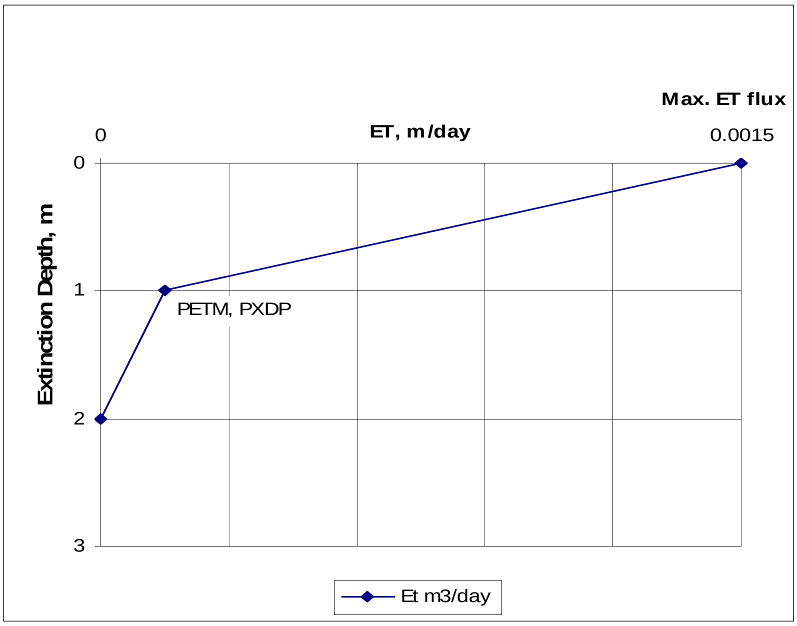


Figure 2.2: Typical graph for ETS1 package

2.2 Limitations of EVT and ETS1 packages: The EVT and ETS1 packages become useless when simulating the unsaturated versions of MODFLOW, UZF1 package and MODFLOW-Hydrus package. But both of them can still be used if simulating the unsaturated version SFR2 package.

2.3 Case Study: A very simple case with nine cells, Figure 2.3 was studied and the results were compared. In one case, EVT was used, and in the other case, ETS1 package was used to simulate the evapotranspiration. The size of each cell was 25 m*25m and all of the cells have a constant top elevation of 100 m. All of the nine cells were considered as active cells. The initial head was kept equal to 95m in all cells. A well was kept at the center pumping at -4 m3/day. The hydraulic conductivity of the cells were kept equal to a constant value of 0.2496 m/day. Specific yield was kept equal to a constant value of 0.28. Recharge of 0.005511 m/day was applied all over the cells. The number of stress periods was taken equal to 1, with length equal to 180 days. Also the number of time steps were taken equal to 180 days, so $\Delta t=1$ day.

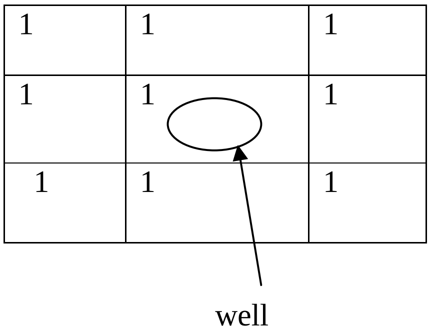
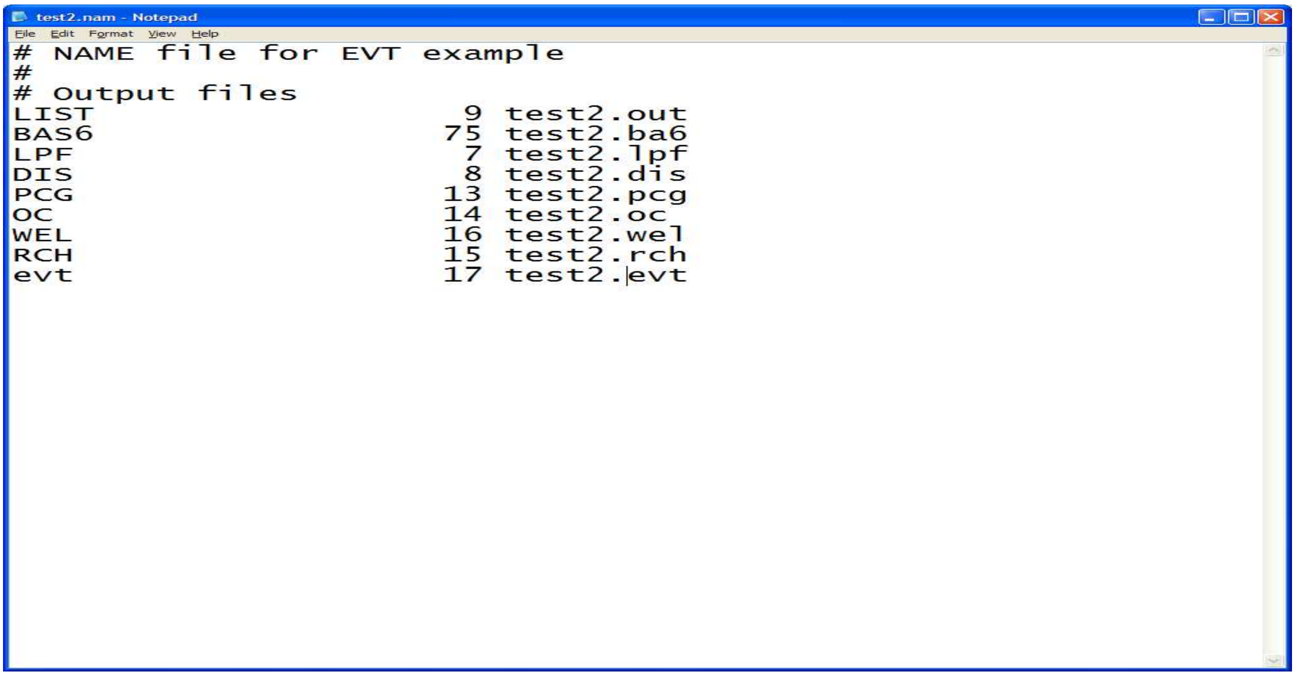


Figure 2.3

2.4.1 MODFLOW Execution using EVT package: In order to simulate evapotranspiration using EVT package the ET surface was kept equal to 100 m for every cell. The maximum evapotranspiration flux at the surface was kept equal to 0.0015 m/day, and extinction depth was kept equal to 2 m for every cell, Figure 2.1. Input to the evapotranspiration (EVT) package is read from the file that is type 'EVT' in the name file (Harbaugh and others, 2000). A Name file (Figure 2.4) was created listing all of the input files and output files. This version ran successfully using both MODFLOW 2000 and MODFLOW 2005 executable programs.



```
test2.nam - Notepad
File  Edit  Format  View  Help
# NAME file for EVT example
#
# Output files
LIST                     9 test2.out
BAS6                    75 test2.ba6
LPF                      7 test2.lpf
DIS                      8 test2.dis
PCG                     13 test2.pcg
OC                      14 test2.oc
WEL                     16 test2.wel
RCH                     15 test2.rch
evt                     17 test2.evt
```

Figure 2.4

2.4.2 Output From Simulation: A MODFLOW output file will be created after the simulation with the name of output file as specified in name file. Depending upon the options specified in the output control file, the volumetric budget of entire model, heads, and drawdown will be printed at desired time steps and stress periods in this output file. A sample of output file is as shown below.

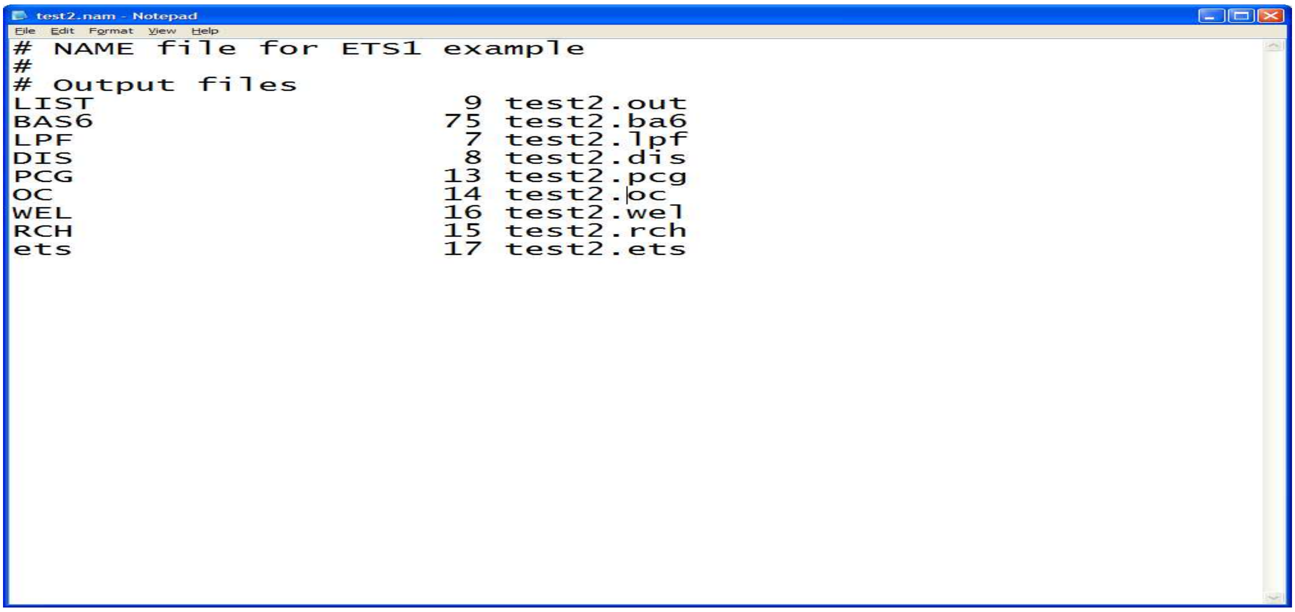
```
HEAD IN LAYER   1 AT END OF TIME STEP 180 IN STRESS PERIOD    1
          1       2       3
    1    98.09   98.09   98.09
    2    98.09   98.05   98.09
    3    98.09   98.09   98.09

DRAWDOWN IN LAYER   1 AT END OF TIME STEP 180 IN STRESS PERIOD    1
           1           2           3
     1   -3.095      -3.086      -3.095
     2   -3.086      -3.049      -3.086
     3   -3.095      -3.086      -3.095

  VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP180 IN STRESS PERIOD   1
  ------------------------------------------------------------------------------

     CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
     ------------------                 ------------------------

           IN:                                     IN:
           ---                                     ---
             STORAGE =           0.0000              STORAGE =           0.0000
       CONSTANT HEAD =           0.0000        CONSTANT HEAD =           0.0000
               WELLS =           0.0000                WELLS =           0.0000
                  ET =           0.0000                   ET =           0.0000
            RECHARGE =        5579.8877             RECHARGE =          30.9994

            TOTAL IN =        5579.8877             TOTAL IN =          30.9994

          OUT:                                    OUT:
          ----                                    ----
             STORAGE =        4859.7773              STORAGE =          26.6445
       CONSTANT HEAD =           0.0000        CONSTANT HEAD =           0.0000
               WELLS =         720.0000                WELLS =           4.0000
                  ET =           1.1179                   ET =           0.3610
            RECHARGE =           0.0000             RECHARGE =           0.0000

            TOTAL OUT =        5580.8950            TOTAL OUT =          31.0055

            IN - OUT =          -1.0073             IN - OUT =      -6.0825E-03

 PERCENT DISCREPANCY =          -0.02     PERCENT DISCREPANCY =          -0.02
```

2.5.1 MODFLOW Execution using ETS1 package: In order to simulate evapotranspiration using the ETS1 package, the ET surface was kept equal to 100 m for every cells. The maximum evapotranspiration flux at the surface was kept equal to 0.0015 m/day, and the extinction depth was kept equal to 2 m for every cell, Figure 2.2. One intermediate point was taken at depth 1 m, which has maximum ET flux of 0.00015 m/day. Therefore,

PXDP=1/2=0.5

PETM=0.00015/0.0015=0.1

Input to the ETS1 package is read from the file that is type 'ETS' in the Name file (Banta, 2000). A name file (Figure 2.5) was created listing all of the input files and output files. This version ran successfully using both MODFLOW 2000 and MODFLOW 2005 executable programs.



```
# NAME file for ETS1 example
#
# Output files
LIST                         9 test2.out
BAS6                        75 test2.ba6
LPF                          7 test2.lpf
DIS                          8 test2.dis
PCG                         13 test2.pcg
OC                          14 test2.oc
WEL                         16 test2.wel
RCH                         15 test2.rch
ets                         17 test2.ets
```

Figure 2.5

2.5.2 Output From Simulation: A MODFLOW output file will be created after the simulation with the name of output file as specified in the name file. Depending upon the options specified in the output control file, the volumetric budget of entire model, heads, and drawdown will be printed at desired time steps and stress periods in this output file. A sample of output file is as shown below.

```
HEAD IN LAYER   1 AT END OF TIME STEP 180 IN STRESS PERIOD    1
           1       2       3
   1    98.10   98.09   98.10
   2    98.09   98.05   98.09
   3    98.10   98.09   98.10

 DRAWDOWN IN LAYER   1 AT END OF TIME STEP 180 IN STRESS PERIOD    1

            1           2           3
   1   -3.095      -3.086      -3.095
   2   -3.086      -3.050      -3.086
   3   -3.095      -3.086      -3.095


VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP180 IN STRESS PERIOD   1
  ------------------------------------------------------------------------------

     CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
     ------------------                 ------------------------

           IN:                                     IN:
           ---                                     ---
             STORAGE =          0.0000               STORAGE =          0.0000
       CONSTANT HEAD =          0.0000         CONSTANT HEAD =          0.0000
               WELLS =          0.0000                 WELLS =          0.0000
            RECHARGE =       5579.8877              RECHARGE =         30.9994
         ET SEGMENTS =          0.0000           ET SEGMENTS =          0.0000

            TOTAL IN =       5579.8877              TOTAL IN =         30.9994

          OUT:                                    OUT:
          ----                                    ----
             STORAGE =       4860.6890               STORAGE =         26.9335
       CONSTANT HEAD =          0.0000         CONSTANT HEAD =          0.0000
               WELLS =        720.0000                 WELLS =          4.0000
            RECHARGE =          0.0000              RECHARGE =          0.0000
         ET SEGMENTS =          0.2248           ET SEGMENTS =      7.2691E-02

           TOTAL OUT =       5580.9136             TOTAL OUT =         31.0062

            IN - OUT =         -1.0259              IN - OUT =     -6.8531E-03

 PERCENT DISCREPANCY =           -0.02     PERCENT DISCREPANCY =           -0.02
```

2.6 Result: Compared to the EVT package, the loss from evapotranspiration using ETS1 package is very low. The difference in the results can be explained from the calculation for EVT and ETS1 as shown below:

EVT package: This package uses equation 1 mentioned in Open File Report 00-46 by Banta., 2000.

$Q=Q_{etm}*(1-D/X)$, where

Q is the volumetric evapotranspiration rate for the cell (L3/T)

Q_{etm} is the maximum evapotranspiration flux rate times the area of the cell (L3/T)

D is the depth of the head below the ET surface (L), which was set at 100 m

X is the extinction depth, which was set at 2 m.

For cells with calculated head 98.05 m, Q_{etm}=0.0015*25*25=0.9375 m^3/day

Therefore Q=0.9375*(1-1.95/2)=0.0234375 m3/day

For cells with calculated head 98.09m, Q_{etm}=0.0015*25*25*8=7.5 m^3/day

Therefore Q=7.5*(1-1.91/2)=.3375 m3/day

Total Evapotranspiration loss=0.0234375+.3375=0.36094 m^3/day

ETS1 package: This package uses equation 2 mentioned in Open File Report 00-46 by Banta, 2000. For simplicity equation 1 can still be used to analyze the output. For example, in our case the calculated head values are 98.05, 98.09, and 98.1 m. Since the water table intersects the second segment, the value of 0.00015 is taken into consideration for all of the cells for maximum ET flux. Also the extinction depth, X will be equal to 1m for the second segment, and D will be equal to (99 m-calculated head) for all of the cells. Therefore,

For cells with calculated head 98.05 m, Q_{etm}=0.00015*25*25=0.09375 m^3/day

Therefore Q=0.09375*(1-.95/1)=0.0046875 m3/day

For cells with calculated head 98.1 m, Q_{etm}=0.00015*25*25*4=0.375 m^3/day

Therefore Q=0.375*(1-0.9/1)=0.0375 m3/day

For cells with calculated head 98.09 m, Q_{etm}=0.00015*25*25*4=0.375 m^3/day

Therefore Q=0.375*(1-0.91/1)=0.03375 m3/day

Total Evapotranspiration loss=0.046875+0.0375+0.03375=0.0759375 m^3/day

CHAPTER 3: UZF1 package

3.1 Introduction: The UZF1 package simulates the unsaturated zone between the land surface and a water table. This unsaturated version is compatible with MODFLOW 2005 only. The previous versions of MODFLOW do not support the UZF1 package. Detailed description of this package can be found in USGS report 'Documentation of the Unsaturated-Zone Flow (UZF1) Package for Modeling Unsaturated Flow Between the Land Surface and the Water Table with MODFLOW-2005' ;Technique and Methods 6-A19 by Richard G. Niswonger, David E. Prudic, and R. Steven Regan.

The UZF1 package is a Substitution for the Recharge and Evapotranspiration packages of MODFLOW-2005 (Niswonger and others, 2006). The UZF1 package differs from the recharge package in that an infiltration rate is applied at land surface instead of a specified recharge rate directly to ground water (Niswonger and others, 2006). The applied infiltration rate is further limited by the saturated vertical hydraulic conductivity (Niswonger and others, 2006). The UZF1 package differs from the evapotranspiration package in that evapotranspiration losses are first removed from the unsaturated zone above the evapotranspiration extinction depth, and if the evapotranspiration demand is not met, water can be removed directly from ground water whenever the depth to ground water is less than the extinction depth (Niswonger and others, 2006). The UZF1 package also differs from the Evapotranspiration Package in that water is discharged directly to the land surface whenever the altitude of the water table exceeds land surface (Niswonger and others, 2006). Water that is discharged to land surface, as well as applied infiltration in excess of the saturated vertical hydraulic conductivity, may be routed directly as inflow to specified streams or lakes if these packages are active; otherwise, this water is removed from the model (Niswonger and others, 2006).

Variables used by the UZF1 package include initial and saturated water contents, saturated vertical hydraulic conductivity, and an exponent in the Brooks-Corey function (Niswonger and others, 2006). Residual water content is calculated internally by the UZF1 package on the basis of the difference between saturated water content and specific yield (Niswonger and others, 2006). However initial water content is not required when the initial stress period is specified as steady state but it is required if the stress period is transient. The UZF1 package relies on the specific yield values as specified in the LPF package or BCF package (Niswonger and others, 2006). Thus the option to simulate unsaturated flow using UZF1 package is available when either LPF or BCF package is included in the simulation. Vertical saturated hydraulic conductivity of the unsaturated zone can be read either from LPF or BCF package or can be specified in the UZF1 package itself.

3.2 Limitations of UZF1 package: The initial version of this UZF1 package does not simulate unsaturated flow through multiple layers of varying hydraulic properties (Niswonger and others, 2006). Infiltration is applied to the model cells, and the UZF1 package calculates recharge based upon infiltration rate and hydraulic conductivity of the model cell, so an extra recharge package (RCH) can not be included in the simulation. Also, the evapotranspiration versions EVT and ETS1 can not be included in the simulation since the evapotranspiration data (ET max, extinction depth) are specified in UZF1 package itself. It should, however, be noted that in order to simulate evapotranspiration through UZF1 package, ET surfaces are not specified and an extra variable ‘Extinction water content’ [value between (Ɵs-Sy) and Ɵs], is specified where Ɵs is saturated water content and Sy is specific yield. Extinction water content is the value below which ET can not be removed from the unsaturated zone (Niswonger and others, 2006).

3.3 Case Study: A simple case with nine cells was considered (Figure 3.1). All of the nine cells were considered active cells. The initial head was kept equal to 95m in all cells. A well was kept at the center pumping at -4 m3/day. The hydraulic conductivity of the cells was kept equal to constant value of 0.2496 m/day. Specific yield was kept equal to a constant value of 0.28. Infiltration at a rate of 0.005511 m/day was applied all over the cells. Evapotranspiration flux was kept equal to 0.0015 m/day with extinction depth 2.0 m in all of the cells. Extinction water content was kept equal to 0.16 (value between Θ_s-S_y and Θ_s) in all of the cells. Transient simulation was performed and the number of stress periods was taken equal to 1, with length equal to 180 days. Also the number of time steps was taken equal to 180, so Δt=1 day. The hydraulic properties of the aquifer were as shown below:

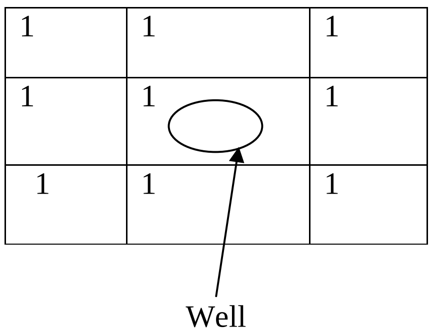


Figure 3.1

Saturated vertical hydraulic conductivity of unsaturated zone=0.2496 m/day

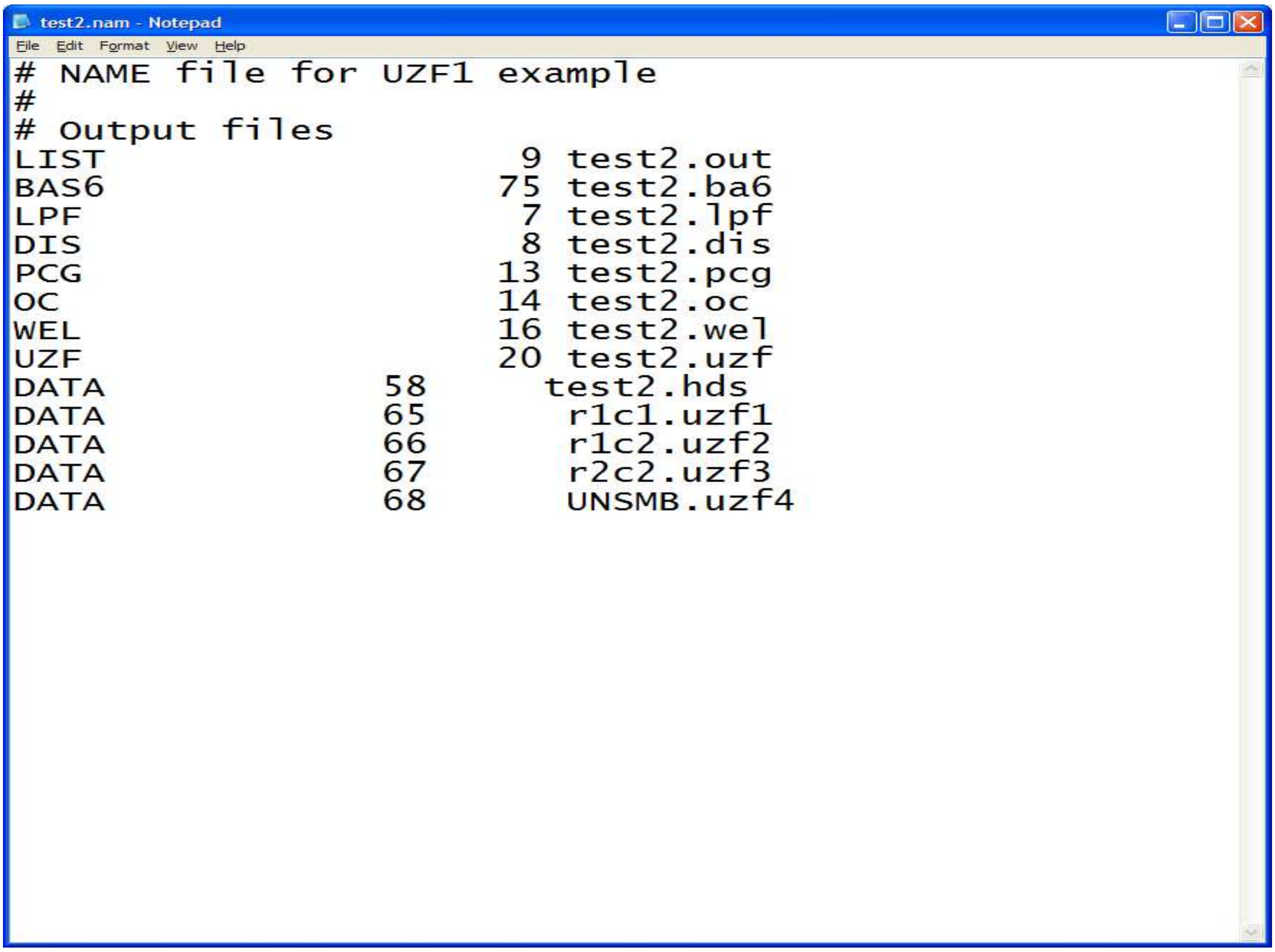
Brooks and Corey Epsilon=6.571

Saturated water content (Θ_s)=0.43

Initial water content=0.1478

3.4.1 MODFLOW Execution: Percolation of water through an unsaturated zone is activated by including a record in the MODFLOW Name file using the file type (Ftype) 'UZF' to indicate that relevant calculations are to be made in the model, and to specify the related input data file (Niswonger and others, 2006) . The user can specify unsaturated zone water budgets and water content profiles for selected model cells by including a record in the MODFLOW name file using the file type (Ftype) "DATA" that specifies the relevant output data file name for each model cell (Niswonger and others, 2006). Three types of information may be printed to the specified file for each model cell depending on the OUTTYPE option specified. The three OUTTYPE options are: option 1 prints volumes of water entering, leaving, and stored in the unsaturated zone, option 2 prints volumes and rates for water entering, leaving, and stored within the unsaturated zone; and option 3 prints the water content profile between land surface and the water table. Additionally, a time series of infiltration, unsaturated zone evapotranspiration, recharge, and ground water discharge summed over the model domain may be printed to a specified file (Niswonger and others, 2006). These options are entered in Item 8 of the UZF1 package *(see page 31, Item 8, Appendix 1 of the UZF1 documentation by Niswonger and others).*

A Name file (Figure 3.2) was created listing all of the input files and output file. In addition to the regular MODFLOW output file, output files for cells (1,1), (1,2), (2,2), and the unsaturated zone mass balance for the entire model will be printed which lists time, corresponding ground-water head, thickness of unsaturated zone, followed by a series of depths and corresponding water contents in the unsaturated zone.



test2.nam - Notepad

File Edit Format View Help

```
# NAME file for UZF1 example
#
# Output files
LIST                      9 test2.out
BAS6                     75 test2.ba6
LPF                       7 test2.lpf
DIS                       8 test2.dis
PCG                      13 test2.pcg
OC                       14 test2.oc
WEL                      16 test2.wel
UZF                      20 test2.uzf
DATA               58      test2.hds
DATA               65        r1c1.uzf1
DATA               66        r1c2.uzf2
DATA               67        r2c2.uzf3
DATA               68        UNSMB.uzf4
```

Figure 3.2

3.5 Output From Simulation: A MODFLOW output file will be created after the simulation with the name of output file as specified in name file. Depending upon the options specified in the output control file, the volumetric budget of entire model, volumetric budget for unsaturated zone, heads, and drawdown will be printed at desired time steps and stress periods in this output file. Also three separate output files for cells (1,1), (1,2), (1,3), and an output file for the unsaturated zone mass balance for the entire model will be created listing time, ground-water head, thickness of unsaturated zone, followed by a series of depths and corresponding water contents in the unsaturated zone. A sample of output file is as shown below.

Output file for Cell Row 1, Column 1

r1c1.uzf1 - WordPad

File Edit View Insert Format Help

```
"LOCATION OF SPECIFIED CELL FOR PRINTING VOLUMES IN UNSATURATED ZONE: GAGE    1 ROW, COLUMN    1,    1 INITIAL LAYER ASSIGMENT    1"
"DATA:  LAYER            TIME        GW-HEAD   UZ-THICKNESS          DEPTH    WATER-CONT. "

          1    1.0000000E+00  9.4999672E+01  4.5003290E+00  1.1250541E-01  1.9874990E-01
                                                            2.2501083E-01  1.5000001E-01
                                                            3.3751625E-01  1.5000001E-01
                                                            4.5002165E-01  1.5000001E-01
                                                            5.6252706E-01  1.5000001E-01
                                                            6.7503250E-01  1.5000001E-01
                                                            7.8753793E-01  1.5000001E-01
                                                            9.0004331E-01  1.5000001E-01
                                                            1.0125487E+00  1.5000001E-01
                                                            1.1250541E+00  1.5000001E-01
                                                            1.2375596E+00  1.5000001E-01
                                                            1.3500650E+00  1.5000001E-01
                                                            1.4625704E+00  1.5000001E-01
                                                            1.5750759E+00  1.5000001E-01
                                                            1.6875812E+00  1.5000001E-01
                                                            1.8000866E+00  1.5000001E-01
                                                            1.9125921E+00  1.5000001E-01
                                                            2.0250974E+00  1.5000001E-01
                                                            2.1376028E+00  1.5000001E-01
                                                            2.2501082E+00  1.5000001E-01
                                                            2.3626137E+00  1.5000001E-01
                                                            2.4751191E+00  1.5000001E-01
                                                            2.5876245E+00  1.5000001E-01
                                                            2.7001300E+00  1.5000001E-01
                                                            2.8126354E+00  1.5000001E-01
                                                            2.9251409E+00  1.5000001E-01
                                                            3.0376463E+00  1.5000001E-01
                                                            3.1501517E+00  1.5000001E-01
                                                            3.2626572E+00  1.5000001E-01
                                                            3.3751624E+00  1.5000001E-01
                                                            3.4876678E+00  1.5000001E-01
                                                            3.6001732E+00  1.5000001E-01
                                                            3.7126787E+00  1.5000001E-01
                                                            3.8251841E+00  1.5000001E-01
                                                            3.9376895E+00  1.5000001E-01
                                                            4.0501947E+00  1.5000001E-01
                                                            4.1627002E+00  1.5000001E-01
                                                            4.2752056E+00  1.5000001E-01
                                                            4.3877110E+00  1.5000001E-01
                                                            4.5003290E+00  1.5000001E-01
          1    2.0000000E+00  9.4998932E+01  4.5010686E+00  1.1252391E-01  2.4725053E-01
                                                            2.2504781E-01  1.5000001E-01
                                                            3.3757171E-01  1.5000001E-01
                                                            4.5009562E-01  1.5000001E-01
                                                            5.6261951E-01  1.5000001E-01
                                                            6.7514342E-01  1.5000001E-01
                                                            7.8766733E-01  1.5000001E-01
                                                            9.0019125E-01  1.5000001E-01
                                                            1.0127151E+00  1.5000001E-01
                                                            1.1252390E+00  1.5000001E-01
                                                            1.2377629E+00  1.5000001E-01
                                                            1.3502868E+00  1.5000001E-01
                                                            1.4628108E+00  1.5000001E-01
```

For Help, press F1   NUM

Output file for Cell Row 1, Column 2

r1c2.uzf2 - WordPad

File Edit View Insert Format Help

```
"LOCATION OF SPECIFIED CELL FOR PRINTING VOLUMES IN UNSATURATED ZONE: GAGE    2 ROW, COLUMN    1,    2 INITIAL LAYER ASSIGMENT    1"
"DATA:  LAYER            TIME          GW-HEAD   UZ-THICKNESS         DEPTH    WATER-CONT. "

            1   1.0000000E+00  9.4998459E+01  4.5015435E+00  1.1253577E-01  1.9873674E-01
                                                             2.2507155E-01  1.5000001E-01
                                                             3.3760732E-01  1.5000001E-01
                                                             4.5014310E-01  1.5000001E-01
                                                             5.6267887E-01  1.5000001E-01
                                                             6.7521465E-01  1.5000001E-01
                                                             7.8775042E-01  1.5000001E-01
                                                             9.0028620E-01  1.5000001E-01
                                                             1.0128220E+00  1.5000001E-01
                                                             1.1253577E+00  1.5000001E-01
                                                             1.2378936E+00  1.5000001E-01
                                                             1.3504293E+00  1.5000001E-01
                                                             1.4629651E+00  1.5000001E-01
                                                             1.5755008E+00  1.5000001E-01
                                                             1.6880367E+00  1.5000001E-01
                                                             1.8005724E+00  1.5000001E-01
                                                             1.9131082E+00  1.5000001E-01
                                                             2.0256441E+00  1.5000001E-01
                                                             2.1381798E+00  1.5000001E-01
                                                             2.2507155E+00  1.5000001E-01
                                                             2.3632512E+00  1.5000001E-01
                                                             2.4757872E+00  1.5000001E-01
                                                             2.5883229E+00  1.5000001E-01
                                                             2.7008586E+00  1.5000001E-01
                                                             2.8133945E+00  1.5000001E-01
                                                             2.9259303E+00  1.5000001E-01
                                                             3.0384660E+00  1.5000001E-01
                                                             3.1510017E+00  1.5000001E-01
                                                             3.2635376E+00  1.5000001E-01
                                                             3.3760734E+00  1.5000001E-01
                                                             3.4886091E+00  1.5000001E-01
                                                             3.6011448E+00  1.5000001E-01
                                                             3.7136807E+00  1.5000001E-01
                                                             3.8262165E+00  1.5000001E-01
                                                             3.9387522E+00  1.5000001E-01
                                                             4.0512881E+00  1.5000001E-01
                                                             4.1638236E+00  1.5000001E-01
                                                             4.2763596E+00  1.5000001E-01
                                                             4.3888955E+00  1.5000001E-01
                                                             4.5015435E+00  1.5000001E-01
            1   2.0000000E+00  9.4996185E+01  4.5038180E+00  1.1259264E-01  2.4719116E-01
                                                             2.2518528E-01  1.5000001E-01
                                                             3.3777791E-01  1.5000001E-01
                                                             4.5037055E-01  1.5000001E-01
                                                             5.6296319E-01  1.5000001E-01
                                                             6.7555583E-01  1.5000001E-01
                                                             7.8814846E-01  1.5000001E-01
                                                             9.0074110E-01  1.5000001E-01
                                                             1.0133338E+00  1.5000001E-01
                                                             1.1259264E+00  1.5000001E-01
                                                             1.2385191E+00  1.5000001E-01
                                                             1.3511117E+00  1.5000001E-01
                                                             1.4637043E+00  1.5000001E-01
```

For Help, press F1   NUM

Output file for Cell Row 2, Column 2

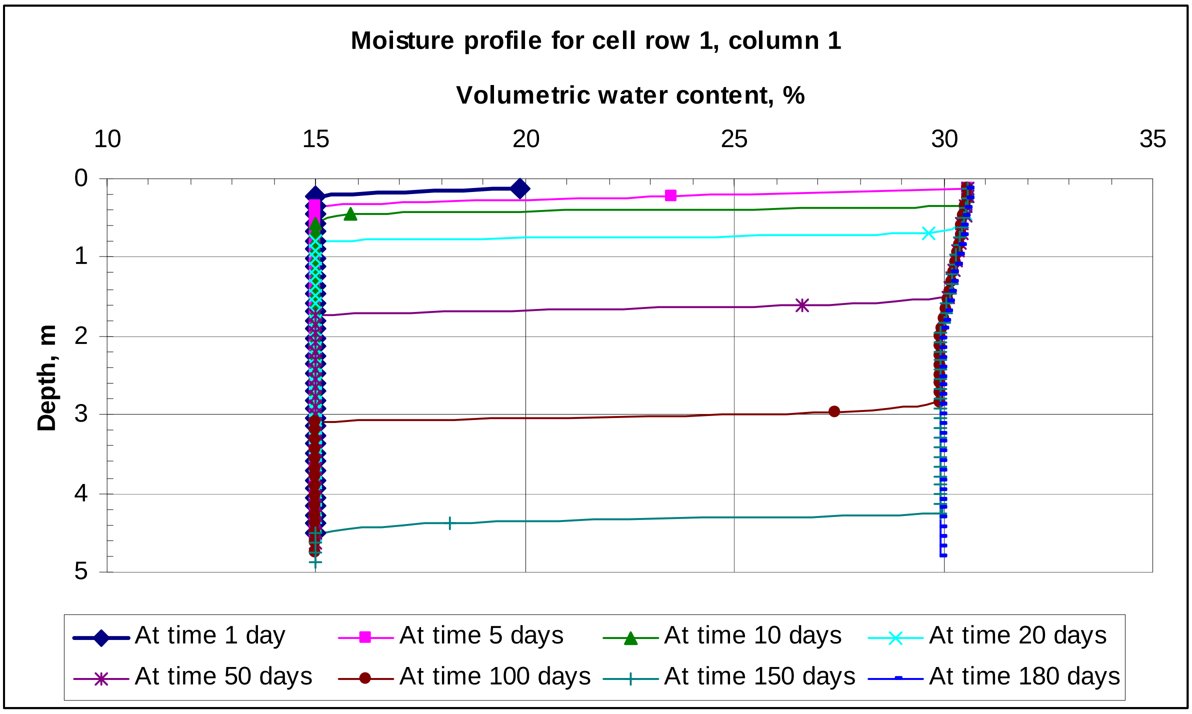
r2c2.uzf3 - WordPad

File Edit View Insert Format Help

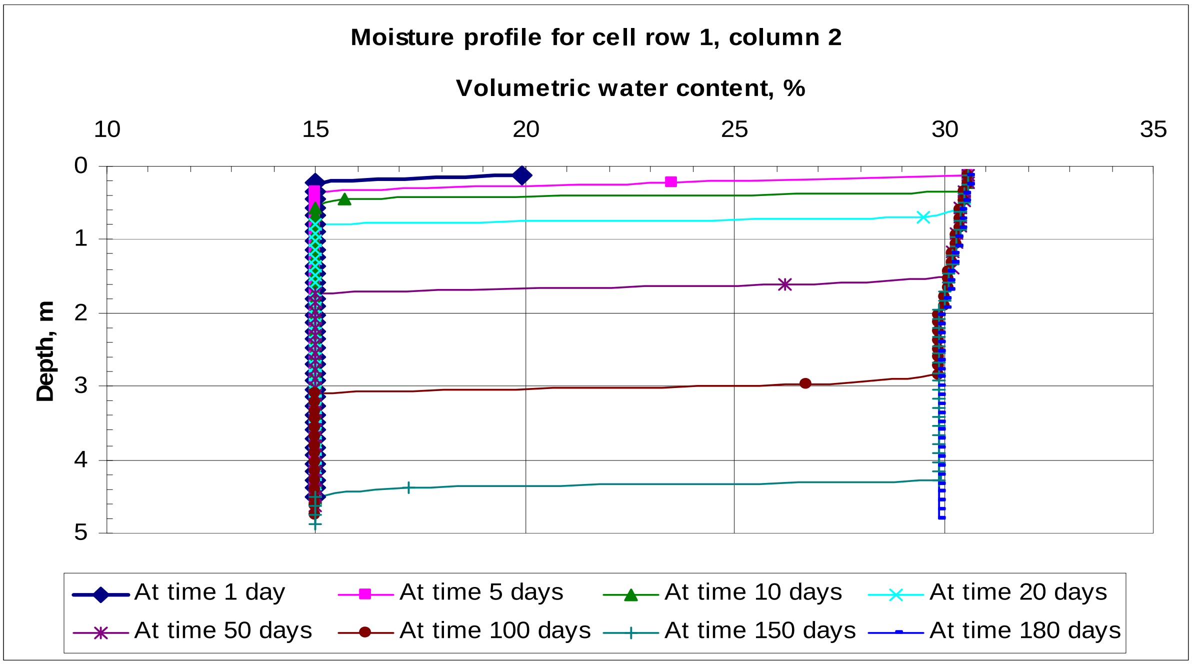
```
"LOCATION OF SPECIFIED CELL FOR PRINTING VOLUMES IN UNSATURATED ZONE: GAGE    3 ROW, COLUMN    2,   2 INITIAL LAYER ASSIGMENT    1"
"DATA:  LAYER           TIME        GW-HEAD   UZ-THICKNESS         DEPTH    WATER-CONT. "

            1    1.0000000E+00  9.4984634E+01  4.5153661E+00  1.1288133E-01  1.9858755E-01
                                                              2.2576267E-01  1.5000001E-01
                                                              3.3864400E-01  1.5000001E-01
                                                              4.5152533E-01  1.5000001E-01
                                                              5.6440663E-01  1.5000001E-01
                                                              6.7728800E-01  1.5000001E-01
                                                              7.9016930E-01  1.5000001E-01
                                                              9.0305066E-01  1.5000001E-01
                                                              1.0159320E+00  1.5000001E-01
                                                              1.1288133E+00  1.5000001E-01
                                                              1.2416947E+00  1.5000001E-01
                                                              1.3545760E+00  1.5000001E-01
                                                              1.4674573E+00  1.5000001E-01
                                                              1.5803386E+00  1.5000001E-01
                                                              1.6932200E+00  1.5000001E-01
                                                              1.8061013E+00  1.5000001E-01
                                                              1.9189826E+00  1.5000001E-01
                                                              2.0318639E+00  1.5000001E-01
                                                              2.1447453E+00  1.5000001E-01
                                                              2.2576265E+00  1.5000001E-01
                                                              2.3705080E+00  1.5000001E-01
                                                              2.4833894E+00  1.5000001E-01
                                                              2.5962706E+00  1.5000001E-01
                                                              2.7091520E+00  1.5000001E-01
                                                              2.8220334E+00  1.5000001E-01
                                                              2.9349146E+00  1.5000001E-01
                                                              3.0477960E+00  1.5000001E-01
                                                              3.1606772E+00  1.5000001E-01
                                                              3.2735586E+00  1.5000001E-01
                                                              3.3864400E+00  1.5000001E-01
                                                              3.4993212E+00  1.5000001E-01
                                                              3.6122026E+00  1.5000001E-01
                                                              3.7250841E+00  1.5000001E-01
                                                              3.8379653E+00  1.5000001E-01
                                                              3.9508467E+00  1.5000001E-01
                                                              4.0637279E+00  1.5000001E-01
                                                              4.1766095E+00  1.5000001E-01
                                                              4.2894907E+00  1.5000001E-01
                                                              4.4023719E+00  1.5000001E-01
                                                              4.5153661E+00  1.5000001E-01
            1    2.0000000E+00  9.4973869E+01  4.5261331E+00  1.1315050E-01  2.4671198E-01
                                                              2.2630100E-01  1.5000001E-01
                                                              3.3945149E-01  1.5000001E-01
                                                              4.5260200E-01  1.5000001E-01
                                                              5.6575251E-01  1.5000001E-01
                                                              6.7890298E-01  1.5000001E-01
                                                              7.9205346E-01  1.5000001E-01
                                                              9.0520400E-01  1.5000001E-01
                                                              1.0183544E+00  1.5000001E-01
                                                              1.1315050E+00  1.5000001E-01
                                                              1.2446555E+00  1.5000001E-01
                                                              1.3578060E+00  1.5000001E-01
                                                              1.4709564E+00  1.5000001E-01
```

For Help, press F1 NUM

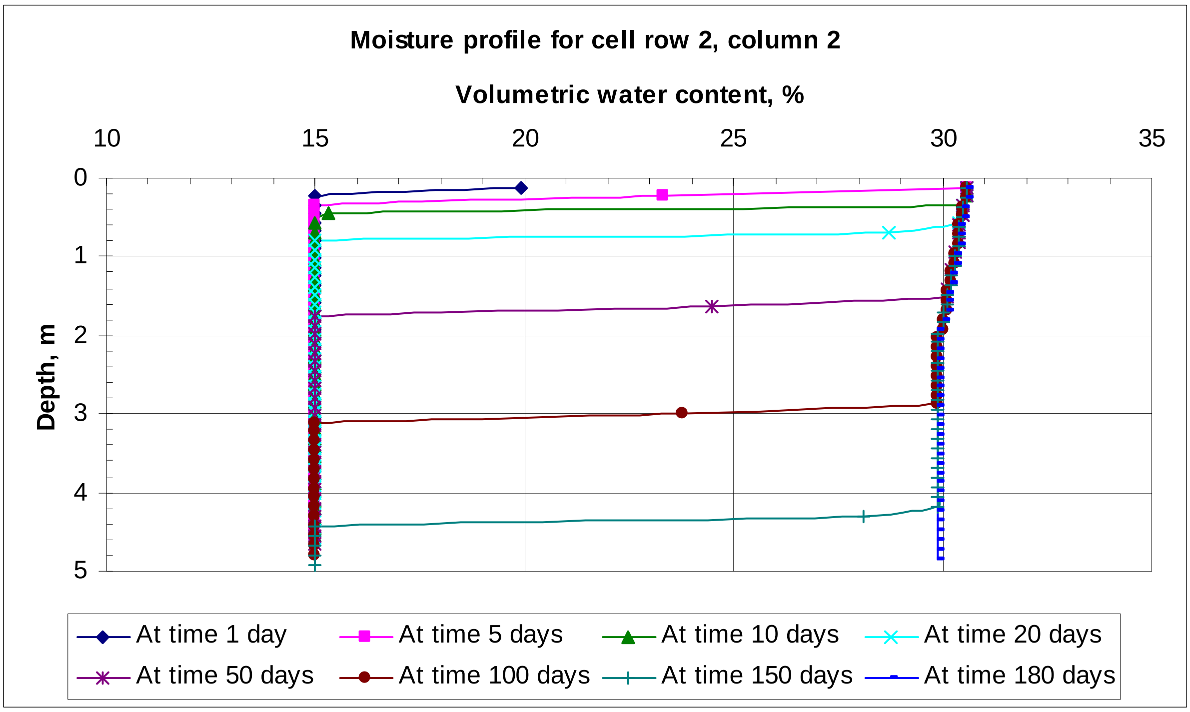
3.5.1 Graphical representation of water profiles of above-mentioned cells at time 1 day, 5 days, 10 days, 20 days, 50 days, 100, 150, and 180 days.



Moisture profile of cell (row1, column1)



Moisture profile of cell (row 1, column 2)



Moisture profile of cell (row 2, column 2)

Figures 3.3. Moisture profiles for cells

3.5.2 UNSATURATED MASS BALANCE COMPONENTS FOR ENTIRE MODEL

TIME	APPLIED-INFIL.	RUNOFF	ACTUAL-INFIL.	SURFACE-LEAK.	UZ-ET	GW-ET	UZSTOR-CHANGE	RECHARGE
1	30.999	0.000	30.999	0.000	0.148	0.000	30.851	0.000
2	30.999	0.000	30.999	0.000	0.296	0.000	30.703	0.000
3	30.999	0.000	30.999	0.000	0.443	0.000	30.556	0.000
4	30.999	0.000	30.999	0.000	0.589	0.000	30.410	0.000
5	30.999	0.000	30.999	0.000	0.735	0.000	30.265	0.000
6	30.999	0.000	30.999	0.000	0.879	0.000	30.120	0.000
7	30.999	0.000	30.999	0.000	1.024	0.000	29.975	0.000
8	30.999	0.000	30.999	0.000	1.168	0.000	29.831	0.000
9	30.999	0.000	30.999	0.000	1.312	0.000	29.688	0.000
10	30.999	0.000	30.999	0.000	1.454	0.000	29.545	0.000
11	30.999	0.000	30.999	0.000	1.596	0.000	29.403	0.000
12	30.999	0.000	30.999	0.000	1.738	0.000	29.262	0.000
13	30.999	0.000	30.999	0.000	1.878	0.000	29.121	0.000
14	30.999	0.000	30.999	0.000	2.019	0.000	28.980	0.000
15	30.999	0.000	30.999	0.000	2.159	0.000	28.840	0.000
16	30.999	0.000	30.999	0.000	2.298	0.000	28.701	0.000
17	30.999	0.000	30.999	0.000	2.437	0.000	28.562	0.000

18	30.999	0.000	30.999	0.000	2.575	0.000	28.424	0.000
19	30.999	0.000	30.999	0.000	2.712	0.000	28.287	0.000
20	30.999	0.000	30.999	0.000	2.849	0.000	28.150	0.000
21	30.999	0.000	30.999	0.000	2.986	0.000	28.013	0.000
22	30.999	0.000	30.999	0.000	3.122	0.000	27.877	0.000
23	30.999	0.000	30.999	0.000	3.257	0.000	27.742	0.000
24	30.999	0.000	30.999	0.000	3.392	0.000	27.607	0.000
25	30.999	0.000	30.999	0.000	3.526	0.000	27.473	0.000
26	30.999	0.000	30.999	0.000	3.659	0.000	27.340	0.000
27	30.999	0.000	30.999	0.000	3.793	0.000	27.207	0.000
28	30.999	0.000	30.999	0.000	3.925	0.000	27.074	0.000
29	30.999	0.000	30.999	0.000	4.057	0.000	26.942	0.000
30	30.999	0.000	30.999	0.000	4.189	0.000	26.810	0.000
31	30.999	0.000	30.999	0.000	4.320	0.000	26.680	0.000
32	30.999	0.000	30.999	0.000	4.450	0.000	26.550	0.000
33	30.999	0.000	30.999	0.000	4.579	0.000	26.420	0.000
34	30.999	0.000	30.999	0.000	4.709	0.000	26.290	0.000
35	30.999	0.000	30.999	0.000	4.838	0.000	26.161	0.000
36	30.999	0.000	30.999	0.000	4.966	0.000	26.033	0.000
37	30.999	0.000	30.999	0.000	5.094	0.000	25.906	0.000
38	30.999	0.000	30.999	0.000	5.221	0.000	25.779	0.000
39	30.999	0.000	30.999	0.000	5.347	0.000	25.652	0.000
40	30.999	0.000	30.999	0.000	5.473	0.000	25.526	0.000
41	30.999	0.000	30.999	0.000	5.599	0.000	25.400	0.000
42	30.999	0.000	30.999	0.000	5.724	0.000	25.275	0.000
43	30.999	0.000	30.999	0.000	5.849	0.000	25.151	0.000
44	30.999	0.000	30.999	0.000	5.973	0.000	25.027	0.000
45	30.999	0.000	30.999	0.000	6.096	0.000	24.903	0.000
46	30.999	0.000	30.999	0.000	6.219	0.000	24.781	0.000
47	30.999	0.000	30.999	0.000	6.341	0.000	24.658	0.000
48	30.999	0.000	30.999	0.000	6.463	0.000	24.536	0.000
49	30.999	0.000	30.999	0.000	6.585	0.000	24.414	0.000
50	30.999	0.000	30.999	0.000	6.706	0.000	24.294	0.000
51	30.999	0.000	30.999	0.000	6.826	0.000	24.173	0.000
52	30.999	0.000	30.999	0.000	6.946	0.000	24.054	0.000
53	30.999	0.000	30.999	0.000	7.065	0.000	23.934	0.000
54	30.999	0.000	30.999	0.000	7.184	0.000	23.815	0.000
55	30.999	0.000	30.999	0.000	7.303	0.000	23.697	0.000
56	30.999	0.000	30.999	0.000	7.421	0.000	23.579	0.000
57	30.999	0.000	30.999	0.000	7.538	0.000	23.461	0.000
58	30.999	0.000	30.999	0.000	7.655	0.000	23.345	0.000
59	30.999	0.000	30.999	0.000	7.771	0.000	23.228	0.000
60	30.999	0.000	30.999	0.000	7.887	0.000	23.112	0.000
61	30.999	0.000	30.999	0.000	8.003	0.000	22.997	0.000
62	30.999	0.000	30.999	0.000	8.118	0.000	22.882	0.000
63	30.999	0.000	30.999	0.000	8.232	0.000	22.767	0.000

64	30.999	0.000	30.999	0.000	8.346	0.000	22.654	0.000
65	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
66	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
67	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
68	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
69	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
70	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
71	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
72	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
73	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
74	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
75	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
76	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
77	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
78	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
79	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
80	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
81	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
82	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
83	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
84	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
85	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
86	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
87	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
88	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
89	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
90	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
91	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
92	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
93	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
94	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
95	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
96	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
97	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
98	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
99	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
100	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
101	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
102	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
103	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
104	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
105	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
106	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
107	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
108	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
109	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000

110	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
111	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
112	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
113	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
114	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
115	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
116	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
117	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
118	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
119	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
120	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
121	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
122	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
123	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
124	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
125	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
126	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
127	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
128	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
129	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
130	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
131	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
132	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
133	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
134	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
135	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
136	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
137	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
138	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
139	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
140	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
141	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
142	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
143	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
144	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
145	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
146	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
147	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
148	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
149	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
150	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
151	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
152	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
153	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
154	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
155	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000

156	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
157	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
158	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
159	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
160	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
161	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
162	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
163	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
164	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
165	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
166	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
167	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
168	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
169	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
170	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
171	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
172	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
173	30.999	0.000	30.999	0.000	8.438	0.000	22.562	0.000
174	30.999	0.000	30.999	0.000	8.438	0.000	22.169	0.393
175	30.999	0.000	30.999	0.000	8.438	0.000	-8.058	30.620
176	30.999	0.000	30.999	0.000	8.438	0.000	-17.956	40.518
177	30.999	0.000	30.999	0.000	8.438	0.000	-21.164	43.725
178	30.999	0.000	30.999	0.000	8.438	0.000	-21.250	43.812
179	30.999	0.000	30.999	0.000	8.438	0.000	-21.120	43.682
180	30.999	0.000	30.999	0.000	8.438	0.000	-21.117	43.678

Table 3.1

3.5.3 Graphical representation of Table 3.1

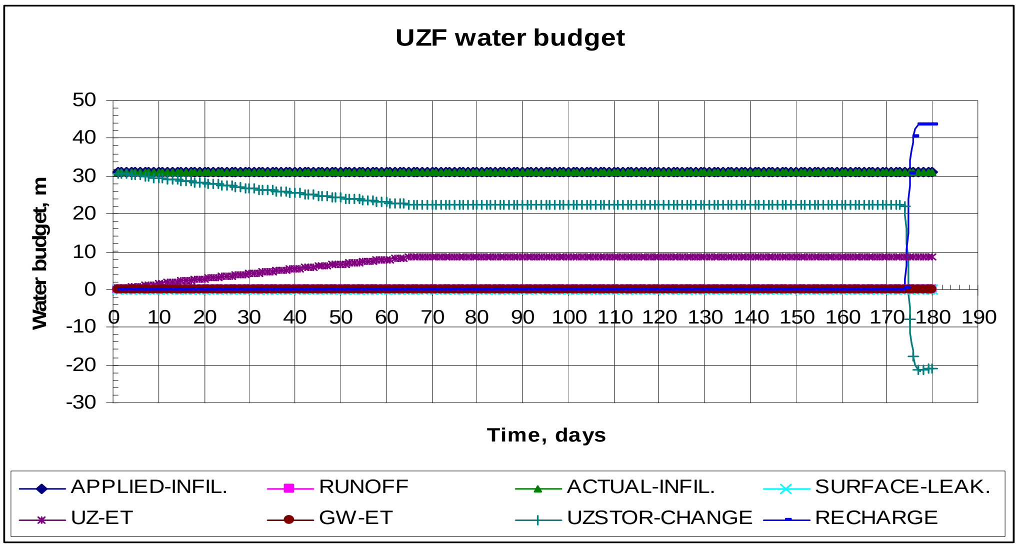


Figure 3.4. Water budget component time series of the entire model.

```
HEAD IN LAYER   1 AT END OF TIME STEP 180 IN STRESS PERIOD    1

           1       2       3
   1    94.71   94.70   94.71
   2    94.70   94.66   94.70
   3    94.71   94.70   94.71

DRAWDOWN IN LAYER   1 AT END OF TIME STEP 180 IN STRESS PERIOD    1
          1           2           3
   1   0.2909      0.3009      0.2909
   2   0.3009      0.3392      0.3009
   3   0.2909      0.3009      0.2909



 UNSATURATED ZONE PACKAGE VOLUMETRIC BUDGET FOR  TIME STEP  180 STRESS PERIOD    1
  ------------------------------------------------------------------------------


     CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
     ------------------                 ------------------------

           IN:                                   IN:
           ---                                   ---
        INFILTRATION =        5579.8873          INFILTRATION =          30.9994

          OUT:                                  OUT:
          ----                                  ----
              UZF ET =        1261.8134                UZF ET =           8.4375
        UZF RECHARGE =         246.4295          UZF RECHARGE =          43.6784

            IN - OUT =        4071.6444              IN - OUT =         -21.1166

          STORAGE:                              STORAGE:
          --------                              --------
      STORAGE CHANGE =        4071.6444        STORAGE CHANGE =         -21.1166

 PERCENT DISCREPANCY IS DIFFERENCE BETWEEN IN-OUT MINUS CHANGE IN STORAGE
 DIVIDED BY THE AVERAGE OF IN AND OUT TIMES 100

 PERCENT DISCREPANCY =           0.00     PERCENT DISCREPANCY =           0.00
```

```
VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP180 IN STRESS PERIOD   1
  ------------------------------------------------------------------------------

     CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
     ------------------                 ------------------------

           IN:                                   IN:
           ---                                   ---
             STORAGE =         695.3317             STORAGE =           0.0000
       CONSTANT HEAD =           0.0000       CONSTANT HEAD =           0.0000
               WELLS =           0.0000               WELLS =           0.0000
        UZF RECHARGE =         246.4295        UZF RECHARGE =          43.6784
               GW ET =           0.0000               GW ET =           0.0000
     SURFACE LEAKAGE =           0.0000     SURFACE LEAKAGE =           0.0000

            TOTAL IN =         941.7612            TOTAL IN =          43.6784

          OUT:                                  OUT:
          ----                                  ----
             STORAGE =         221.6983             STORAGE =          39.6089
       CONSTANT HEAD =           0.0000       CONSTANT HEAD =           0.0000
               WELLS =         720.0000               WELLS =           4.0000
        UZF RECHARGE =           0.0000        UZF RECHARGE =           0.0000
               GW ET =      -2.8172E-11               GW ET =           0.0000
     SURFACE LEAKAGE =           0.0000     SURFACE LEAKAGE =           0.0000

           TOTAL OUT =         941.6982           TOTAL OUT =          43.6089

            IN - OUT =       6.2988E-02            IN - OUT =       6.9511E-02

 PERCENT DISCREPANCY =           0.01     PERCENT DISCREPANCY =           0.16
```

3.6 Results: From Figure 3.4 it can be seen that all of the applied infiltration goes into the soil profile and becomes the actual infiltration, thus there is no runoff created and there is no leakage from the water table to the surface. All evapotranspiration takes place from the unsaturated zone, and evapotranspiration from the water table is zero. Evapotranspiration rate is supplied by the storage in the unsaturated zone.

CHAPTER 4 : MODFLOW HYDRUS PACKAGE

4.1 Introduction: The HYDRUS package for MODFLOW 2000 was developed to consider the effects of infiltration, soil moisture storage, evaporation, plant water uptake, precipitation, and water accumulation at the ground surface (Seo et al., 2007). Details of this package can be found in 'Documentation of the Hydrus Package for MODFLOW-2000, The U.S. Geological Survey Modular Ground-Water Model' by Hyeyoung Sophia Seo, Jirka Simunek, and Eileen P. Poeter.

The HYDRUS package discretizes the soil profile into finite elements, and defines the vertical distribution of hydraulic conductivity and other parameter characterizing the soil profile (Seo et al., 2007). MODFLOW zone arrays identify cells to which each unsaturated soil profile applies (Seo et al., 2007). The HYDRUS package determines the flux from the variably saturated rigid porous medium and connects to MODFLOW as a head dependent flux boundary (Seo et al., 2007). Information about the average depth to water in each cell MODFLOW zone is delivered to the HYDRUS package, which returns flux calculated using its own time discretization for each MODFLOW time step (Seo et al., 2007). The flux is applied to every cell in the zone. The HYDRUS package uses prescribed pressure head and flux boundaries, and boundaries controlled by atmospheric condition such as precipitation, evaporation, and transpiration (Seo et al., 2007).

The user defines precipitation, potential evaporation, and potential transpiration rates for the profile (Seo et al., 2007). The net infiltration rate, i.e the difference between precipitation and evaporation, is estimated during the simulation (Seo et al., 2007). Therefore there is no need to use MODFLOW 2000 evapotranspiration (EVT) package and recharge (RCH) package simultaneously in the same vertical column with the HYDRUS package (Seo et al., 2007). The RCH package can be used to simulate recharge from surfaces other than surface processes if desired (Seo et al., 2007). The EVT package can not be used with the Hydrus package (Seo et al., 2007). When a zone of cells is used for a profile, the average depth to water for all cells in the zone is used as lower boundary condition for the soil profiles (Seo et al., 2007)Consequently the user may want to use same profile for many different zones (Seo et al., 200677 The Soil profile needs to represent materials from the surface to the deepest level expected for the water table at any time during the simulation (Seo et al., 2007).

The user is allowed to make as many unsaturated profiles as he/she likes, i.e., one unsaturated profile for every cell or a group of cells (Seo et al., 2007) The average depth to ground water (ground surface-water table elevation) of all model cells in the zone is used to determine the boundary pressure head value in the Hydrus profile (Seo et al., 2007)

The unsaturated zone finite element mesh is constructed by dividing the soil profiles into one dimensional linear elements connected at nodal elements (Seo et al., 2007). The thickness between two nodes should be relatively small at locations where large hydraulic gradients are expected (Seo et al., 2007). Such a region is usually located close to the soil surface where highly variable meteorological factors can cause rapid changes in the soil water content and corresponding pressure heads (Seo et al., 2007). Note that the bottom of soil the profile needs to be below the water table throughout the simulation. But it is not necessary that the soil mesh construction has to be done up to the bottom of next the layer. For example, if there are three layers of aquifer lying over each other, and the water table lies somewhere in the first layer, then construction of mesh and nodes are done only up to the bottom of this first layer. Flux is calculated at the bottom of the soil profile, which must always be saturated.

Variables used by MODFLOW-Hydrus package include initial pressure distribution (or initial water content distribution) up to a depth below water table, residual water content (Θr), saturated water content (Θs), Alpha (inverse of the air-entry value or bubbling pressure in the Brooks and Corey function) and an empirical shape parameter in the van Genuchten function (Seo et al., 2007), saturated hydraulic conductivity (K_s), pore size distribution index (N), and pore connectivity or tortuosity parameter (L). The initial equilibrium pressure head distribution of the soil profile is calculated from the equation shown below:

$H=Z_{top}-D-Z$ ---equation 1

where,

H=Pressure head of the soil profile (or node) under consideration (L)

Ztop=Elevation of the ground surface (L)

D= Depth to ground water from the surface (L)

Z=Elevation of bottom of soil profile node under consideration (L)

If it is desired to consider evapotranspiration along with evaporation from the root zone, then, information about the plant parameters also have to be included in the input. The plant parameters include:

BETA= Value of water uptake distribution in the soil root zone at node n.

P0=Value of pressure head below which the roots start to extract water from the soil.

P2H=Value of the limiting pressure head at which the roots cannot extract water at the maximum rate (assuming a potential transpiration rate of r2H).

P2L=Value of the limiting pressure head at which the roots cannot extract water at the maximum rate (assuming a potential transpiration rate of r2L).

P3=Value of the pressure head below which root water uptake ceases (usually equal to wilting point).

r2H=Highest potential transpiration rate (L/T)

r2L=Lowest potential transpiration rate (L/T)

POPTM=Value of the pressure head below which roots start to extraxt to water at the maximum possible rate.

4.2 Sign Convention:

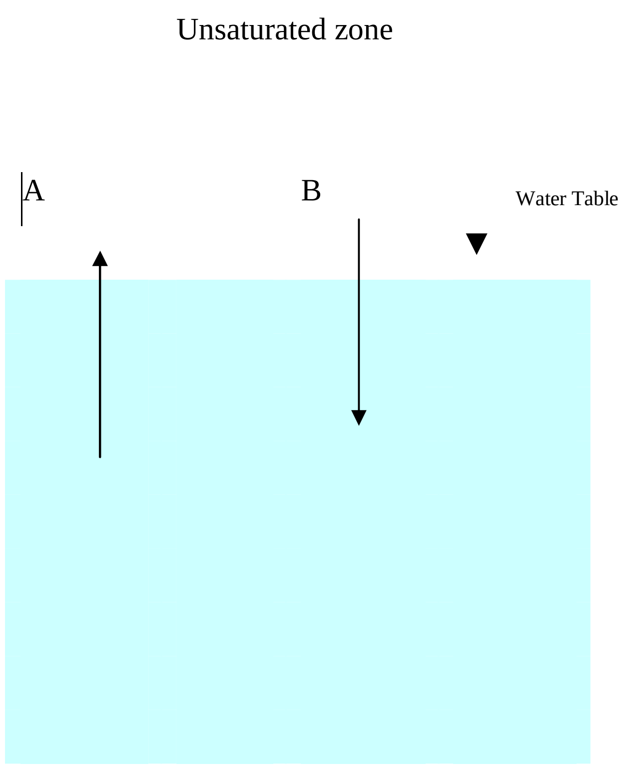


Figure 4.1

The flux coming out of the unsaturated zone (B), which has negative values in the flux matrix in the output file, is the input to the water table. All of these negative values are added and multiplied by the area of a cell to give the unsaturated flow, and appear in 'IN' section of the volumetric budget as 'Unsat flow'. Similarly the flux going into the unsaturated zone (A) from the water table is the positive values in the flux matrix in the output file. These are added and multiplied by area of a cell to give the unsaturated flow, and appear in the 'OUT' section of the volumetric budget as 'Unsat flow'.

4.3 Types of Modflow for HYDRUS Package:

Two types of executable MODFLOW 2000 were developed for HYDRUS package. They are M2K.exe (VERSION 1.14.00 07/01/2004) and mf2k.exe (VERSION 1.14.00 07/01/2004). There is also MODFLOW 2000 (VERSION 1.18.00 08/23/2007). But this version does not support the unsaturated package.

4.3.1 Difference between M2K.exe and mf2k.exe:

The only difference in the mf2k version is the addition of a flag for printing HYDRUS profile information at selected print times, which can not be found in the M2K version. This option to print at selected times can not be found in the M2K version but still this version prints HYDRUS profiles on its own. The additional variables in the mf2k version are 'PROPR, PROINF, PRINT TIMES'. Please look at 'DOCUMENTATION FOR PREAPRING THE INPUT FILE OF THE UPDATED HYDRUS PACKAGE FOR MODFLOW-2000' by Navin Kumar C. Twarakavi, Hyeyoung Sophia Seo, and Jirka Simunek (http://www.pc-progress.cz/_Downloads/MODFLOW/UpdatedInput_Hydrus.pdf).

4.4 Case Study: A simple case similar to the case studied in UZF1 package (Chapter 3, Section 3.3) was considered. This case has nine cells as shown in figure 4.2. All nine cells were considered as active cells. The initial head was kept equal to 95m in all cells. A well was kept at the center pumping at -4 m3/day. The hydraulic conductivity of the cells was kept equal to a constant value of 0.2496 m/day. Specific yield was kept equal to a constant value of 0.28. Precipitation rate of 0.005511 m/day was applied all over the cells. Evaporation from the cells was kept 0.0005 m/day, and evapotranspiration flux was kept equal to 0.001 m/day. Because evapotranspiration was also included in the simulation, the plant parameters were considered as shown below:

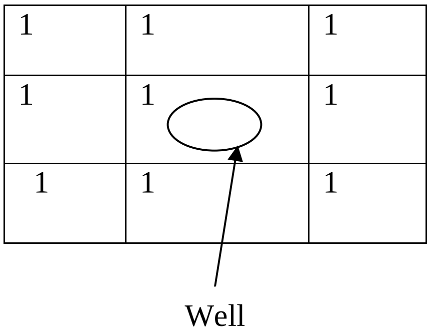


Figure 4.2

P0=-0.1 m

P2H=-2.0 m

P2L=-8.0

P3=-80.0

r2H=0.005

r2L=0.001

POPTM=-0.25

As the extinction depth was 2.0 m, the ‘Beta’ value was kept equal to 1 up to node elevation of 98.0 m. A zone file was created and listed in the Name file as well. All of the cells except the one with the pumping well were designated as zone 1, and the cell with the pumping well was designated as zone 2. Although they were designated with zones 1 and 2 all of the properties are the same in both zones. The pressure head distribution of the soil profile was calculated for each of the node using equation 1 (Figure 4.3).

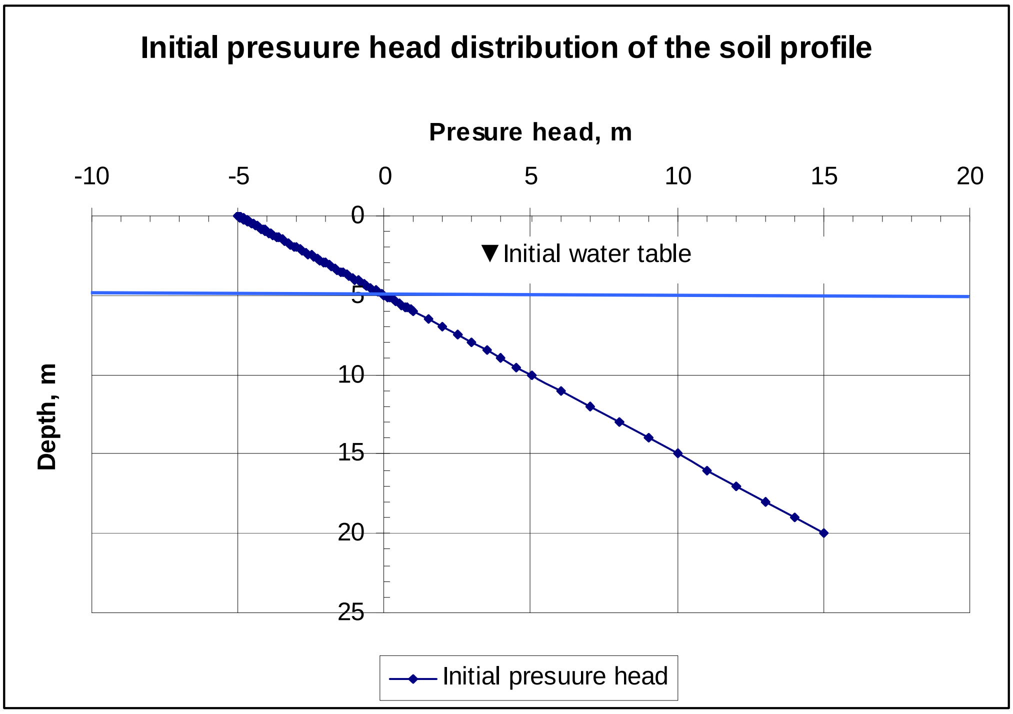


Figure 4.3

The hydraulic properties of soil were:

Residual water content (ϴr)=0.078

Saturated water content (ϴs)=0.43

Bubbling Pressure (Alpha)=3.6

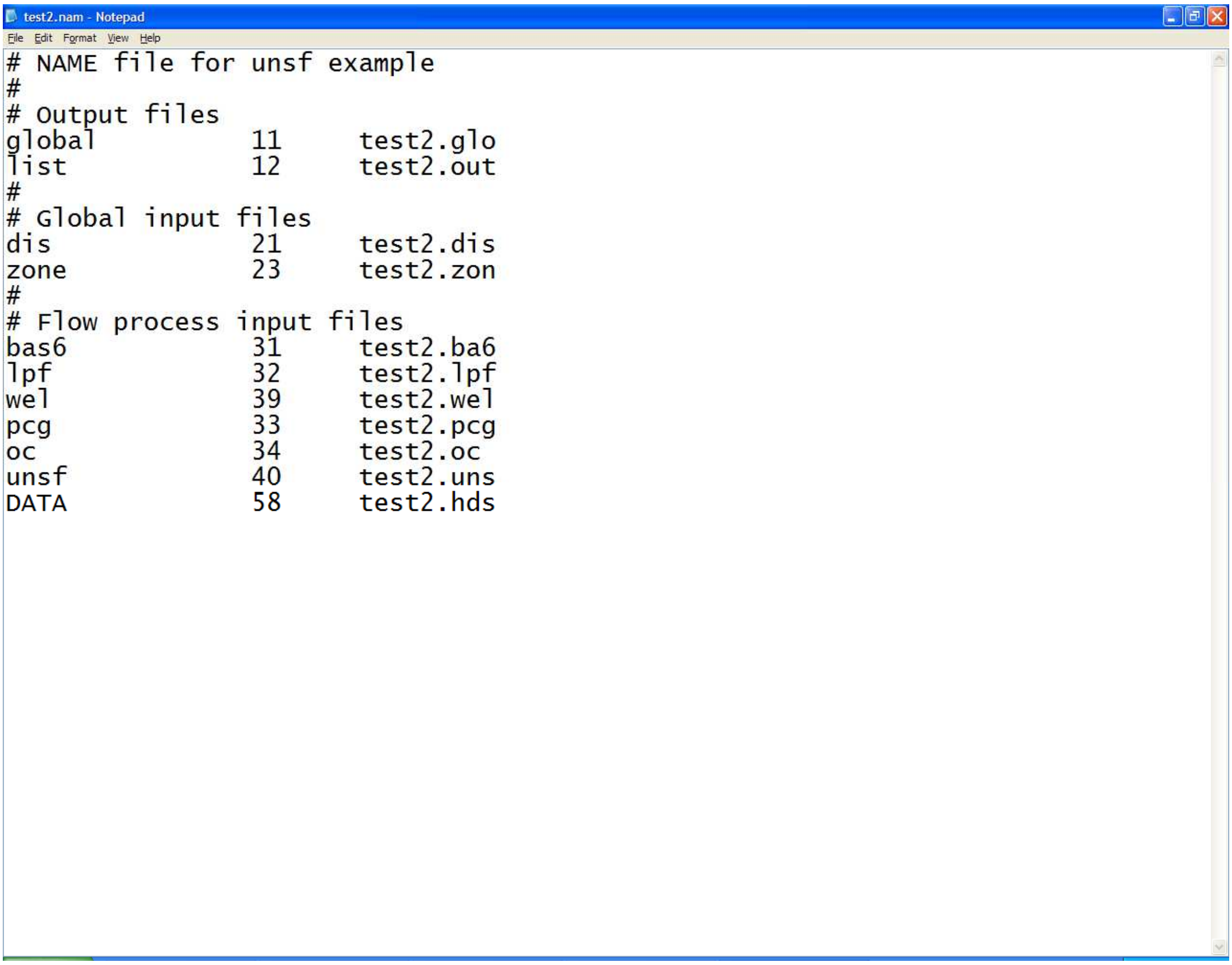
Pore size distribution index (N)=1.56

Saturated Hydraulic conductivity=0.2496 m/day

Pore connectivity parameter=0.5

Transient simulation was performed, and the number of stress periods was taken equal to 1, with length equal to 180 days. Also the number of time steps was taken equal to 180, so Δt=1 day.

4.5 MODFLOW Execution: Input to the Hydrus package is read from the file that is type 'UNSF' in the Name file (Seo et al., 2006). A name file (Figure 4.4) was created listing all of the input files and output files.



```
# NAME file for unsf example
#
# Output files
global             11     test2.glo
list               12     test2.out
#
# Global input files
dis                21     test2.dis
zone               23     test2.zon
#
# Flow process input files
bas6               31     test2.ba6
lpf                32     test2.lpf
wel                39     test2.wel
pcg                33     test2.pcg
oc                 34     test2.oc
unsf               40     test2.uns
DATA               58     test2.hds
```

Figure 4.4

The case was executed using mf2k.exe (VERSION 1.14.00 07/01/2004).

4.6 Output From Simulation: A MODFLOW output file will be created after the simulation with the name of output file as specified in Name file. Depending upon the options specified in the output control file, the volumetric budget of the entire model, heads and drawdown will be printed at desired time steps and stress periods in this output file. Also an output file ‘Hyd_profile.out’ will be created, listing moisture of the soil profile for the desired time for the two zones. Data from this file could be used to plot the moisture profile of the soil at different times. Another output file ‘Hyd_TInf.out’ will also be created that gives a flux calculated for two zones at all time steps. ‘Hyd_profile.out’ and ‘Hyd_TInf.out’ files are created automatically by the program and are not required to be listed in the Name file. A sample of output file is as shown below:

```
HEAD IN LAYER   1 AT END OF TIME STEP 180 IN STRESS PERIOD    1

          1       2       3
   1    94.72   94.72   94.72
   2    94.72   94.68   94.72
   3    94.72   94.72   94.72

DRAWDOWN IN LAYER   1 AT END OF TIME STEP 180 IN STRESS PERIOD    1

           1           2           3
   1   0.2752      0.2846      0.2752
   2   0.2846      0.3222      0.2846
   3   0.2752      0.2846      0.2752



  VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP180 IN STRESS PERIOD   1
  ------------------------------------------------------------------------------

     CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
     ------------------                 ------------------------

           IN:                                   IN:
           ---                                   ---
             STORAGE =        448.2572             STORAGE =          2.2951
       CONSTANT HEAD =          0.0000       CONSTANT HEAD =          0.0000
               WELLS =          0.0000               WELLS =          0.0000
          UNSAT FLOW =        271.7858          UNSAT FLOW =          1.7127

            TOTAL IN =        720.0431            TOTAL IN =          4.0078

          OUT:                                  OUT:
          ----                                  ----
             STORAGE =          0.0000             STORAGE =          0.0000
       CONSTANT HEAD =          0.0000       CONSTANT HEAD =          0.0000
               WELLS =        720.0000               WELLS =          4.0000
          UNSAT FLOW =          0.0000          UNSAT FLOW =          0.0000

           TOTAL OUT =        720.0000           TOTAL OUT =          4.0000

            IN - OUT =      4.3091E-02            IN - OUT =      7.8130E-03

 PERCENT DISCREPANCY =          0.01     PERCENT DISCREPANCY =          0.20
```

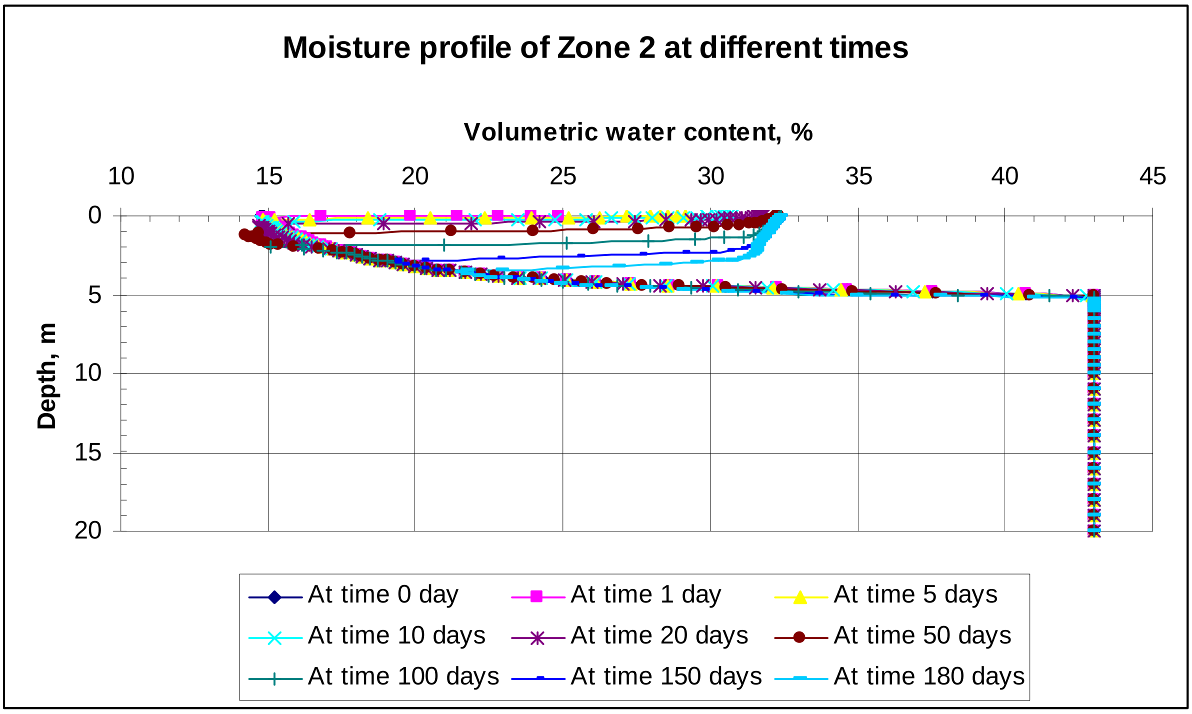


Figure 4.5

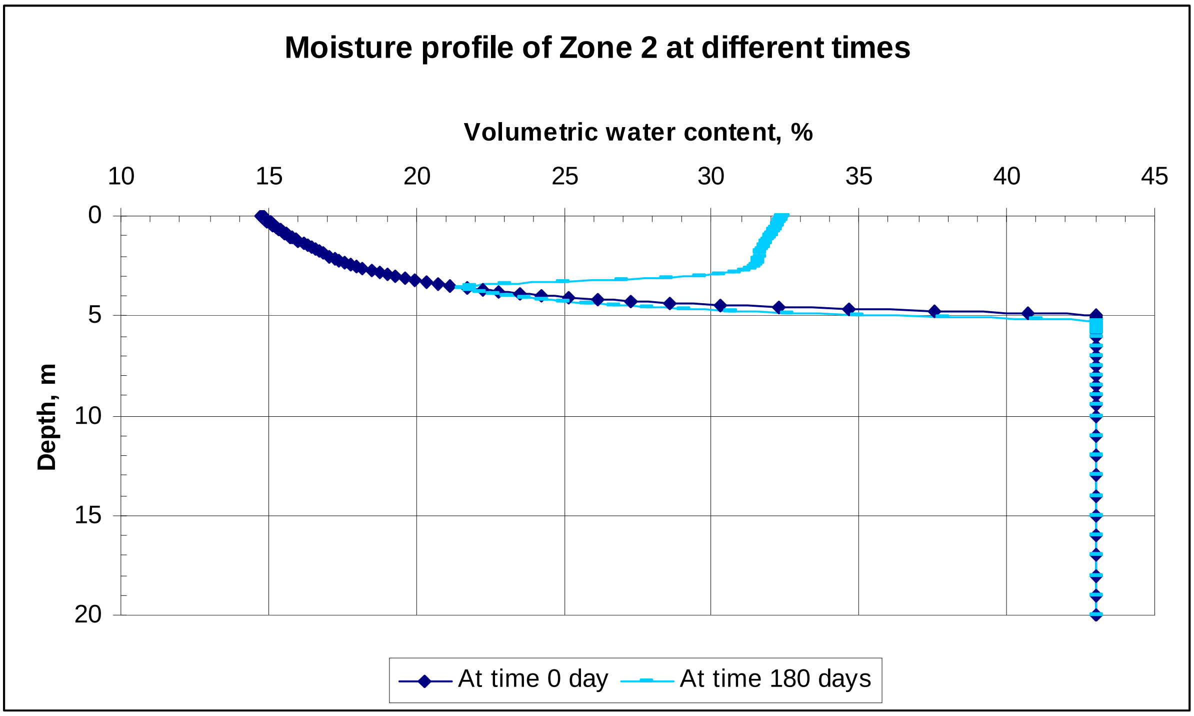


Figure 4.6

4.7 Results and comparison with UZF1 package: Drawdowns and heads in the cells calculated by both UZF package and MODFLOW Hydrus packages are almost similar to each other. But the volumetric budget calculated by each package is quite different. UZF recharge calculated by the UZF package is 43.6784 m3/day, whereas the unsaturated flow (recharging the aquifer) calculated by MODFLOW Hydrus package is 1.7127 m3/day. The moisture profile from the UZF package is obtained only up to the depth of the unsaturated zone (Figure 3.3), whereas the MODFLOW Hydrus package gives the moisture profile up to the depth where the soil profile is discretized (Figures 4.5 and 4.6). Both the cases shown in UZF and MODFLOW Hydrus package were run under similar conditions. Figure 4.7 shows the moisture profile obtained from both of these packages at 180 days.

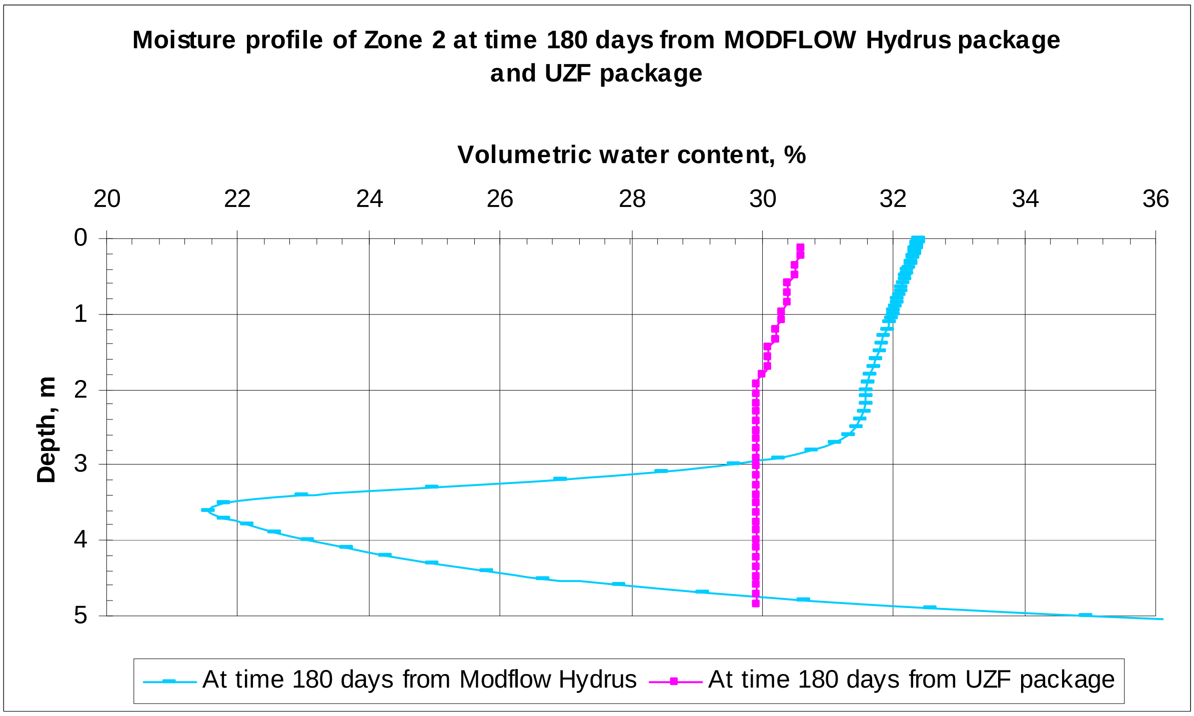


Figure 4.7: Comparison of Moisture profile calculated by MODFLOW Hydrus and UZF package

The difference in the moisture profiles and volumetric budget between these two packages may be because MODFLOW Hydrus uses initial condition based upon initial head (or water content) for the whole profile (Figure 4.3), whereas only one value of initial moisture content (0.1478) is used by the UZF package for the entire layer. Thus, MODFLOW Hydrus package looks more realistic than the UZF package, and the MODFLOW Hydrus is recommended, rather than the UZF package, to simulate the unsaturated soil-water balance.

4.8 Testing this same case using Hydrus 1D software: Hydrus 1D is an interactive graphics-based user interface. HYDRUS-1D was developed in support of the HYDRUS computer model. HYDRUS-1D may be used to simulate one-dimensional unsaturated water flow, heat transport, and the movement of solutes involved in consecutive first-order decay reactions in variably-saturated soils. HYDRUS uses the Richards equation for simulating variably-saturated flow and Fickian-based advection-dispersion equations for heat and solute transport (Simunek et al., 2008). The input to MODFLOW Hydrus package in 'UNSF' type file (see Figure 4.4) is the same as the input in this software. So the case with MODFLOW Hydrus was again simulated but with zero pumping because no well can pump water from the unsaturated zone simulated by Hydrus 1-D. Precipitation was changed to 0.003647 m/day. The plots of moisture profile at time 0 and 180 days (Figure 4.8) from Hydrus 1D and from MODFLOW Hydrus with zero pumping (Figure 4.9) are shown below (Note: Hydrus 1D software allows to input data for soil nodes and pressure head only up to 101 rows, so discretization of soil should be done such that all of the data fit in 100 rows).

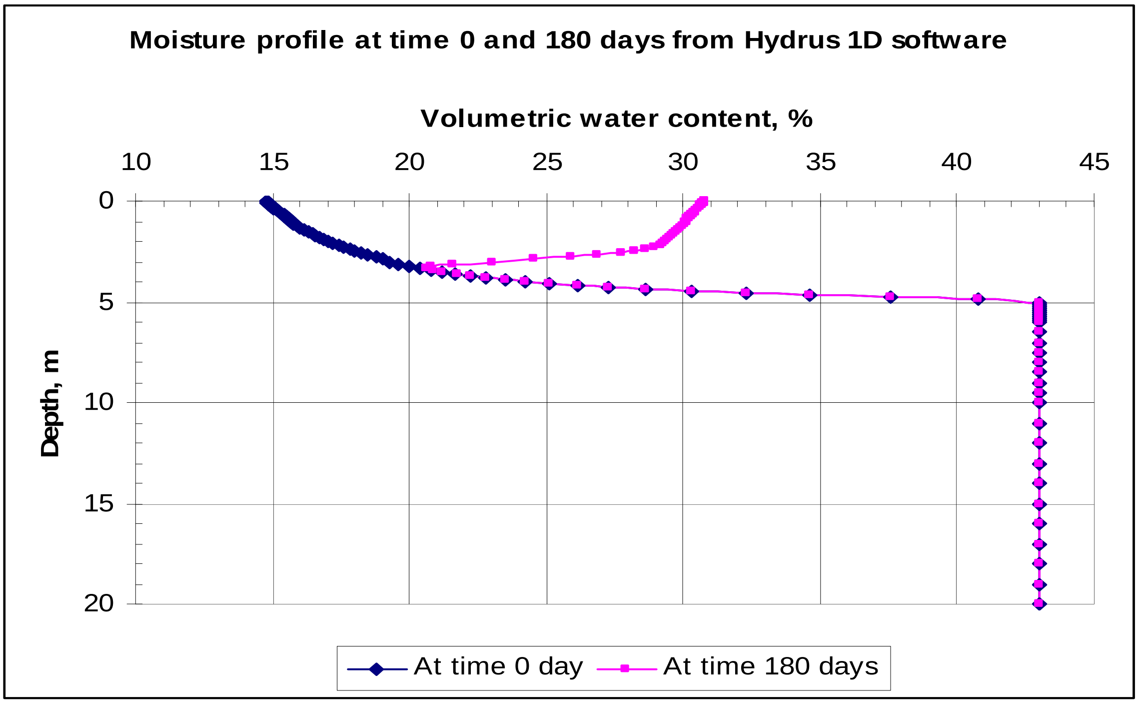


Figure 4.8

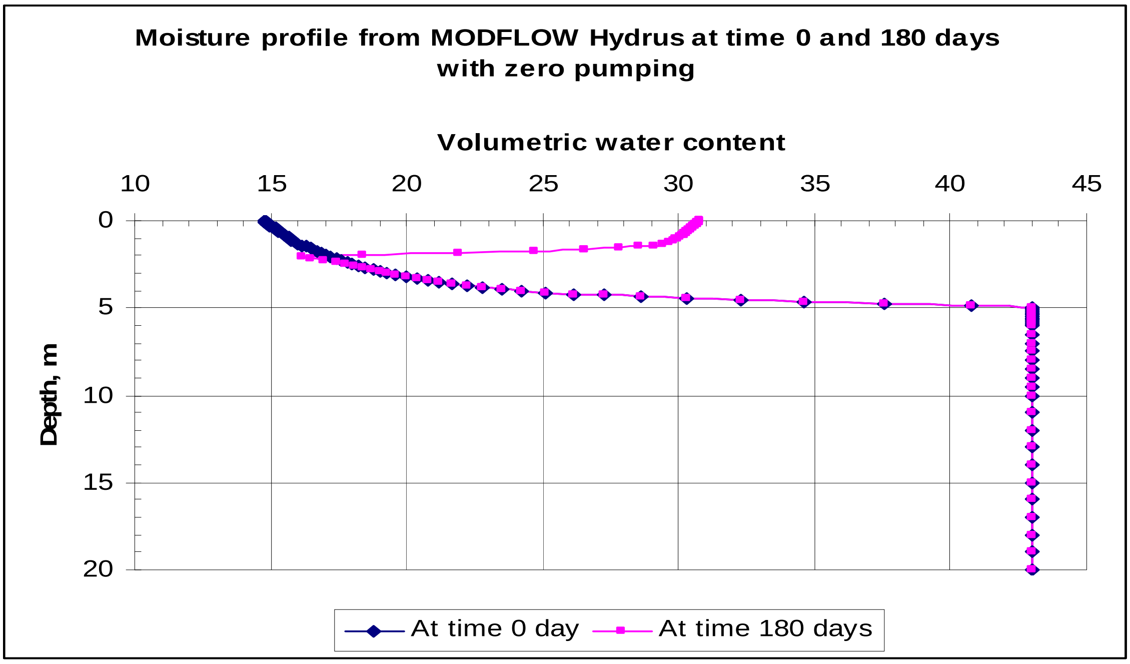


Figure 4.9

4.8.1 Comparison of Moisture profiles from MODFLOW Hydrus and Hydrus 1-D: The difference in moisture profile from these packages was due to coupling issues. MODFLOW Hydrus had 180 time steps in the Discretization file, which equals the number of atmospheric boundary conditions. Every time a MODFLOW stress period ends, the Hydrus restarts the calculations with the last profile as the initial condition. This means that the Hydrus time discretization needs to be restarted from scratch resulting in numerical dispersion leading to the differences (Twarakavi, personal communication, 2008). According to Twarakavi, the number of time steps do not have to equal the number of atmospheric boundary conditions. So the number of time steps was decreased to 10 and the length of a stress period was decreased to 20 days, so that Δt=2 days. Now the moisture profiles from MODFLOW Hydrus package and Hydrus 1-D software match closer with each other (Figure 4.10 and 4.11).

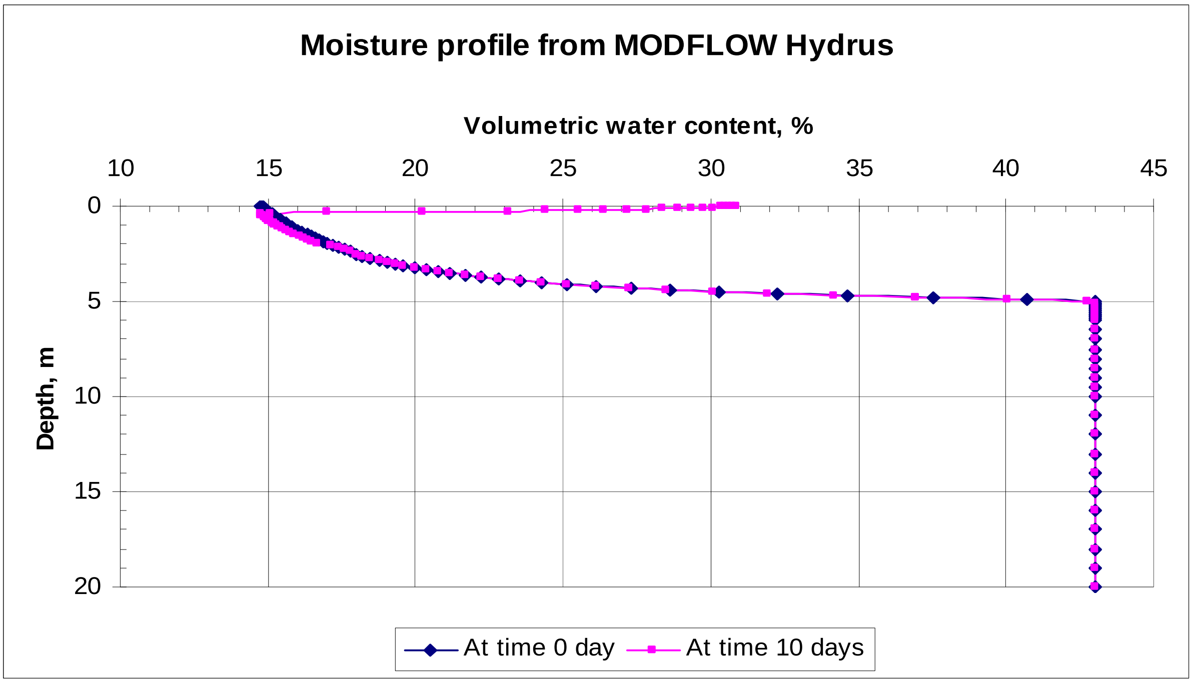


Figure 4.10

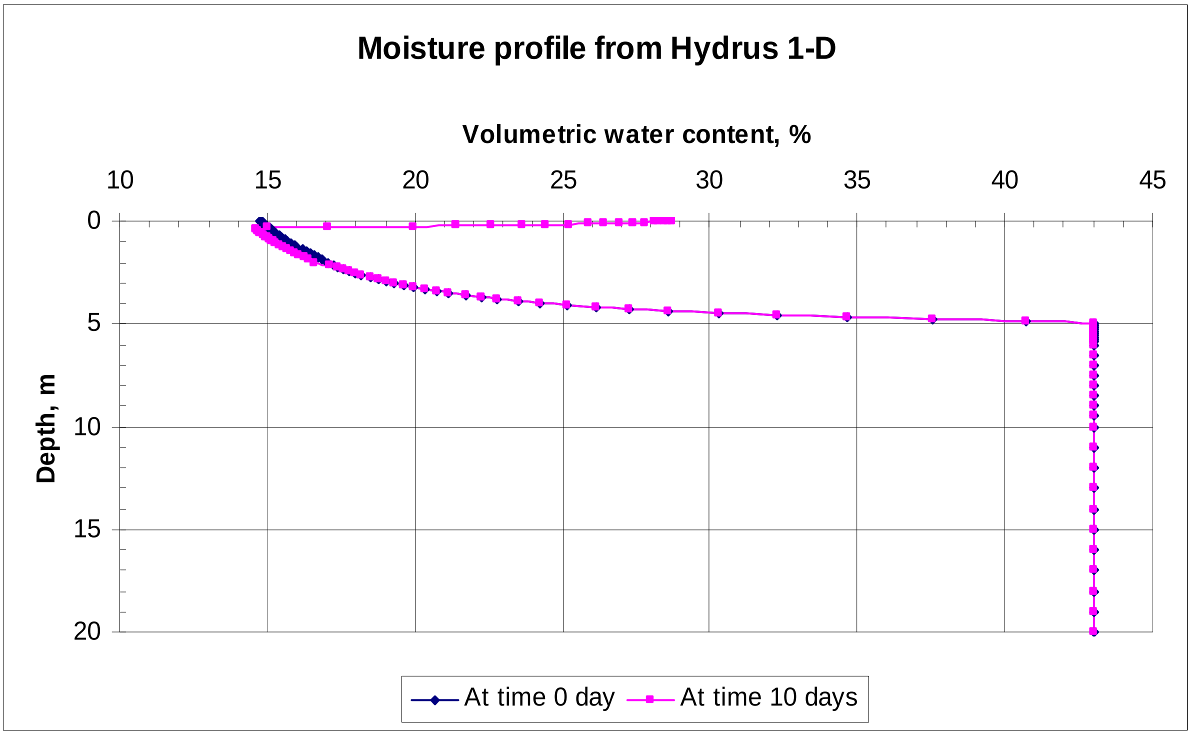


Figure 4.11

4.8.2 Importance of Boundary condition: Proper boundary conditions are important in Hydrus 1D simulation. A sensitivity analysis (Figures 4.12 and 4.13) was done with the lower boundary condition in order to investigate its effect in the moisture profile. A case studied in Section 4.8.1 where precipitation equals to 0.003647 m/day and other properties are as shown in Section 4.4 was considered and the moisture profiles at time 10 days were considered to see the effect of the boundary condition. Figure 4.8 shown above is based upon the lower boundary condition of zero constant flux. Detailed description on boundary conditions can be found in ' The HYDRUS-1D Software Package for Simulating the One-Dimensional Movement of Water, Heat, and Multiple Solutes in Variably-Saturated Media', Version 4.0, April 2008 by J. Simunek, M. Sejna, H. Saito, M. Sakai, and M. Th. Van Genuchten. Some of the lower boundary conditions in Hydrus 1-D are:

Constant pressure head: Pressure remains constant throughout the simulation at any time.
$h(x, t) = h_0(t)$ at x=0 or x=L, where h is the prescribed value of pressure head at surface (x=L) or bottom (x=0)

Constant flux: A constant flux of water leaves from the bottom of the soil profile. In our case it is zero, which means water is not leaving.

Free Drainage: A zero-gradient boundary condition can be used to simulate a freely draining soil profile. Such a situation often occurs in field studies of water flow and drainage in the vadose zone. This lower boundary condition is most appropriate for a situation where the water table lies far below the domain of interest (Simunek et al., 2008).

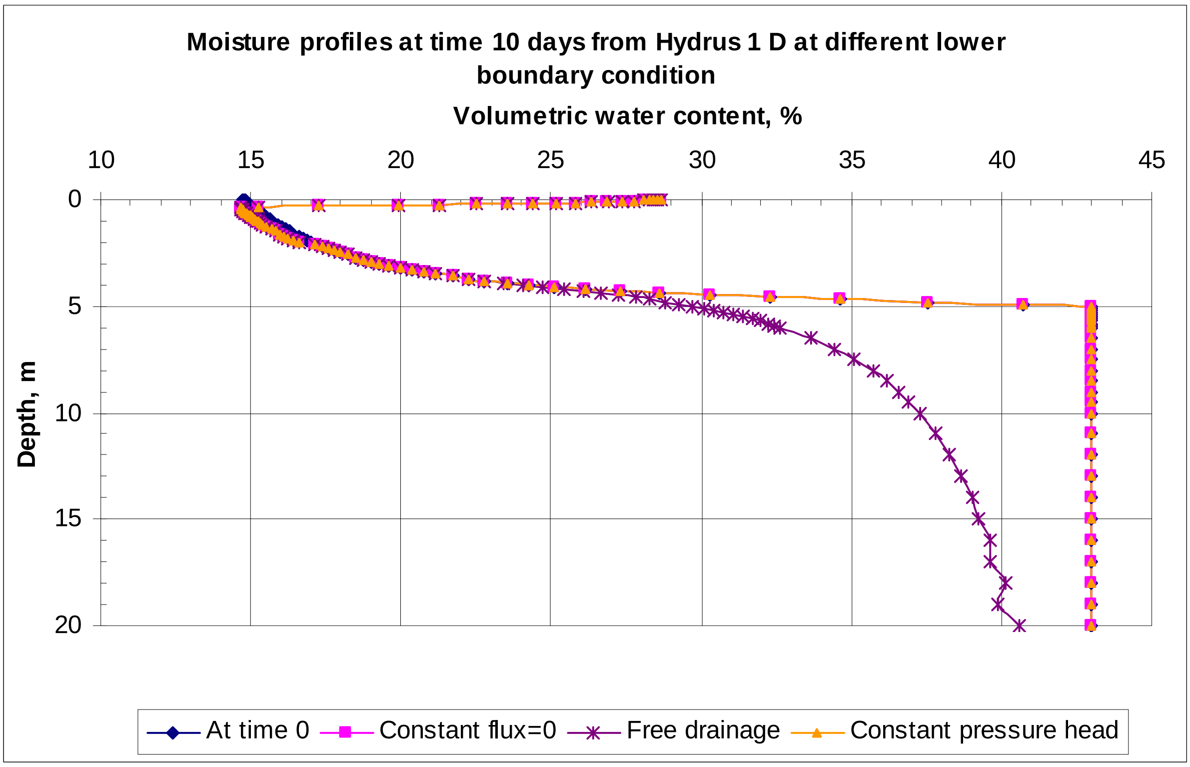


Figure 4.12 (Equivalent plot in terms of head shown in Figure 4.13)

Seepage face: This type of boundary condition is often applied to laboratory soil columns when the bottom of the soil column is exposed to the atmosphere (gravity drainage of a finite soil column). The condition assumes that the boundary flux will remain zero as long as the pressure head is negative. However, when the lower end of the soil profile becomes saturated, a zero pressure head is imposed at the lower boundary and the outflow calculated accordingly. This type of boundary condition is often used for lysimeters (Simunek et al., 2008).

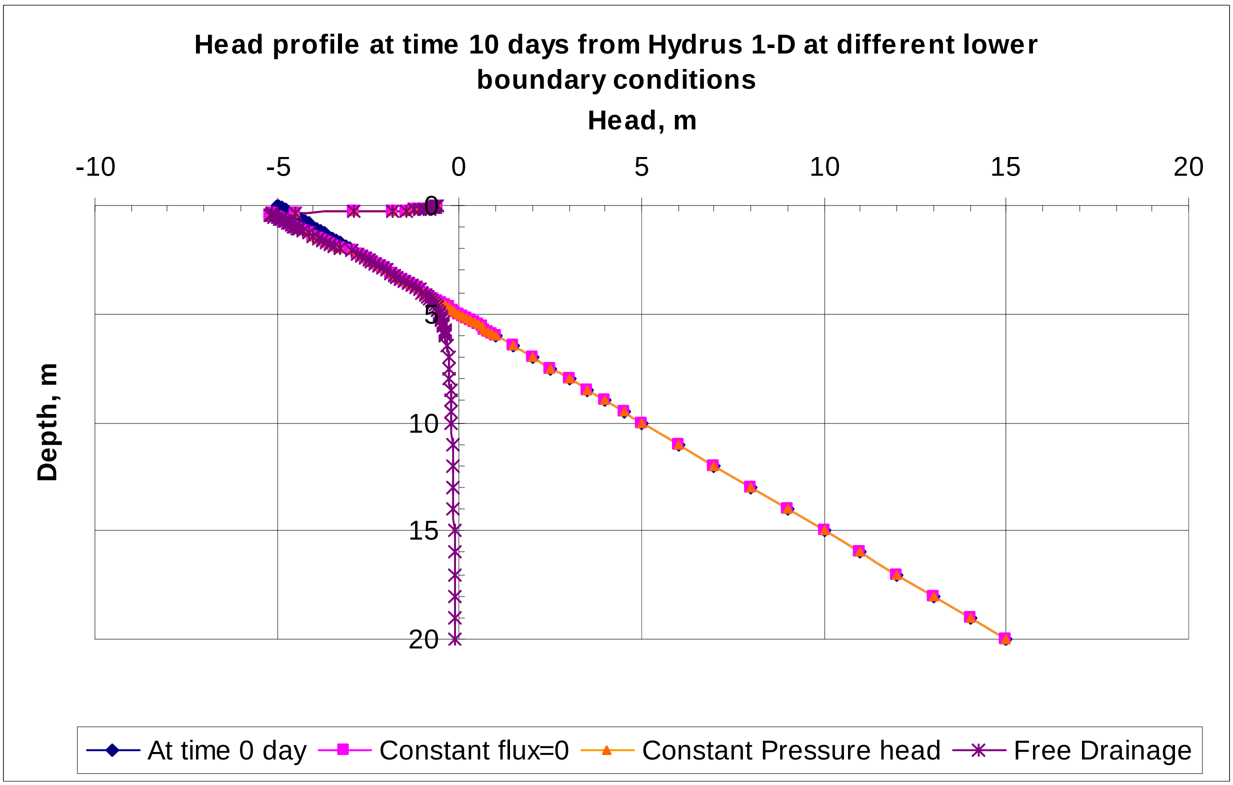


Figure 4.13 (Equivalent plot in terms of moisture shown in Figure 4.12)

(Note: Lower boundary condition: Seepage face with h=0 did not converge to a solution.)

The case run in Hydrus 1-D software (Section 4.8) was considered to have lower boundary condition as constant flux equal to zero since the water surface profile matched closely with MODFLOW Hydrus (Figures 4.10 and 4.11).

CHAPTER 5: CONDUIT FLOW PROCESS

5.1 Introduction: The Conduit Flow Process (CFP) package simulates dual porosity aquifers that can be mathematically approximated by coupling the traditional ground water flow equation with a discrete network of cylindrical pipes (Mode 1) and (or) inserting a preferential flow layer that uses a turbulent hydraulic conductivity to simulate turbulent horizontal flow conditions, Mode 2 (Shoemaker et al., 2007), and a combination of Mode 1 and Mode 2 identified as Mode 3. Detailed description of this package can be found in USGS report 'Documentation of a Conduit Flow Process (CFP) for MODFLOW-2005', 2007, Techniques and Methods, Book 6, Chapter A 24 by W. Barclay Shoemaker, Eve L. Kuniansky, Steffen Birk, Sebastian Bauer, and Eric D. Swain.

The CFP has the ability to simulate turbulent ground water flow conditions by: (1) coupling the traditional ground water flow equation with the formulations for a discrete network of cylindrical pipes (Mode 1), (2) inserting a high conductivity flow layer that can switch between laminar and turbulent flow (Mode 2), or (3) simultaneously coupling a discrete pipe network while inserting a high conductivity flow layer that can switch between laminar and turbulent flow (Mode 3) (Shoemaker et al., 2007). CFP, Mode 1 may represent dissolution or biological burrowing features in carbonate aquifers, voids in rocks and or lava tubes in basaltic aquifers, and can be fully or partially saturated under laminar or turbulent flow conditions. Preferential flow layers (Mode 2) may represent: (1) porous media where turbulent flow is suspected to occur under the observed hydraulic gradients; (2) a single secondary porosity subsurface feature, such as a well-defined laterally extensive underground cave; or (3) a horizontal preferential flow layer consisting of many interconnected voids. In this second case, the input data are effective parameters, such as a very high hydraulic conductivity, representing multiple features (Shoemaker et al., 2007).

Data requirements for simulating CFP using Mode 1 are more complex than using Mode 2. For Mode 1 data requirements include conduit pipe locations, length, pipe diameter, water temperature, turtuosity, internal roughness, critical Reynolds's number, and exchange conductances are required. Mode 2 requires less hydraulic information and specific location information of the conduit. Two nodes are associated with a single pipe and a node can be a location for meeting of up to six pipes only. Each node is located in a finite difference cell, and there can be only one node within a finite difference cell (Shoemaker et al., 2007). Finite difference cells can have equal or different row and column lengths (Shoemaker et al., 2007). Pipes can connect diagonally between two finite difference cells within and adjacent model layers (Shoemaker et al., 2007). The data required for Mode 2 includes water temperature, mean void diameter, and critical Reynolds's number. If simulating CFP using Mode 3, then the data requirements include the combination of Mode 1 and Mode 2. Shoemaker et al. (2007) mentions the step-by-step method to create a CFP input file (page 27-30). For example, if CFP is simulated using Mode 1, then input data are specified according to ITEM numbers 0 to 29, if simulated using Mode 2 then ITEM numbers 0,1, and 30 to 39 have to be specified, and if simulated using Mode 3, then ITEM numbers 0 to 39 have to be specified.

Many results from CFP calculations are written to the MODFLOW 2005 output file. Some results not written to the MODFLOW output file can be written to separate output files for post processing, which include node heads, flow, etc. To create this separate output file for post processing, an extra output file type 'COC' has to be written, indicating for which nodes and conduits the output is desired. It should, however, be noted that the provision to write output in separate files is achieved only if CFP is simulated using Mode 1 or Mode 3. Shoemaker et al. (2007, p. 30) mentions a step-by-step method to create this file.

Another file that could be included in CFP simulation is the conduit recharge package (CRCH) for routing a fraction of the diffuse areal recharge into nodes of conduit pipes. This functionality is useful in scenarios where rainfall runs directly into karst features, such as sinkholes or swallets (Shoemaker et al., 2007). It should however be noted that the recharge (RCH) package should be active when CRCH package is also included in the simulation, and this feature is applicable when simulating CFP using Mode 1 or Mode 3. Shoemaker et al. (2007, pp. 30, 31) has mention a step-by-step method to create this file.

5.2 Case Study: A simple case similar to that studied in UZF1 package (Chapter 3, Section 3.3) was considered. This case has nine cells as shown in Figure 5.1. All nine cells were considered active cells, and each has a size of 25m by 25 m. The initial head was kept equal to 98 m in all cells. A well was kept at the center pumping at -20 m^3/day (5.92 ac-ft/yr). The hydraulic conductivity of the cells was kept equal to a constant value of 0.2496 m/day. Specific yield was kept equal to a constant value of 0.28. Precipitation rate of 0.003647 m/day was applied all over the cells. ETS1 package was included in the simulation with ET surface equal to 100 m, Maximum ET flux at surface equal to 0.08 m/day, extinction depth equal to 2 m, and ET flux at 1 meter depth from surface equal to 0.032 m/day (So, PXDP=0.5, PETM=0.4).

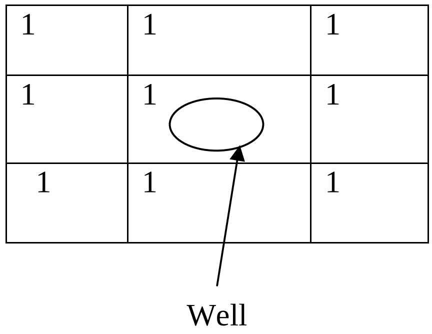


Figure 5.1

<u>5.2.1 MODFLOW execution using Mode 1:</u> Input to the Conduit Flow Process package is read from the file that is type ‘CFP’ in the Name file (Figure 5.4). Execution using Mode 1 to simulate CFP is achieved by specifying ‘1’ in ITEM 2 of the CFP file (bold number in Figure 5.2.1). The location of nodes and pipes (Figures 5.2 and 5.3) and other inputs are as shown below.

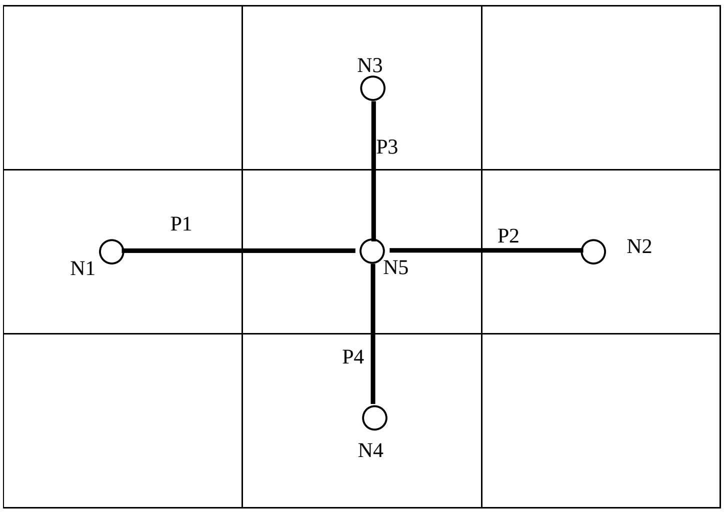


Figure 5.2: Plan showing nodes and conduits

Top Elevation 100 m

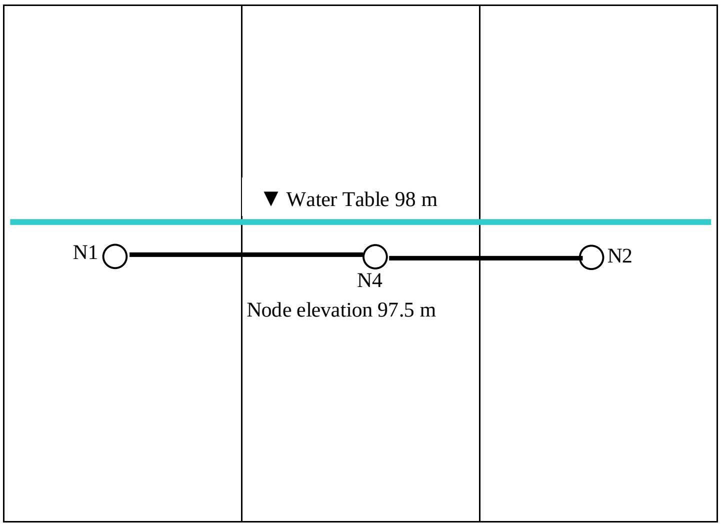


Figure 5.3: Front view showing nodes and conduits

Elevations of all five nodes= 97.5 m

Diameter of all conduits (P1, P2, P3, P4)= 0.1 m

Turtuosity of all conduits= 1.0

Roughness of all conduits= 0.01

Lower critical Reynolds's for all conduits (turbulent to laminar) = 10

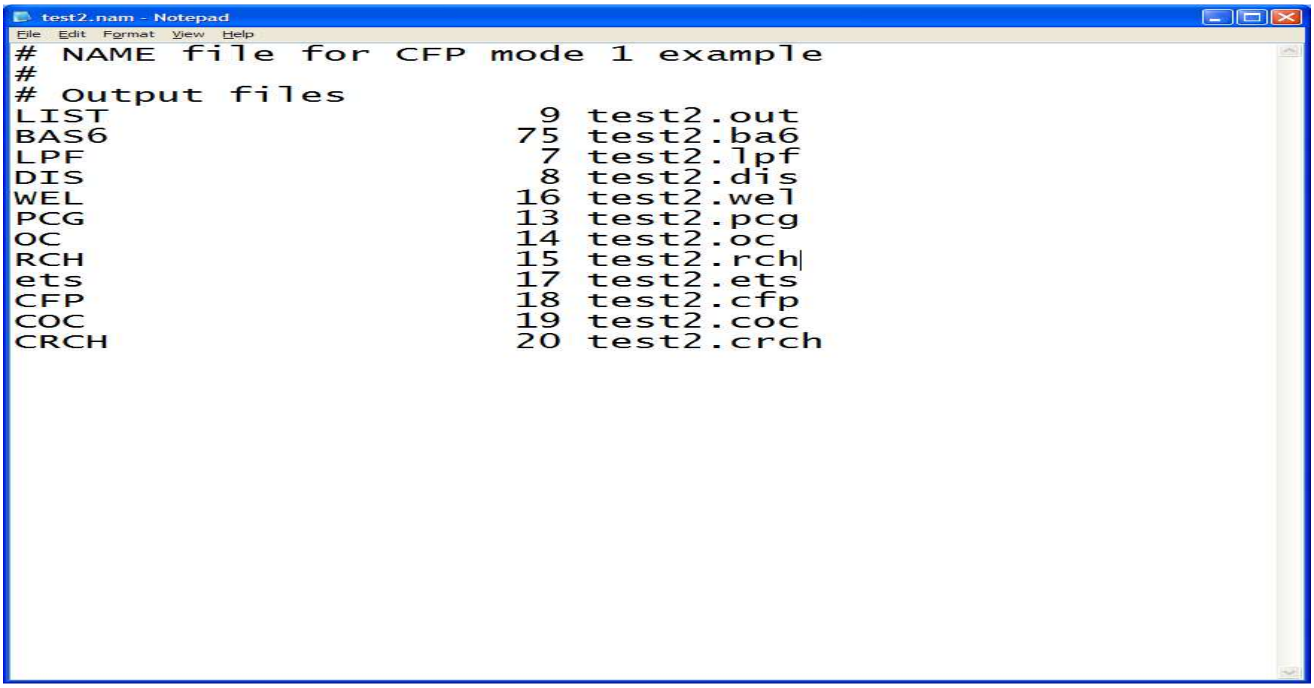
Upper critical Reynolds's for all conduits (laminar to turbulent) =20

Conduit wall permeability of all conduits=5 m/day

It was assumed that all of the recharge falling over cell (row 2, column 3) will be routed directly into the node 2. So an extra file type 'CRCH' (Figure 5.5) was created and included in the name file as shown in Figure 5.4 below. Also another extra file type 'COC' (Figure 5.6) was created and included in the name file as shown in figure 5.4 below in order to write node heads and flows for all of the nodes and pipes. MODFLOW 2005 version 1.2.01_cfp 01/17/2007 was used in the simulation.

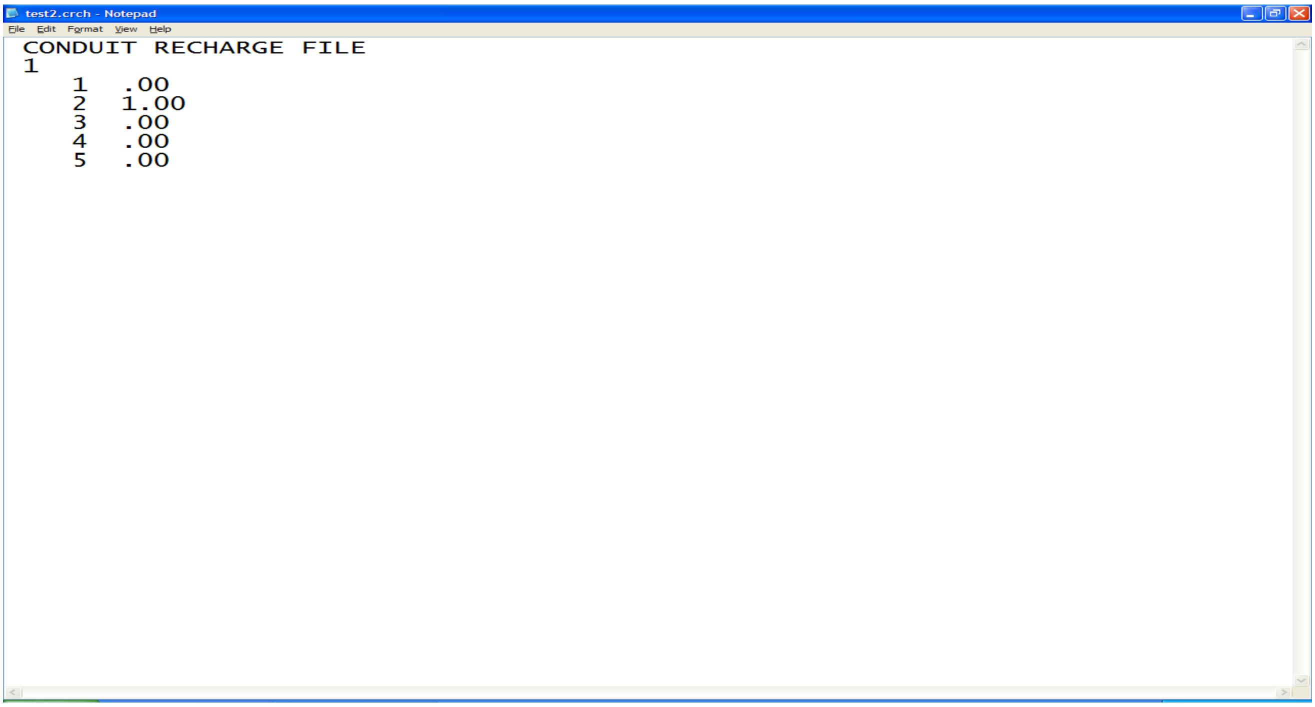
```
# mode
1
#data for mode 1 conduit pipe system
#number of nodes / tubes / layers
5  4  1
#temperature
25.
#No_N   mc mr ml  Nb1   Nb2  Nb3  Nb4 Nb5 Nb6 Pb1 Pb2 Pb3 Pb4 Pb5 Pb6
1        1  2  1   5     0    0    0   0    0   1   0   0   0   0   0
2        3  2  1   5     0    0    0   0    0   2   0   0   0   0   0
3        2  1  1   5     0    0    0   0    0   3   0   0   0   0   0
4        2  3  1   5     0    0    0   0    0   4   0   0   0   0   0
5        2  2  1   1     2    3    4   0    0   1   2   3   4   0   0
#elevation of conduit nodes. Two possibilites
#first: node #  elevation (1 line for each node)
#second: nbrnodes elevation(only one line used to assign constant value)
1 97.5
2 97.5
3 97.5
4 97.5
5 97.5
#surface dependent exchange (set 1) or constant exchange (set 0)
1
#criterion for convergence
1.0D-6
#maximum number for loop iterations
100
#parameter of relaxation
1
#newton raphson print flag
1
#data for tube parameters:
#no. diameter  tortuosity  roughness   lreynolds     treynolds
1    0.1       1.0        0.01        10.0         20.0
2    0.1       1.0        0.01        10.0         20.0
3    0.1       1.0        0.01        10.0         20.0
4    0.1       1.0        0.01        10.0         20.0
#node heads (if head unequal -1 the head is fixed)
1    -1
2    -1
3    -1
4    -1
5    -1
#exchange terms for flow between continuum and pipe-network
1   5.0
2   5.0
3   5.0
4   5.0
5   5.0
```

Figure 5.2.1. CFP file for Mode 1



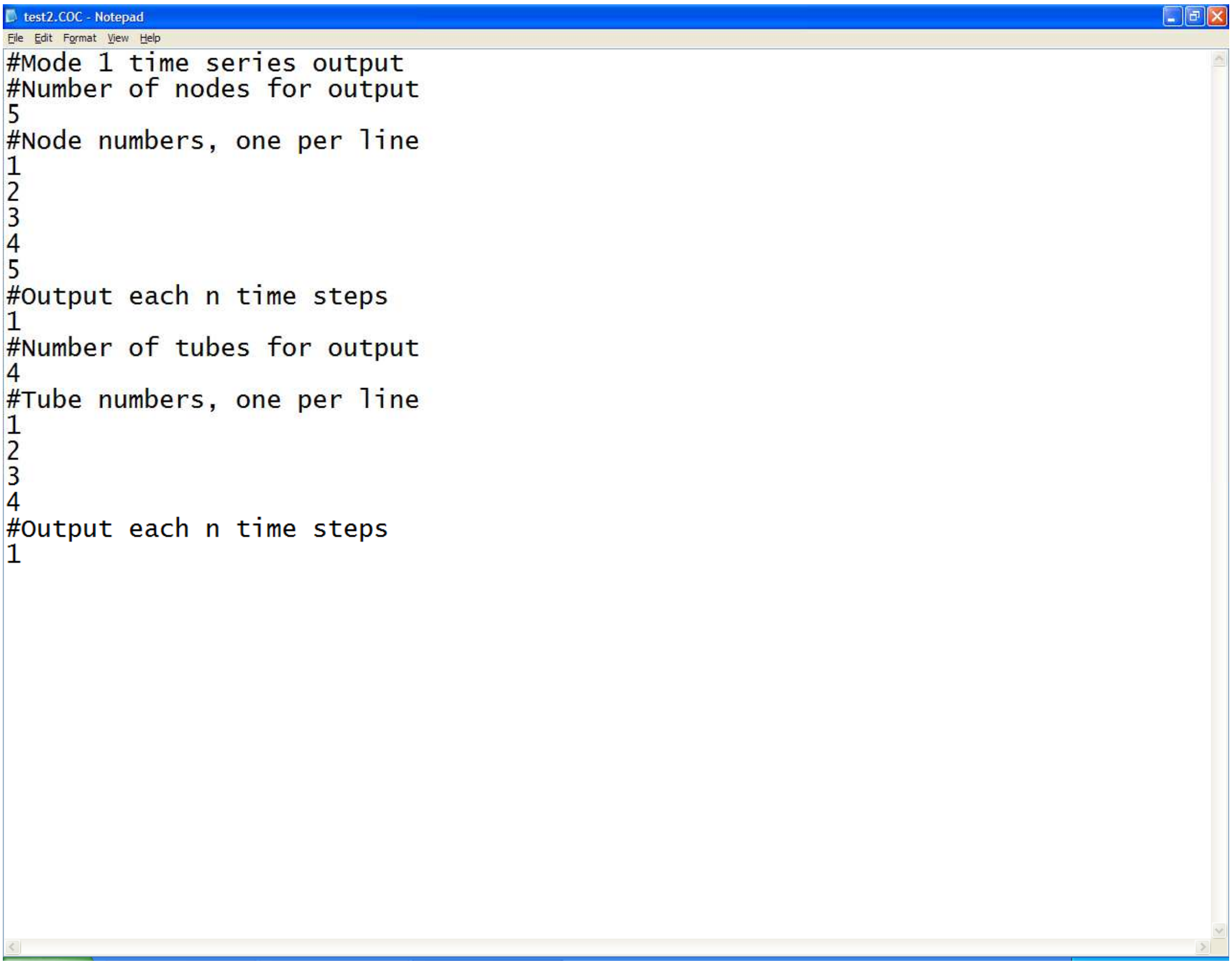
```
# NAME file for CFP mode 1 example
#
# Output files
LIST                      9  test2.out
BAS6                     75  test2.ba6
LPF                       7  test2.lpf
DIS                       8  test2.dis
WEL                      16  test2.wel
PCG                      13  test2.pcg
OC                       14  test2.oc
RCH                      15  test2.rch
ets                      17  test2.ets
CFP                      18  test2.cfp
COC                      19  test2.coc
CRCH                     20  test2.crch
```

Figure 5.4 (Name file)



```
CONDUIT RECHARGE FILE
1
    1   .00
    2  1.00
    3   .00
    4   .00
    5   .00
```

Figure 5.5 (CRCH file)


test2.COC - Notepad

```
#Mode 1 time series output
#Number of nodes for output
5
#Node numbers, one per line
1
2
3
4
5
#Output each n time steps
1
#Number of tubes for output
4
#Tube numbers, one per line
1
2
3
4
#Output each n time steps
1
```

Figure 5.6 (COC file)

<u>5.2.1.1 Output From Simulation:</u> A MODFLOW output file will be created after the simulation with the name of output file as specified in the Name file. Depending upon the options specified in the output control file, the volumetric budget of the entire model, heads, and drawdown will be printed at desired time steps and stress periods in this output file. Also, node water budget and pipe system water budget will be printed in this same file. Because it was desired to get separate output files for each of the pipes and nodes, five output files related to each of the nodes and four output files related to each of the conduits will be created as well (see Figure 5.6 to create 'COC' file and Figure 5.4 to confirm that it is included in the name file). A sample of the output file is as shown below:

STRESS PERIOD/TIME STEP 1 180

NUMBER OF NEWTON RHAPSON ITERATIONS: 3

------- RESULTS OF FLOW CALCULATION -------

NODE #	NODE HEAD[M]	POROUS MEDIA HEAD [M]	EXCHANGE FLOW [M^3/D]	DIRECT RECHARGE
1	97.94711	97.96496	-3.504584	0
2	97.94712	97.95594	-1.730489	2.279375
3	97.94711	97.96467	-3.447645	0
4	97.94711	97.96467	-3.447645	0
5	97.94707	97.92872	14.40974	0

Table 5.1

TUBE	B	E	FLOW	Q [M^3/D]	DIAM.[M]	LEN.[M]	Re	RESIDENCE TIME [D]
1	1	5	turb.	3.50458	0.1	25	578.2672	0.05603
2	2	5	turb.	4.00986	0.1	25	661.64	0.04897
3	3	5	turb.	3.44764	0.1	25	568.872	0.05695
4	4	5	turb.	3.44764	0.1	25	568.872	0.05695

Table 5.2

(B=Beginning, E=End)

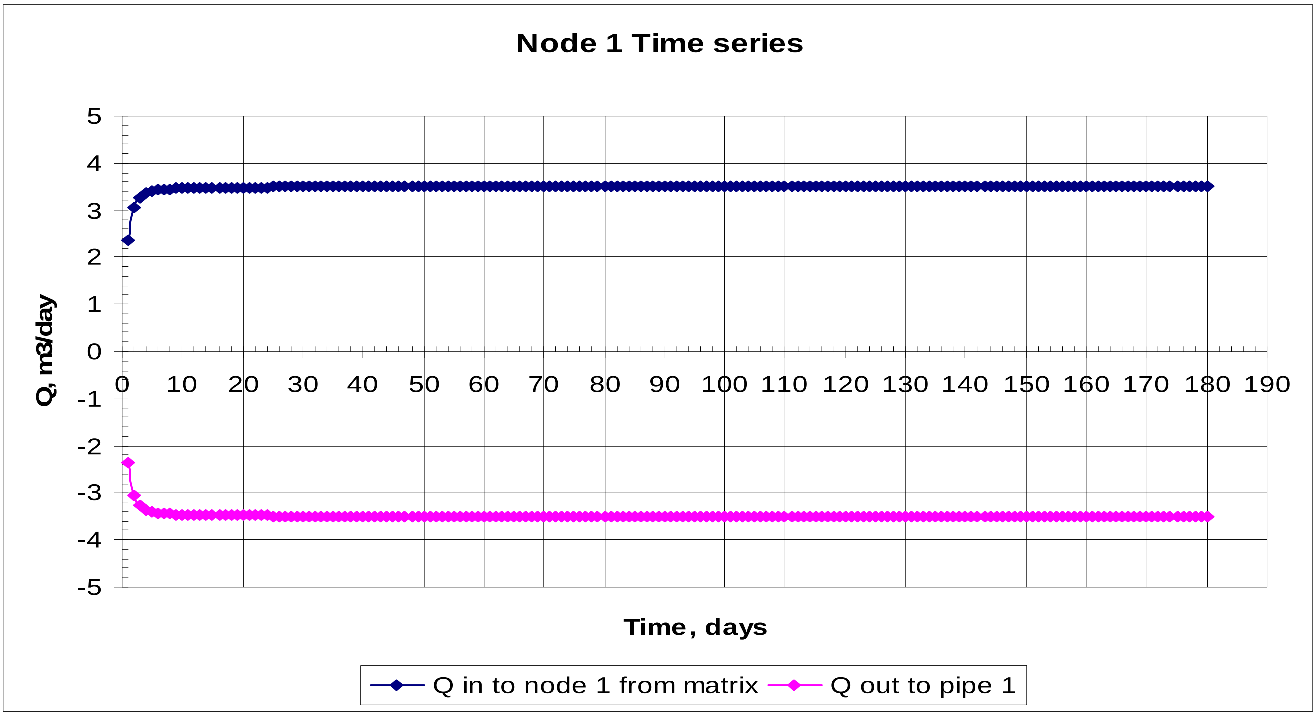
```
BUDGET OF THE PIPE SYSTEM OF TIMESTEP  180 IN STRESS PERIOD    1
------------------------------------------------------------------------

  TOTAL SIMULATION TIME   180.000000000000      s

       CUMULATIVE VALUES (L**3)           RATES THIS TIME STEP (L**3/T)

            IN:                                IN:
     CONSTANT HEAD =   0.0000000          CONSTANT HEAD =   0.0000000
     PIPE RECHARGE =   37131.019          PIPE RECHARGE =   2.2793750
   MATRIX EXCHANGE =   197477.31        MATRIX EXCHANGE =   12.130363
           STORAGE =   0.0000000                STORAGE =   0.0000000
                                               TOTAL IN =   14.409738

           OUT:                                OUT:
     CONSTANT HEAD =   0.0000000          CONSTANT HEAD =   0.0000000
   MATRIX EXCHANGE =   234608.32        MATRIX EXCHANGE =   14.409738
           STORAGE =   0.0000000                STORAGE =   0.0000000
                                              TOTAL OUT =   14.409738

          IN - OUT =  0.23574103E-08            IN - OUT = -0.54036775E-11
     PERCENT ERROR =  0.50241403E-12      PERCENT ERROR = -0.18750089E-10



 ------------------------NODE WATER BUDGET-----------------------
  STRESS PERIOD           1  TIME STEP         180
 TOTAL SIMULATION TIME   180.000000000000
  FLOW TO THE NODE IN M^3/d
```

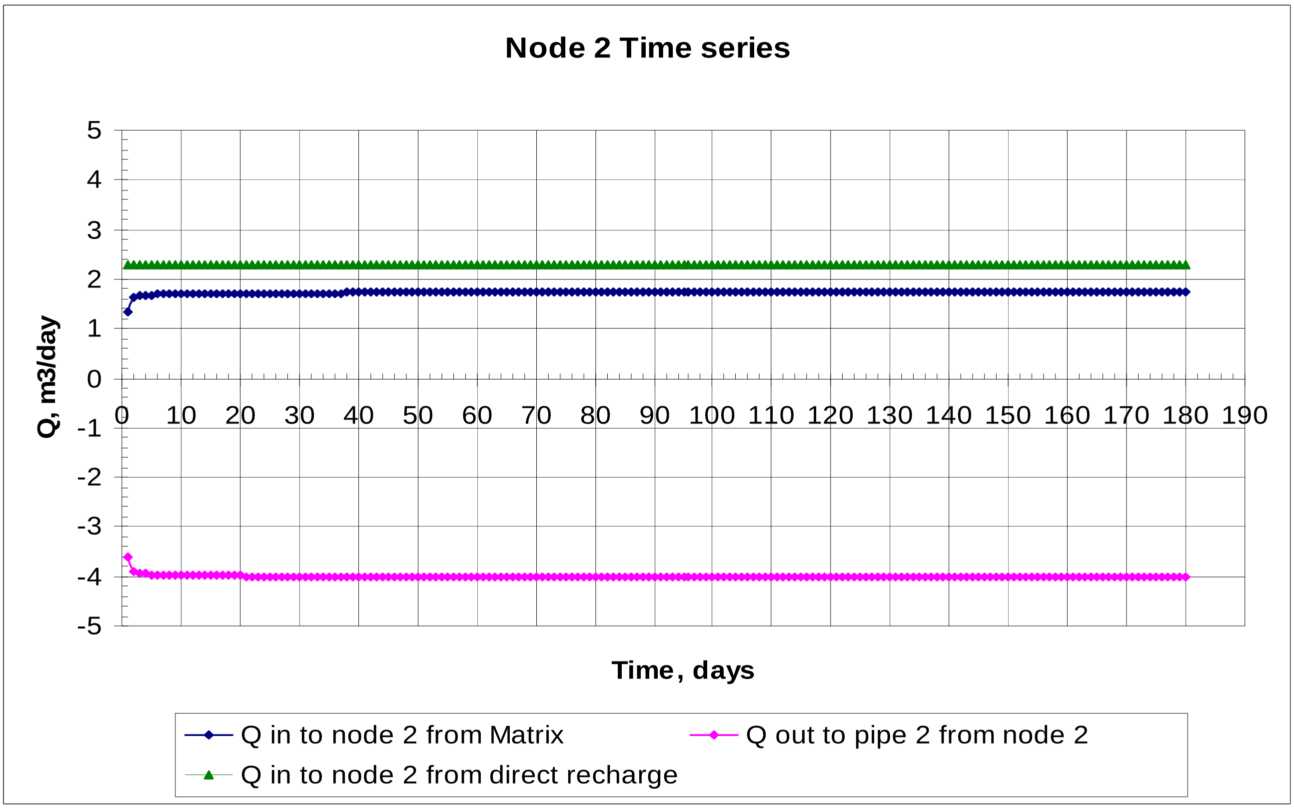
NODE	FIXED H.	RECHARGE	MATRIX	STORAGE	TUBE_IN	TUBE_OUT	IN - OUT
1	0	0	3.5045844	0	0	-3.5045844	-1.18E-10
2	0	2.279375	1.7304895	0	0	-4.0098645	1.75E-10
3	0	0	3.4476449	0	0	-3.4476449	-8.35E-11
4	0	0	3.4476448	0	0	-3.4476448	3.12E-10
5	0	0	-14.409738	0	14.409738	0	-2.91E-10

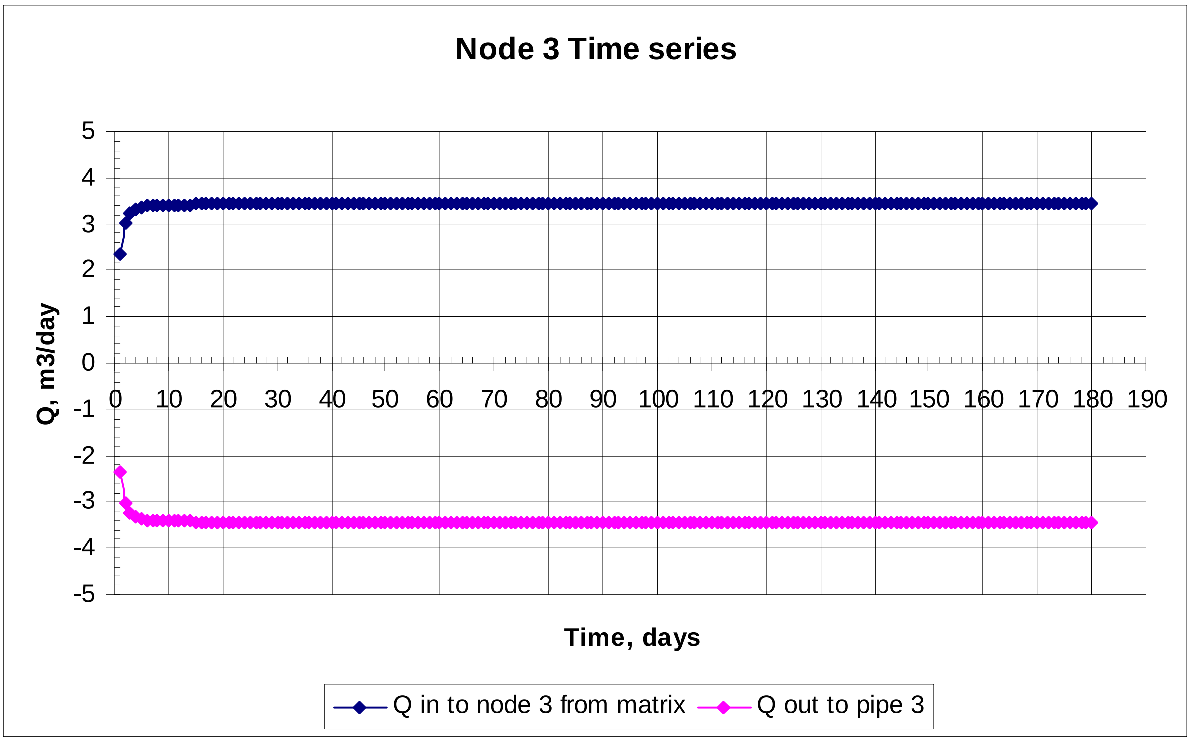
Table 5.3

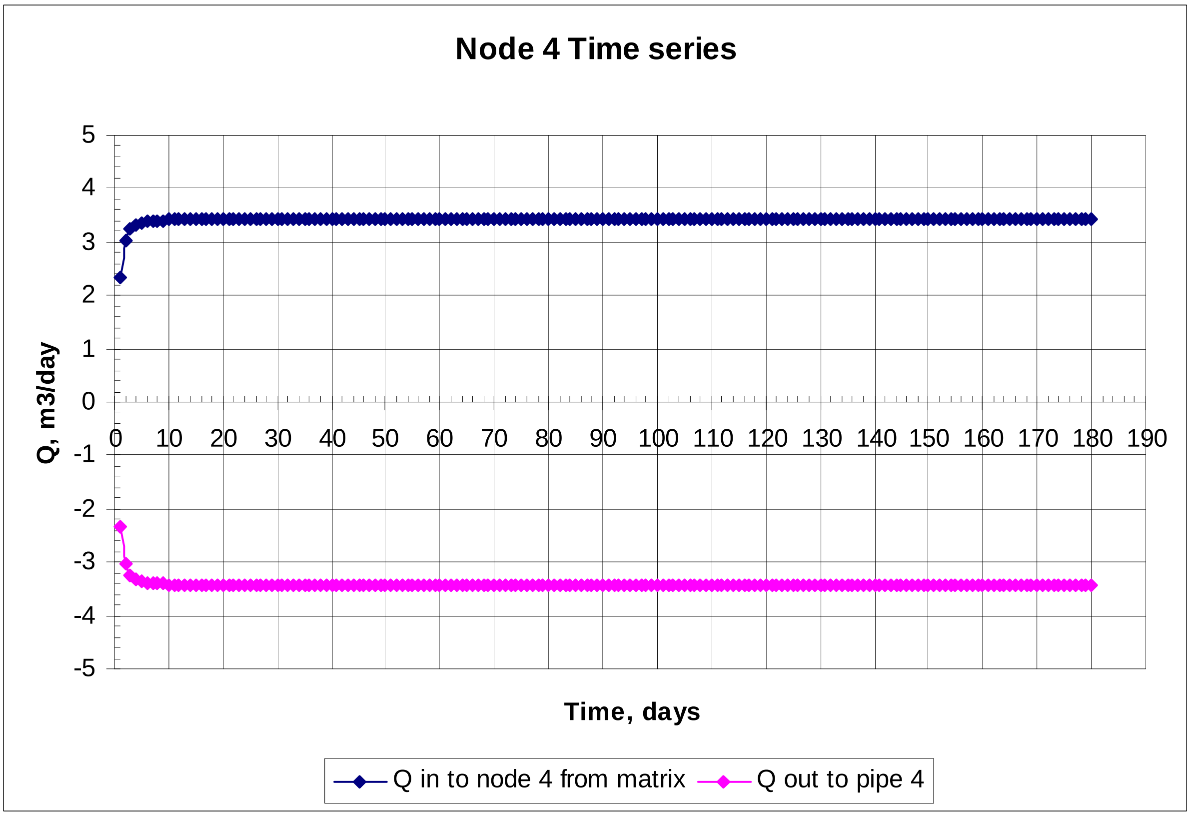
```
HEAD IN LAYER   1 AT END OF TIME STEP 180 IN STRESS PERIOD    1
  ---------------------------------------------------------------------------
           1       2       3
   1    98.01   97.96   98.00
   2    97.96   97.93   97.96
   3    98.01   97.96   98.00

          DRAWDOWN IN LAYER   1 AT END OF TIME STEP 180 IN STRESS PERIOD    1
  ---------------------------------------------------------------------------
            1           2           3
    1  -8.1058E-03  3.5330E-02 -4.9048E-03
   2   3.5039E-02  7.1277E-02  4.4062E-02
   3  -8.1058E-03  3.5330E-02 -4.9047E-03

VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP180 IN STRESS PERIOD   1
  ------------------------------------------------------------------------------

     CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
     ------------------                 ------------------------

           IN:                                      IN:
           ---                                      ---
             STORAGE =         48.7952             STORAGE =       2.8245E-03
       CONSTANT HEAD =          0.0000       CONSTANT HEAD =           0.0000
               WELLS =          0.0000               WELLS =           0.0000
            RECHARGE =       3282.3000            RECHARGE =          18.2350
         ET SEGMENTS =          0.0000         ET SEGMENTS =           0.0000
               PIPES =       2583.4479               PIPES =          14.4097

            TOTAL IN =       5914.5431            TOTAL IN =          32.6476

          OUT:                                     OUT:
          ----                                     ----
             STORAGE =         14.6673             STORAGE =           0.0000
       CONSTANT HEAD =          0.0000       CONSTANT HEAD =           0.0000
               WELLS =       3600.0000               WELLS =          20.0000
            RECHARGE =          0.0000            RECHARGE =           0.0000
         ET SEGMENTS =        128.1934         ET SEGMENTS =           0.5204
               PIPES =       2173.1604               PIPES =          12.1304

           TOTAL OUT =       5916.0211           TOTAL OUT =          32.6508

            IN - OUT =         -1.4780            IN - OUT =      -3.2211E-03

 PERCENT DISCREPANCY =          -0.02     PERCENT DISCREPANCY =          -0.01
```

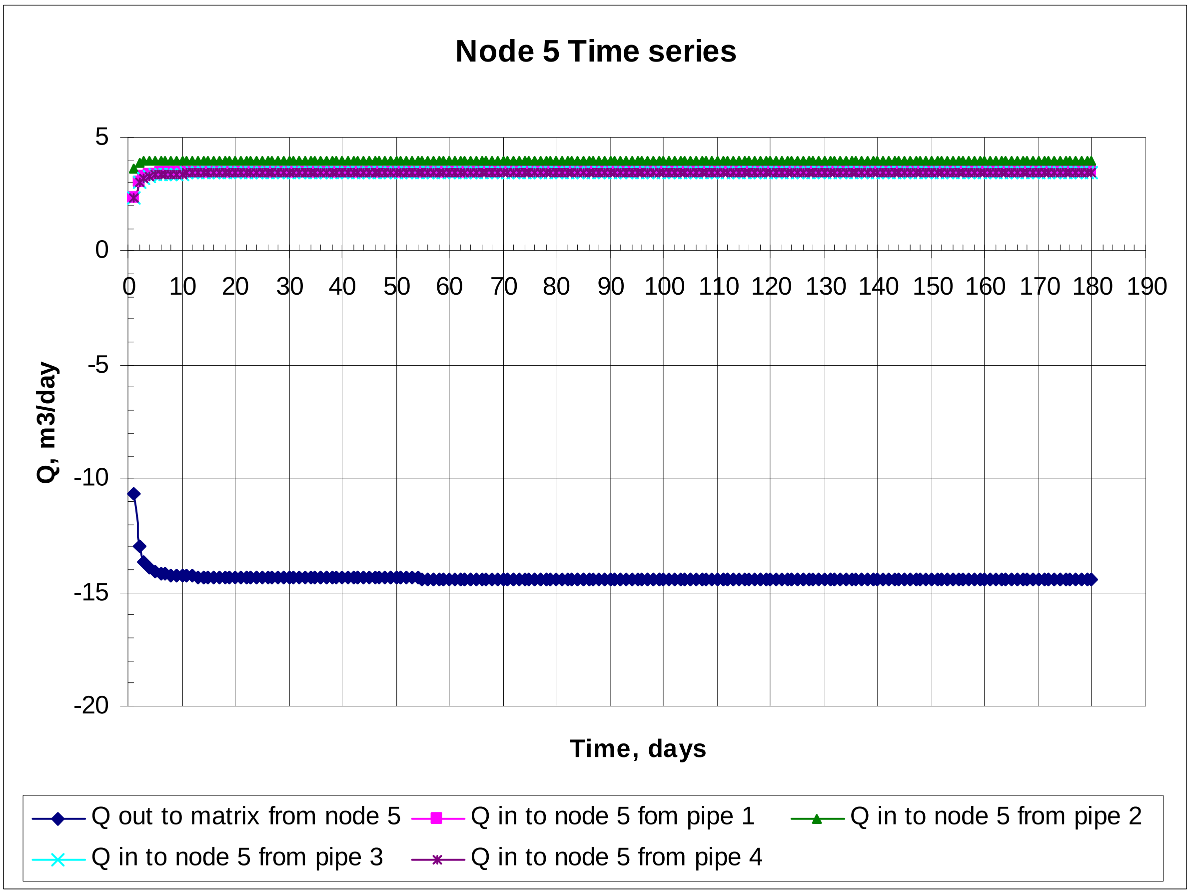
The graphical representation for all of the nodes and pipes (related to the output file created) are as shown below (Figure 5.6.1):

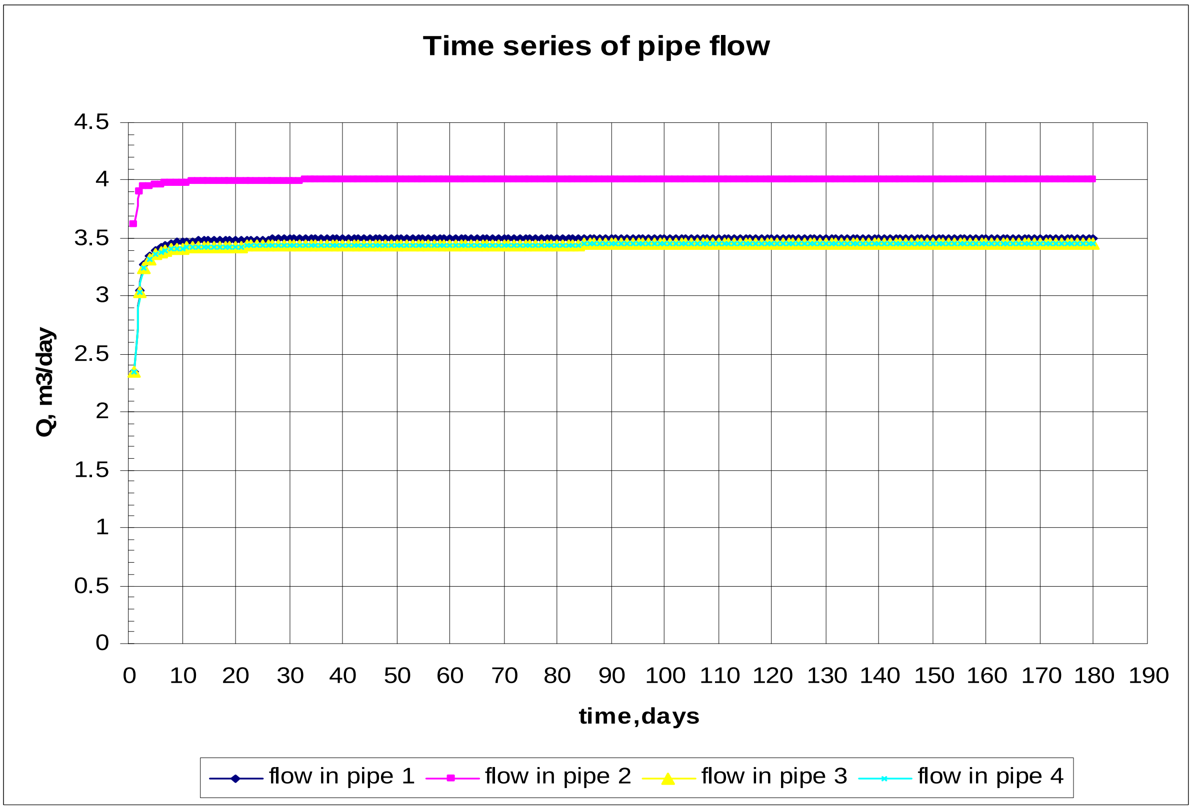





Node 3 Time series
Q, m3/day
5
4
3
2
1
0
-1
-2
-3
-4
-5
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190
Time, days
Q in to node 3 from matrix
Q out to pipe 3


Node 4 Time series
Q, m3/day
5
4
3
2
1
0
-1
-2
-3
-4
-5
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190
Time, days
Q in to node 4 from matrix
Q out to pipe 4


Node 5 Time series
Q, m3/day
Time, days
5
0
-5
-10
-15
-20
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190
Q out to matrix from node 5
Q in to node 5 fom pipe 1
Q in to node 5 from pipe 2
Q in to node 5 from pipe 3
Q in to node 5 from pipe 4


Time series of pipe flow
Q, m3/day
time,days
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190
flow in pipe 1
flow in pipe 2
flow in pipe 3
flow in pipe 4

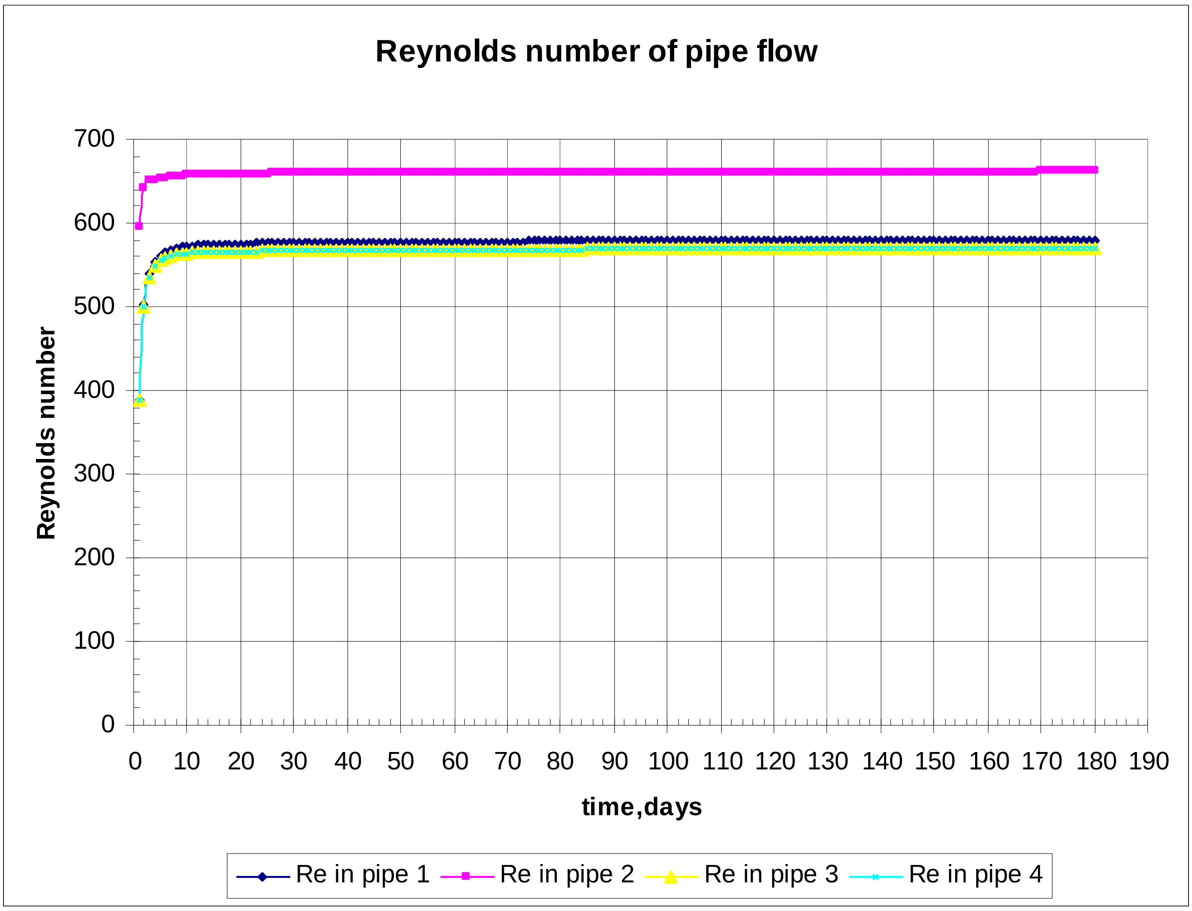


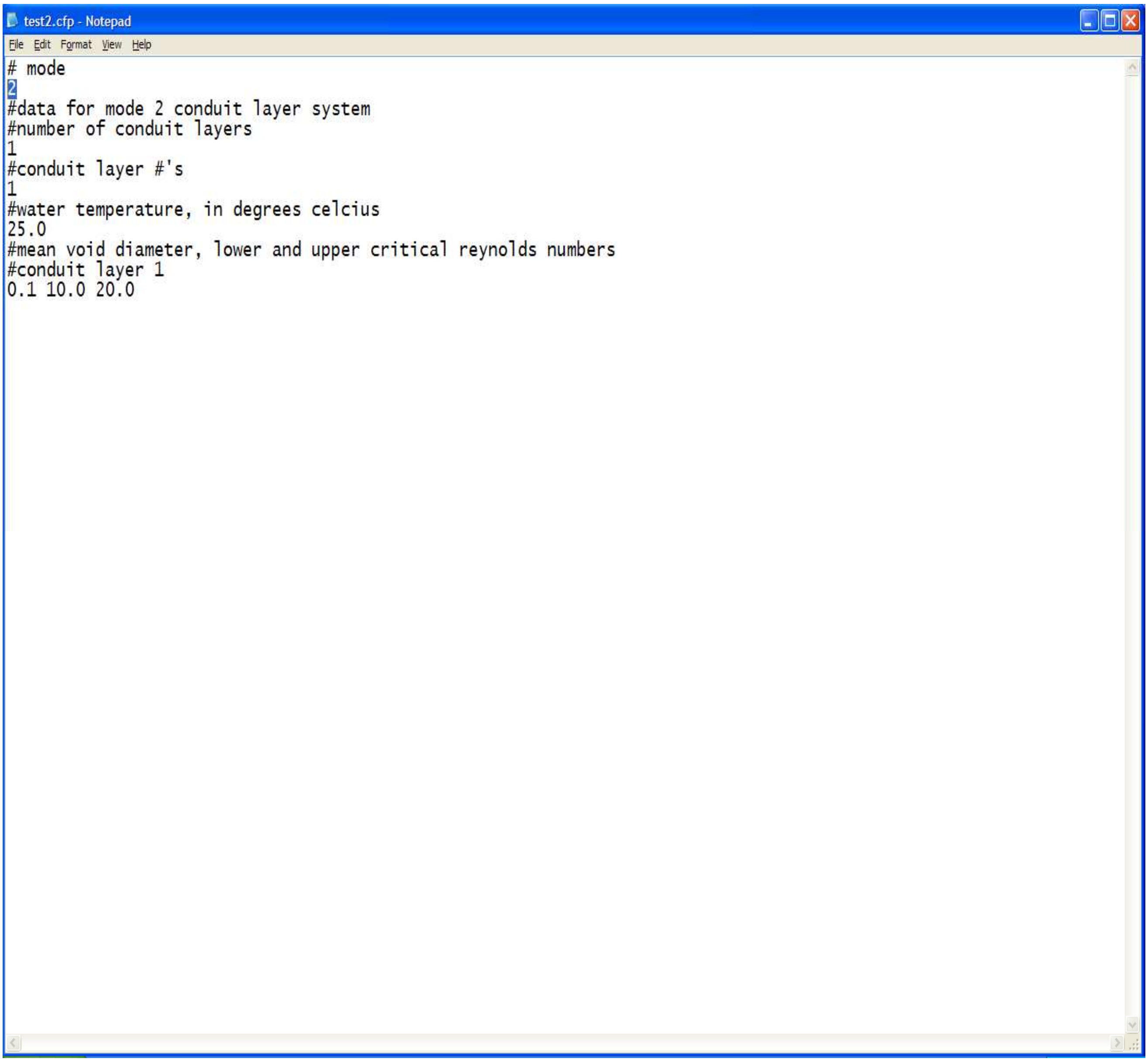
Figure 5.6.1. Graphical representation of flow in the nodes and pipes, and Reynolds's number

5.2.1.2 Results: Table 5.1 shows the head calculated for each of the node and for porous media at the time step 180 and stress period 1. Exchange flow is the flow either from porous media to node or vice versa. Negative sign indicates flow from porous media into the node, whenever the head in porous media is greater than the head in the node. So flow is from porous media into nodes 1, 2, 3, 4, and node 5 is the ultimate drainage for all of the flow coming from other nodes through respective pipes and ultimately node 5 discharges the flow into the porous media. The direct recharge value of 2.279375 m^3/day is the product of recharge in that area (0.003647 m/day) times the area of the cell (25m*25m), where this node is located because we routed all of the recharge falling in this cell to node 2. Table 5.2 shows the flow carried by each of the conduit that is received from the connecting node. Flow in pipe 2 is the sum of the flow received from node 2 and from direct recharge (sum of 1.730489 m^3/day and 2.279375 m^3/day). The total flow from all of the conduits 14.409738 m^3/day is ultimately carried to node 5 and discharged to the porous media at this location because head calculated for node 5 (97.94707 m) is the least of all of the nodes. In the volumetric budget for the entire model section, recharge is the total recharge falling over all of the cells minus the recharge that was routed in node 2 (9*25*25*0.003647 m^3/day -2.279375 m^3/day). This same recharge (12.13 m^3/day) carried in total by all pipes is discharged to node 5, shown as outflow due to pipes in volumetric budget.

5.2.2 MODFLOW execution using Mode 2: Input to the Conduit Flow Process package is read from the file that is type 'CFP' in the Name file. Execution using Mode 2 to simulate CFP is achieved by specifying '2' in ITEM 2 of CFP file (bold number in Figure 5.2.2). Because file types 'COC' and 'CRCH' cannot be included in the simulation, these files were excluded from the name file. The CFP file in this case was written following the items listed in 0-1 and 30-39. The only input required using this mode are:

Water temperature= 25 degree Celsius
Mean void diameter= 0.1 m
Upper critical Reynolds's number= 20
Lower critical Reynolds's number=10

MODFLOW 2005 version 1.2.01_cfp 01/17/2007 was used in the simulation.

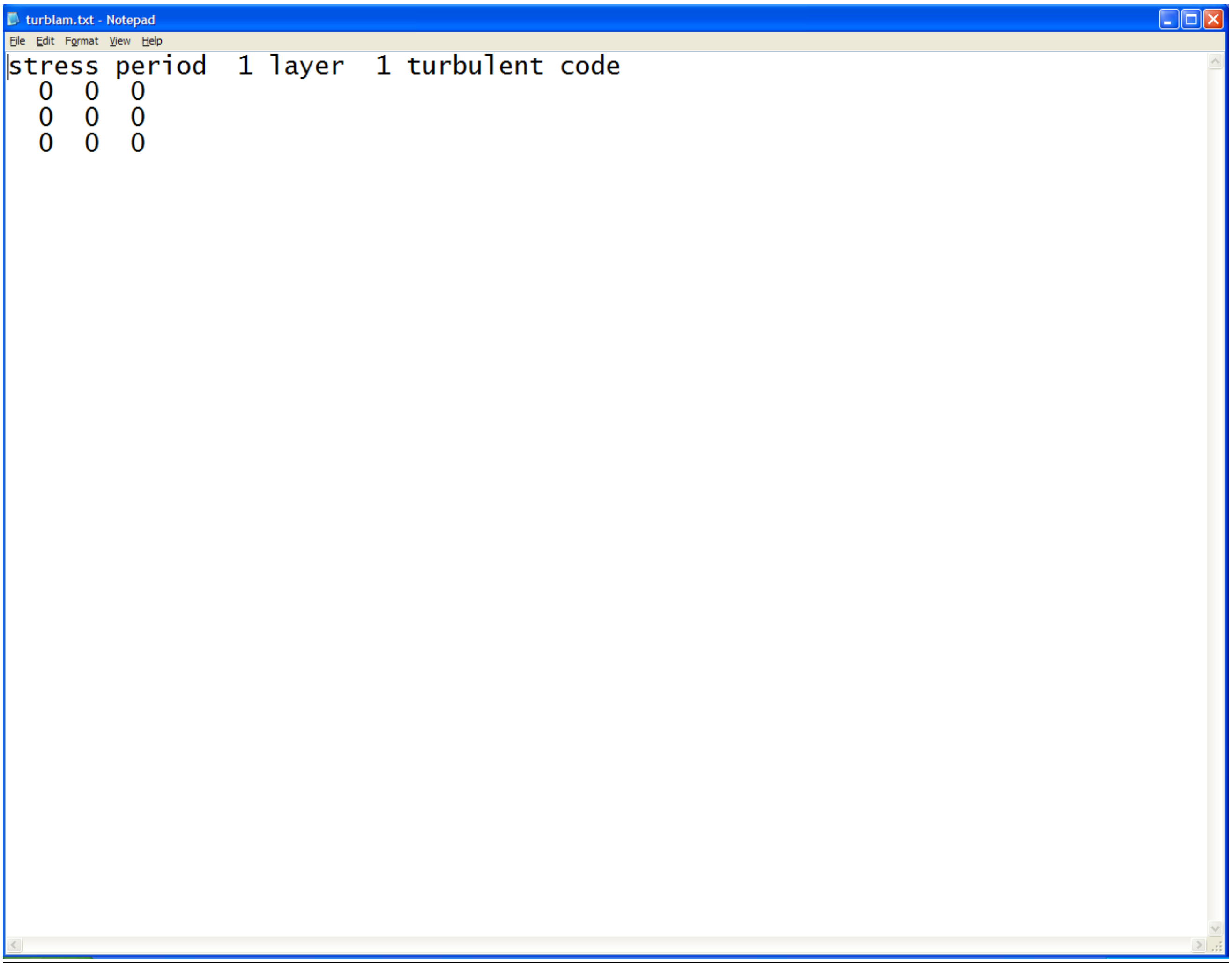



```
# mode
2
#data for mode 2 conduit layer system
#number of conduit layers
1
#conduit layer #'s
1
#water temperature, in degrees celcius
25.0
#mean void diameter, lower and upper critical reynolds numbers
#conduit layer 1
0.1 10.0 20.0
```

Figure 5.2.2. CFP file for Mode 2

<u>5.2.2.1 Output From Simulation:</u> A MODFLOW output file will be created after the simulation with the name of output file as specified in the Name file. Depending upon the options specified in the output control file, the volumetric budget of the entire model, heads, and drawdown will be printed at desired time steps and stress periods in this output file. Turbulence code for mode 2 simulations is automatically written to an output file named ‘turblam.txt’ (Figure 5.2.3). For each conduit layer during each stress period, these codes indicate whether flows at the right and front sides of conduit layer model cells are laminar or turbulent (Shoemaker et al., 2007); 0 indicating laminar and 1 indicating turbulent. A sample of the output file is as shown below:

```
HEAD IN LAYER   1 AT END OF TIME STEP 180 IN STRESS PERIOD    1

          1       2       3
  1    98.01   97.96   98.01
  2    97.96   97.78   97.96
  3    98.01   97.96   98.01

DRAWDOWN IN LAYER   1 AT END OF TIME STEP 180 IN STRESS PERIOD    1
           1          2           3
  1  -6.4454E-03  3.7521E-02 -6.4454E-03
  2   3.7521E-02  0.2189      3.7521E-02
  3  -6.4454E-03  3.7521E-02 -6.4454E-03

 VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP180 IN STRESS PERIOD   1
 ------------------------------------------------------------------------------
    CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
    ------------------                 ------------------------

          IN:                                     IN:
          ---                                     ---
            STORAGE =         84.8072               STORAGE =       1.2555E-03
      CONSTANT HEAD =          0.0000         CONSTANT HEAD =           0.0000
              WELLS =          0.0000                 WELLS =           0.0000
           RECHARGE =       3692.5875              RECHARGE =          20.5144
        ET SEGMENTS =          0.0000           ET SEGMENTS =           0.0000

           TOTAL IN =       3777.3947              TOTAL IN =          20.5156

         OUT:                                    OUT:
         ----                                    ----
            STORAGE =         24.7517               STORAGE =           0.0000
      CONSTANT HEAD =          0.0000         CONSTANT HEAD =           0.0000
              WELLS =       3600.0000                 WELLS =          20.0000
           RECHARGE =          0.0000              RECHARGE =           0.0000
        ET SEGMENTS =        152.6430           ET SEGMENTS =           0.5156

          TOTAL OUT =       3777.3947             TOTAL OUT =          20.5156

           IN - OUT =     -6.7305E-05              IN - OUT =      -3.5147E-07

PERCENT DISCREPANCY =           0.00     PERCENT DISCREPANCY =           0.00
```


turblam.txt - Notepad

File Edit Format View Help

```
stress period  1 layer  1 turbulent code
  0  0  0
  0  0  0
  0  0  0
```

Figure 5.2.3. Turblam.txt created after simulation

5.2.2.2 Results : Recharge in this case is the product of total area of model cells and recharge rate (9*25*25*0.003647 m^3/day). There is a very slight difference in the evapotranspiration value. Because of the absence of the conduits and nodes, the total flow leaving and coming into the aquifer is less than using Mode 1. A test was performed to see the effect if CFP Mode 2 is excluded from the simulation. The head, drawdown and the volumetric budget of the entire model looked exactly the same as using CFP Mode 2 (Case 0). Also, a sensitivity analysis was done by changing the critical Reynolds's number (Case 1) and diameter of voids (Case 2). Since there seemed to be no effect of using CFP Mode 2 in the simulation, the layer was divided into two layers, and CFP Mode 2 was considered for the lower layer only, which is considered as Case 3 here. In another case which also had two layers, the CFP Mode 2 was considered for the upper layer and was considered as Case 4.

Case 0: In this case CFP Mode 2 was excluded from the simulation by removing the file type "CFP" from the name file. The output from this case is as shown below.

```
HEAD IN LAYER   1 AT END OF TIME STEP 180 IN STRESS PERIOD    1
  ---------------------------------------------------------------------------

          1       2       3
  1    98.01   97.96   98.01
  2    97.96   97.78   97.96
  3    98.01   97.96   98.01
         DRAWDOWN IN LAYER   1 AT END OF TIME STEP 180 IN STRESS PERIOD    1
  ---------------------------------------------------------------------------

           1           2           3
  1  -6.4454E-03  3.7521E-02 -6.4454E-03
  2   3.7521E-02  0.2189      3.7521E-02
  3  -6.4454E-03  3.7521E-02 -6.4454E-03

 VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP180 IN STRESS PERIOD   1
  ------------------------------------------------------------------------------
     CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
     ------------------                 ------------------------
           IN:                                     IN:
           ---                                     ---
             STORAGE =          84.8072              STORAGE =       1.2555E-03
       CONSTANT HEAD =           0.0000        CONSTANT HEAD =           0.0000
               WELLS =           0.0000                WELLS =           0.0000
            RECHARGE =        3692.5875             RECHARGE =          20.5144
         ET SEGMENTS =           0.0000          ET SEGMENTS =           0.0000

            TOTAL IN =        3777.3947             TOTAL IN =          20.5156

          OUT:                                    OUT:
          ----                                    ----
             STORAGE =          24.7517              STORAGE =           0.0000
       CONSTANT HEAD =           0.0000        CONSTANT HEAD =           0.0000
               WELLS =        3600.0000                WELLS =          20.0000
            RECHARGE =           0.0000             RECHARGE =           0.0000
         ET SEGMENTS =         152.6430          ET SEGMENTS =           0.5156

           TOTAL OUT =        3777.3947            TOTAL OUT =          20.5156

            IN - OUT =      -6.7305E-05             IN - OUT =      -3.5147E-07

 PERCENT DISCREPANCY =           0.00     PERCENT DISCREPANCY =          0.00
```

Case 1: This case is the same as the base case (Section 5.2.2). The lower and upper Reynolds's number were changed to 1 and 2, respectively. Water temperature was kept equal to 25 ^{o}C and the diameter of the voids were kept equal to 0.1 m. The output from the simulation is as shown below:

```
 HEAD IN LAYER   1 AT END OF TIME STEP 180 IN STRESS PERIOD    1
 ---------------------------------------------------------------------------

          1       2       3
 ..........................
   1    98.01   97.96   98.01
   2    97.96   97.78   97.96
   3    98.01   97.96   98.01

DRAWDOWN IN LAYER   1 AT END OF TIME STEP 180 IN STRESS PERIOD    1
 ---------------------------------------------------------------------------

           1           2           3
 ....................................
   1  -6.4454E-03  3.7521E-02 -6.4454E-03
   2   3.7521E-02  0.2189      3.7521E-02
   3  -6.4454E-03  3.7521E-02 -6.4454E-03

VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP180 IN STRESS PERIOD   1
 ------------------------------------------------------------------------------

     CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
     ------------------                 ------------------------

           IN:                                      IN:
           ---                                      ---
             STORAGE =         84.8072               STORAGE =       1.2555E-03
       CONSTANT HEAD =          0.0000         CONSTANT HEAD =           0.0000
               WELLS =          0.0000                 WELLS =           0.0000
            RECHARGE =       3692.5875              RECHARGE =          20.5144
         ET SEGMENTS =          0.0000           ET SEGMENTS =           0.0000

            TOTAL IN =       3777.3947              TOTAL IN =          20.5156

          OUT:                                     OUT:
          ----                                     ----
             STORAGE =         24.7517               STORAGE =           0.0000
       CONSTANT HEAD =          0.0000         CONSTANT HEAD =           0.0000
               WELLS =       3600.0000                 WELLS =          20.0000
            RECHARGE =          0.0000              RECHARGE =           0.0000
         ET SEGMENTS =        152.6430           ET SEGMENTS =           0.5156

           TOTAL OUT =       3777.3947             TOTAL OUT =          20.5156

            IN - OUT =     -6.7305E-05              IN - OUT =      -3.5147E-07

 PERCENT DISCREPANCY =           0.00     PERCENT DISCREPANCY =           0.00
```

Case 2.1: In this case, the lower and upper Reynolds's numbers were kept equal to 1 and 2, respectively as in Case 1, and the diameters of the voids were kept equal to 1m. The output from the simulation is as shown below:

```
              HEAD IN LAYER   1 AT END OF TIME STEP 180 IN STRESS PERIOD    1
  ---------------------------------------------------------------------------

           1       2       3
 ...........................
   1    98.01   97.96   98.01
   2    97.96   97.78   97.96
   3    98.01   97.96   98.01

DRAWDOWN IN LAYER   1 AT END OF TIME STEP 180 IN STRESS PERIOD    1
  ---------------------------------------------------------------------------

            1           2           3
 ....................................
   1  -6.4454E-03  3.7521E-02 -6.4454E-03
   2   3.7521E-02  0.2189      3.7521E-02
   3  -6.4454E-03  3.7521E-02 -6.4454E-03

  VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP180 IN STRESS PERIOD   1
  ------------------------------------------------------------------------------

     CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
     ------------------                 ------------------------

           IN:                                     IN:
           ---                                     ---
             STORAGE =         84.8072               STORAGE =       1.2555E-03
       CONSTANT HEAD =          0.0000         CONSTANT HEAD =           0.0000
               WELLS =          0.0000                 WELLS =           0.0000
            RECHARGE =       3692.5875              RECHARGE =          20.5144
         ET SEGMENTS =          0.0000           ET SEGMENTS =           0.0000

            TOTAL IN =       3777.3947              TOTAL IN =          20.5156

          OUT:                                    OUT:
          ----                                    ----
             STORAGE =         24.7517               STORAGE =           0.0000
       CONSTANT HEAD =          0.0000         CONSTANT HEAD =           0.0000
               WELLS =       3600.0000                 WELLS =          20.0000
            RECHARGE =          0.0000              RECHARGE =           0.0000
         ET SEGMENTS =        152.6430           ET SEGMENTS =           0.5156

           TOTAL OUT =       3777.3947             TOTAL OUT =          20.5156

            IN - OUT =     -6.7305E-05              IN - OUT =      -3.5147E-07

 PERCENT DISCREPANCY =            0.00     PERCENT DISCREPANCY =           0.00
```

Case 2.2: In this case, the lower and upper Reynolds's numbers were kept equal to 1 and 2, respectively, as in Case 1 and the diameters of the voids were kept equal to 0.01m. The output from the simulation is as shown below:

```
  HEAD IN LAYER   1 AT END OF TIME STEP 180 IN STRESS PERIOD    1
  ---------------------------------------------------------------------------

           1       2       3
 ...........................
   1    98.01   97.96   98.01
   2    97.96   97.78   97.96
   3    98.01   97.96   98.01

DRAWDOWN IN LAYER   1 AT END OF TIME STEP 180 IN STRESS PERIOD    1
---------------------------------------------------------------------------

            1           2           3
 ....................................
   1  -6.4454E-03  3.7521E-02 -6.4454E-03
   2   3.7521E-02  0.2189      3.7521E-02
   3  -6.4454E-03  3.7521E-02 -6.4454E-03

  VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP180 IN STRESS PERIOD   1
  ------------------------------------------------------------------------------

     CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
     ------------------                 ------------------------

           IN:                                   IN:
           ---                                   ---
             STORAGE =         84.8072             STORAGE =       1.2555E-03
       CONSTANT HEAD =          0.0000       CONSTANT HEAD =           0.0000
               WELLS =          0.0000               WELLS =           0.0000
            RECHARGE =       3692.5875            RECHARGE =          20.5144
         ET SEGMENTS =          0.0000         ET SEGMENTS =           0.0000

            TOTAL IN =       3777.3947            TOTAL IN =          20.5156

          OUT:                                  OUT:
          ----                                  ----
             STORAGE =         24.7517             STORAGE =           0.0000
       CONSTANT HEAD =          0.0000       CONSTANT HEAD =           0.0000
               WELLS =       3600.0000               WELLS =          20.0000
            RECHARGE =          0.0000            RECHARGE =           0.0000
         ET SEGMENTS =        152.6430         ET SEGMENTS =           0.5156

           TOTAL OUT =       3777.3947           TOTAL OUT =          20.5156

            IN - OUT =     -6.7305E-05            IN - OUT =      -3.5147E-07

 PERCENT DISCREPANCY =          0.00     PERCENT DISCREPANCY =          0.00
```

Case 3: This case, as shown in the Figure 5.7 below, has two layers with bottom elevation of top layer at 50 m. CFP Mode 3 was applied in the lower layer only.

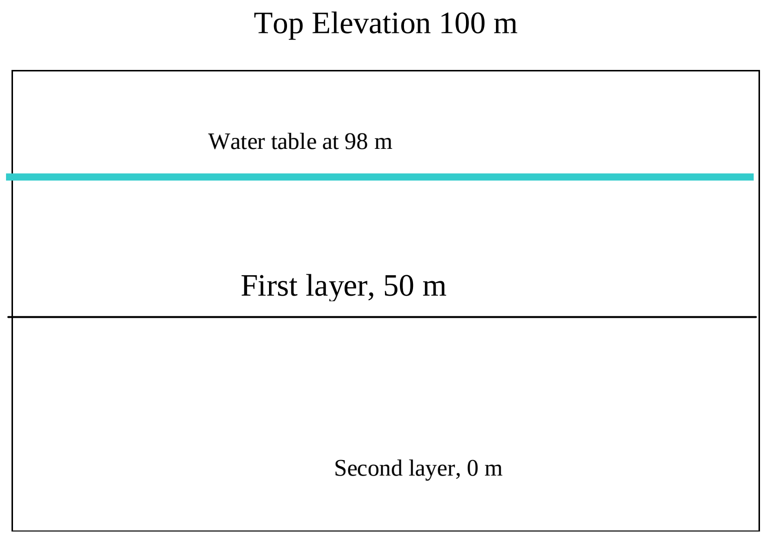


Figure 5.7

The output from the simulation, shown below, shows that except for the storage in the 'IN' section, there is no change in the volumetric budget of the entire model, but some changes in drawdown and head of the cells in layer 1.

```
            HEAD IN LAYER   1 AT END OF TIME STEP 180 IN STRESS PERIOD    1
  ---------------------------------------------------------------------------

          1       2       3
 ...........................
   1    98.01   97.93   98.01
   2    97.93   97.58   97.93
   3    98.01   97.93   98.01
1
            HEAD IN LAYER   2 AT END OF TIME STEP 180 IN STRESS PERIOD    1
  ---------------------------------------------------------------------------

          1       2       3
 ...........................
   1    97.93   97.92   97.93
   2    97.92   97.90   97.92
   3    97.93   97.92   97.93
```

```
 DRAWDOWN IN LAYER   1 AT END OF TIME STEP 180 IN STRESS PERIOD    1
   ------------------------------------------------------------------------

            1           2           3
 ....................................
   1  -6.5045E-03  7.3216E-02 -6.5045E-03
   2   7.3216E-02  0.4232      7.3216E-02
   3  -6.5045E-03  7.3216E-02 -6.5045E-03



 DRAWDOWN IN LAYER   2 AT END OF TIME STEP 180 IN STRESS PERIOD    1
   ------------------------------------------------------------------------

            1           2           3
 ....................................
   1   6.9162E-02  7.8812E-02  6.9161E-02
   2   7.8812E-02  9.9543E-02  7.8812E-02
   3   6.9161E-02  7.8812E-02  6.9162E-02

  VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP180 IN STRESS PERIOD   1
  ---------------------------------------------------------------------------

     CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
     ------------------                 ------------------------

           IN:                                      IN:
           ---                                      ---
             STORAGE =         159.8423               STORAGE =      5.9817E-03
       CONSTANT HEAD =           0.0000         CONSTANT HEAD =          0.0000
               WELLS =           0.0000                 WELLS =          0.0000
            RECHARGE =        3692.5875              RECHARGE =         20.5144
         ET SEGMENTS =           0.0000           ET SEGMENTS =          0.0000

            TOTAL IN =        3852.4298              TOTAL IN =         20.5204

          OUT:                                     OUT:
          ----                                     ----
             STORAGE =          38.7617               STORAGE =          0.0000
       CONSTANT HEAD =           0.0000         CONSTANT HEAD =          0.0000
               WELLS =        3600.0000                 WELLS =         20.0000
            RECHARGE =           0.0000              RECHARGE =          0.0000
         ET SEGMENTS =         213.6682           ET SEGMENTS =          0.5204

           TOTAL OUT =        3852.4299             TOTAL OUT =         20.5204

            IN - OUT =      -9.4479E-05              IN - OUT =     -2.1233E-06

 PERCENT DISCREPANCY =           0.00     PERCENT DISCREPANCY =          0.00
```

Case 4: Similar to Case 1, except that CFP mode 2 is applied to first layer only. The output from the simulation is as shown below, which is same as the output from Case 3.

```
          HEAD IN LAYER   1 AT END OF TIME STEP 180 IN STRESS PERIOD    1
           1       2       3
  1    98.01   97.93   98.01
  2    97.93   97.58   97.93
  3    98.01   97.93   98.01

              HEAD IN LAYER   2 AT END OF TIME STEP 180 IN STRESS PERIOD    1
           1       2       3
  1    97.93   97.92   97.93
  2    97.92   97.90   97.92
  3    97.93   97.92   97.93

          DRAWDOWN IN LAYER   1 AT END OF TIME STEP 180 IN STRESS PERIOD    1
            1           2           3
 ....................................
  1  -6.5045E-03  7.3216E-02 -6.5045E-03
  2   7.3216E-02  0.4232      7.3216E-02
  3  -6.5045E-03  7.3216E-02 -6.5045E-03

          DRAWDOWN IN LAYER   2 AT END OF TIME STEP 180 IN STRESS PERIOD    1

            1           2           3
 ....................................
  1   6.9162E-02  7.8812E-02  6.9161E-02
  2   7.8812E-02  9.9543E-02  7.8812E-02
  3   6.9161E-02  7.8812E-02  6.9162E-02

  VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP180 IN STRESS PERIOD   1
  ------------------------------------------------------------------------------

     CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
     ------------------                 ------------------------

           IN:                                      IN:
           ---                                      ---
             STORAGE =         159.8423               STORAGE =       5.9817E-03
       CONSTANT HEAD =           0.0000         CONSTANT HEAD =           0.0000
               WELLS =           0.0000                 WELLS =           0.0000
            RECHARGE =        3692.5875              RECHARGE =          20.5144
         ET SEGMENTS =           0.0000           ET SEGMENTS =           0.0000

            TOTAL IN =        3852.4298              TOTAL IN =          20.5204

          OUT:                                     OUT:
          ----                                     ----
             STORAGE =          38.7617               STORAGE =           0.0000
       CONSTANT HEAD =           0.0000         CONSTANT HEAD =           0.0000
               WELLS =        3600.0000                 WELLS =          20.0000
            RECHARGE =           0.0000              RECHARGE =           0.0000
         ET SEGMENTS =         213.6682           ET SEGMENTS =           0.5204

           TOTAL OUT =        3852.4299             TOTAL OUT =          20.5204

            IN - OUT =      -9.4479E-05              IN - OUT =      -2.1233E-06
```

```
PERCENT DISCREPANCY =          0.00     PERCENT DISCREPANCY =          0.00
```

5.2.2.3 Sensitivity Results: There was no impact of using CFP Mode 2. CFP Mode 2 was also tested by increasing and decreasing the diameter of voids by one order of magnitude, but the results were still the same. It was even tested by increasing K_s in the LPF package by three orders of magnitude, increasing pumping to -200 m^3/day, and increasing recharge by one order of magnitude. The Reynolds' numbers do not seem to have any impact on simulation no matter what the ranges of values between upper and lower Reynolds' numbers were. The only difference was in the storage of the 'IN' section (Case 0, 1, 2) and (Case 3,4).

5.2.3 MODFLOW execution using Mode 3: Input to the Conduit Flow Process package is read from the file that is type 'CFP' in the Name file (Figure 5.8). Execution using Mode 3 to simulate CFP is achieved by specifying '3' in ITEM 2 of CFP file (Bold number in Figure 5.2.3). 'COC' and 'CRCH' were included in the simulation. The CFP file in this case was written following the items listed in 0-39, page 27 of documentation by Shoemaker et al. (2007). The input to this case is the combination of input data used in Mode 1 and Mode 2. So an aquifer listed above with 1 layer is simulated using Mode 3 of CFP, and input data listed above for Mode 1 and Mode 2 were used in the simulation. It was also assumed that all of the recharge falling over cell (row 2, column 3) will be routed directly into the node 2. So an extra file type 'CRCH' (See Figure 5.5) was created and included in the Name file as shown in Figure 5.8 below. Also another extra file type 'COC' (See Figure 5.6) was created and included in the Name file as shown in Figure 5.8 below in order to write node heads, and flows for all of the nodes and pipes. MODFLOW 2005 version 1.2.01_cfp 01/17/2007 was used in the simulation.

test2.CFP - Notepad

File Edit Format View Help

```
# mode
3
#data for mode 3 conduit pipe system
#number of nodes / tubes / layers
5  4  1
#temperature
25.
#No_N  mc mr ml  Nb1   Nb2  Nb3  Nb4 Nb5 Nb6 Pb1 Pb2 Pb3 Pb4 Pb5 Pb6
1       1  2  1   5     0    0    0   0   0   1   0   0   0   0   0
2       3  2  1   5     0    0    0   0   0   2   0   0   0   0   0
3       2  1  1   5     0    0    0   0   0   3   0   0   0   0   0
4       2  3  1   5     0    0    0   0   0   4   0   0   0   0   0
5       2  2  1   1     2    3    4   0   0   1   2   3   4   0   0
#elevation of conduit nodes. Two possibilites
#first: node #  elevation (1 line for each node)
#second: nbrnodes elevation(only one line used to assign constant value)
1 97.5
2 97.5
3 97.5
4 97.5
5 97.5
#surface dependent exchange (set 1) or constant exchange (set 0)
1
#criterion for convergence
1.0D-6
#maximum number for loop iterations
100
#parameter of relaxation
1
#newton raphson print flag
1
#data for tube parameters:
#no. diameter  tortuosity  roughness   lreynolds     treynolds
1    0.1        1.0        0.01        10.0          20.0
2    0.1        1.0        0.01        10.0          20.0
3    0.1        1.0        0.01        10.0          20.0
4    0.1        1.0        0.01        10.0          20.0
#node heads (if head unequal -1 the head is fixed)
1    -1
2    -1
3    -1
4    -1
5    -1
#exchange terms for flow between continuum and pipe-network
1   5.0
2   5.0
3   5.0
4   5.0
5   5.0
#data for mode 2 conduit layer system
#number of conduit layers
1
#conduit layer #'s
1
#water temperature, in degrees celcius
25.0
#mean void diameter, lower and upper critical reynolds numbers
#conduit layer 1
0.1 10.0 20.0
```

Figure 5.2.3. CFP file for Mode 3

test2.nam - Notepad

```
# NAME file for CFP Mode 3 example
#
# Output files
LIST                    9 test2.out
BAS6                   75 test2.ba6
LPF                     7 test2.lpf
DIS                     8 test2.dis
WEL                    16 test2.wel
PCG                    13 test2.pcg
OC                     14 test2.oc
RCH                    15 test2.rch
ets                    17 test2.ets
CFP                    18 test2.cfp
COC                    19 test2.coc
CRCH                   20 test2.crch
```

Figure 5.8

<u>5.2.3.1. Output From Simulation:</u> A MODFLOW output file will be created after the simulation with the name of output file as specified in the Name file. Depending upon the options specified in the output control file, the volumetric budget of the entire model, heads, and drawdown will be printed at desired time steps and stress periods in this output file. Also node water budget and pipe system water budget will be printed in this same file. Because it was desired to get separate output files for each of the pipes and nodes (See Figure 5.6), five output files related to each of the node and four output files related to each of the conduits will be created as well. Also turbulence code from the simulation is automatically written to an output file named ‘turblam.txt’. A sample of the output file is as shown below:

STRESS PERIOD/TIME STEP 1 180

NUMBER OF NEWTON RHAPSON ITERATIONS: 3

------- RESULTS OF FLOW CALCULATION -------

Table 5 .4

NODE #	NODE HEAD[M]	POROUS MEDIA HEAD [M]	EXCHANGE FLOW [M^3/D]	DIRECT RECHARGE
1	97.94711	97.96496	-3.504584	0
2	97.94712	97.95594	-1.730489	2.279375
3	97.94711	97.96467	-3.447645	0
4	97.94711	97.96467	-3.447645	0
5	97.94707	97.92872	14.40974	0

Table 5.5

TUBE	B	E	FLOW	Q [M^3/D]	DIAM.[M]	LEN.[M]	Re	RESIDENCE TIME [D]
1	1	5	turb.	3.50458	0.1	25	578.2672	0.05603
2	2	5	turb.	4.00986	0.1	25	661.64	0.04897
3	3	5	turb.	3.44764	0.1	25	568.872	0.05695
4	4	5	turb.	3.44764	0.1	25	568.872	0.05695

```
BUDGET OF THE PIPE SYSTEM OF TIMESTEP  180 IN STRESS PERIOD    1
-----------------------------------------------------------------------

  TOTAL SIMULATION TIME   180.000000000000      s

       CUMULATIVE VALUES (L**3)           RATES THIS TIME STEP (L**3/T)

            IN:                                IN:
     CONSTANT HEAD =   0.0000000          CONSTANT HEAD =   0.0000000
     PIPE RECHARGE =   37131.019          PIPE RECHARGE =   2.2793750
   MATRIX EXCHANGE =   197477.31        MATRIX EXCHANGE =   12.130363
           STORAGE =   0.0000000                STORAGE =   0.0000000
                                               TOTAL IN =   14.409738

           OUT:                               OUT:
     CONSTANT HEAD =   0.0000000          CONSTANT HEAD =   0.0000000
   MATRIX EXCHANGE =   234608.32        MATRIX EXCHANGE =   14.409738
           STORAGE =   0.0000000                STORAGE =   0.0000000
                                              TOTAL OUT =   14.409738

        IN - OUT =  0.23574103E-08             IN - OUT = -0.54036775E-11
   PERCENT ERROR =  0.50241403E-12        PERCENT ERROR = -0.18750089E-10



 ------------------------NODE WATER BUDGET-----------------------
  STRESS PERIOD           1  TIME STEP         180
 TOTAL SIMULATION TIME   180.000000000000

 FLOW TO THE NODE IN M^3/d
```

Table 5.6

NODE	FIXED H.	RECHARGE	MATRIX	STORAGE	TUBE_IN	TUBE_OUT	IN - OUT
1	0	0	3.5045844	0	0	-3.5045844	-1.18E-10
2	0	2.279375	1.7304895	0	0	-4.0098645	1.75E-10
3	0	0	3.4476449	0	0	-3.4476449	-8.35E-11
4	0	0	3.4476448	0	0	-3.4476448	3.12E-10
5	0	0	-14.409738	0	14.409738	0	-2.91E-10

```
HEAD IN LAYER   1 AT END OF TIME STEP 180 IN STRESS PERIOD    1
---------------------------------------------------------------------------
           1       2       3
   1    98.01   97.96   98.00
   2    97.96   97.93   97.96
   3    98.01   97.96   98.00

  DRAWDOWN IN LAYER   1 AT END OF TIME STEP 180 IN STRESS PERIOD    1
            1            2            3
    1  -8.1058E-03  3.5330E-02 -4.9048E-03
   2   3.5039E-02  7.1277E-02  4.4062E-02
   3  -8.1058E-03  3.5330E-02 -4.9047E-03

VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP180 IN STRESS PERIOD   1
  ------------------------------------------------------------------------------

     CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
     ------------------                 ------------------------
           IN:                                      IN:
           ---                                      ---
             STORAGE =         48.7952              STORAGE =      2.8245E-03
       CONSTANT HEAD =          0.0000        CONSTANT HEAD =          0.0000
               WELLS =          0.0000                WELLS =          0.0000
            RECHARGE =       3282.3000             RECHARGE =         18.2350
         ET SEGMENTS =          0.0000          ET SEGMENTS =          0.0000
               PIPES =       2583.4479                PIPES =         14.4097

            TOTAL IN =       5914.5431             TOTAL IN =         32.6476

          OUT:                                     OUT:
          ----                                     ----
             STORAGE =         14.6673              STORAGE =          0.0000
       CONSTANT HEAD =          0.0000        CONSTANT HEAD =          0.0000
               WELLS =       3600.0000                WELLS =         20.0000
            RECHARGE =          0.0000             RECHARGE =          0.0000
         ET SEGMENTS =        128.1934          ET SEGMENTS =          0.5204
               PIPES =       2173.1604                PIPES =         12.1304

           TOTAL OUT =       5916.0211            TOTAL OUT =         32.6508

            IN - OUT =         -1.4780             IN - OUT =      -3.2211E-03

 PERCENT  DISCREPANCY  =                  -0.02          PERCENT  DISCREPANCY  =                   -0.01
```

5.2.3.2 Results: The output using Mode 3 is exactly the same as using Mode 1, indicating no significant effect of Mode 2 combined in the simulation. Therefore, a sensitivity analysis was done by dividing the whole aquifer into two layers. In Case A, CFP Mode 1 was applied to first layer and Mode 2 was applied to second layer. In Case B, CFP Mode 1 was applied to the second layer and Mode 2 was applied to the first layer.

Case A: The bottom elevation of first layer is 50 m, and second layer is 0 m, as shown in Figure 5.7, of Case 3 of Section 5.2.2.2. The water table elevation is 98 m and top elevation is 100 m, as shown in the same figure. CFP Mode 1 was applied to layer 1 and CFP Mode 3 was applied to layer 2. Output from the simulation is as shown below:

STRESS PERIOD/TIME STEP 1 180

NUMBER OF NEWTON RHAPSON ITERATIONS: 3

------- RESULTS OF FLOW CALCULATION -------

Table 5.7

NODE #	NODE HEAD[M]	POROUS MEDIA HEAD [M]	EXCHANGE FLOW [M^3/D]	DIRECT RECHARGE
1	97.90597	97.92565	-3.865765	0
2	97.90597	97.9157	-1.909228	2.279375
3	97.90597	97.92552	-3.839206	0
4	97.90597	97.92552	-3.839206	0
5	97.90591	97.88588	15.73278	0

Table 5.8

TUBE	B	E	FLOW	Q [M^3/D]	DIAM.[M]	LEN.[M]	Re	RESIDENCE TIME [D]
1	1	5	turb.	3.86576	0.1	25	637.86306	0.05079
2	2	5	turb.	4.1886	0.1	25	691.13236	0.04688
3	3	5	turb.	3.83921	0.1	25	633.4807	0.05114
4	4	5	turb.	3.83921	0.1	25	633.48069	0.05114

```
BUDGET OF THE PIPE SYSTEM OF TIMESTEP  180 IN STRESS PERIOD    1
------------------------------------------------------------------------

  TOTAL SIMULATION TIME   180.000000000000      s

       CUMULATIVE VALUES (L**3)           RATES THIS TIME STEP (L**3/T)

            IN:                                IN:
     CONSTANT HEAD =   0.0000000          CONSTANT HEAD =   0.0000000
     PIPE RECHARGE =   37131.019          PIPE RECHARGE =   2.2793750
   MATRIX EXCHANGE =   218891.49        MATRIX EXCHANGE =   13.453404
           STORAGE =   0.0000000                STORAGE =   0.0000000
                                               TOTAL IN =   15.732779

           OUT:                                OUT:
     CONSTANT HEAD =   0.0000000          CONSTANT HEAD =   0.0000000
   MATRIX EXCHANGE =   256022.51        MATRIX EXCHANGE =   15.732779
           STORAGE =   0.0000000                STORAGE =   0.0000000
                                              TOTAL OUT =   15.732779

          IN - OUT = -0.44237822E-08             IN - OUT = -0.26147973E-11
     PERCENT ERROR = -0.86394401E-12        PERCENT ERROR = -0.83100299E-11



 ------------------------NODE WATER BUDGET-----------------------
  STRESS PERIOD           1  TIME STEP         180
 TOTAL SIMULATION TIME   180.000000000000

 FLOW TO THE NODE IN M^3/d
```

Table 5.9

NODE	FIXED H.	RECHARGE	MATRIX	STORAGE	TUBE_IN	TUBE_OUT	IN - OUT
1	0	0	3.8657648	0	0	-3.8657648	6.95E-11
2	0	2.279375	1.9092281	0	0	-4.1886031	-1.26E-10
3	0	0	3.8392056	0	0	-3.8392056	7.75E-11
4	0	0	3.8392055	0	0	-3.8392055	2.31E-10
5	0	0	-15.732779	0	15.732779	0	-2.54E-10

```
HEAD IN LAYER   1 AT END OF TIME STEP 180 IN STRESS PERIOD    1
  ---------------------------------------------------------------------------

            1       2       3
 ...........................
   1    98.01   97.93   98.01
   2    97.93   97.89   97.92
   3    98.01   97.93   98.01
1
              HEAD IN LAYER   2 AT END OF TIME STEP 180 IN STRESS PERIOD    1
  ---------------------------------------------------------------------------

            1       2       3
 ...........................
   1    97.96   97.95   97.96
   2    97.95   97.95   97.95
   3    97.96   97.95   97.96


          DRAWDOWN IN LAYER   1 AT END OF TIME STEP 180 IN STRESS PERIOD    1
  ---------------------------------------------------------------------------

             1           2           3
 ....................................
   1  -7.8824E-03  7.4482E-02 -5.2973E-03
   2   7.4346E-02  0.1141      8.4302E-02
   3  -7.8825E-03  7.4482E-02 -5.2973E-03

          DRAWDOWN IN LAYER   2 AT END OF TIME STEP 180 IN STRESS PERIOD    1
  ---------------------------------------------------------------------------

             1           2           3
 ....................................
   1   3.9743E-02  4.5958E-02  4.0621E-02
   2   4.5677E-02  5.0227E-02  4.6998E-02
   3   3.9743E-02  4.5958E-02  4.0621E-02
```

```
  VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP180 IN STRESS PERIOD   1
  ------------------------------------------------------------------------------

     CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
     ------------------                 ------------------------

           IN:                                      IN:
           ---                                      ---
             STORAGE =          91.1438             STORAGE =      5.7559E-03
       CONSTANT HEAD =           0.0000       CONSTANT HEAD =          0.0000
               WELLS =           0.0000               WELLS =          0.0000
            RECHARGE =        3282.3000            RECHARGE =         18.2350
         ET SEGMENTS =           0.0000         ET SEGMENTS =          0.0000
               PIPES =        2814.8621               PIPES =         15.7328

            TOTAL IN =        6188.3059            TOTAL IN =         33.9735

          OUT:                                     OUT:
          ----                                     ----
             STORAGE =          21.7690             STORAGE =          0.0000
       CONSTANT HEAD =           0.0000       CONSTANT HEAD =          0.0000
               WELLS =        3600.0000               WELLS =         20.0000
            RECHARGE =           0.0000            RECHARGE =          0.0000
         ET SEGMENTS =         163.7014         ET SEGMENTS =          0.5272
               PIPES =        2404.5746               PIPES =         13.4534

           TOTAL OUT =        6190.0450           TOTAL OUT =         33.9806

            IN - OUT =          -1.7391            IN - OUT =     -7.0583E-03

 PERCENT DISCREPANCY =          -0.03     PERCENT DISCREPANCY =         -0.02
```

Case B: In this case, CFP Mode 1 was applied to the second layer, and Mode 2 was applied to the first layer. The plan looks the same as shown in Figure 5.2 section 5.2.1 but the front view is different, which is as shown below. Top elevation is 100 m, bottom elevation of first layer is 50 m, and bottom elevation of second layer is 0 m. Since the conduits are in the second layer, the elevations of the conduits are assigned as 45 m. Output from the simulation is as shown below:

Top Elevation 100 m

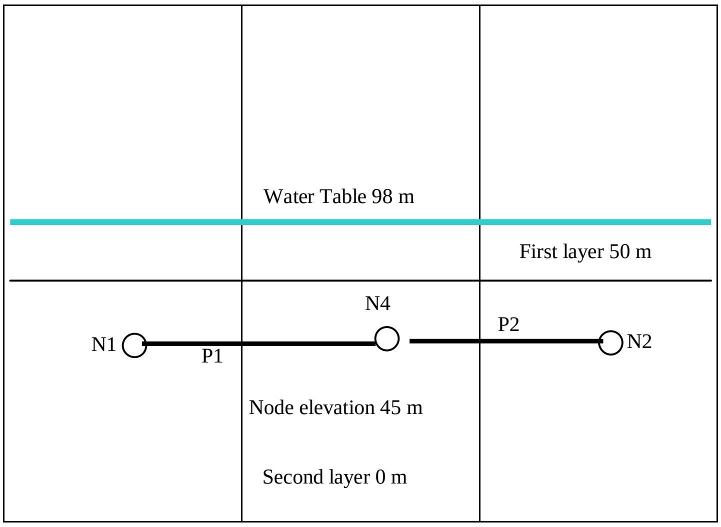


Figure 5.9: Front view showing nodes and conduits

STRESS PERIOD/TIME STEP 1 180

NUMBER OF NEWTON RHAPSON ITERATIONS: 3

------- RESULTS OF FLOW CALCULATION -------

Table 5.10

NODE #	NODE HEAD[M]	POROUS MEDIA HEAD [M]	EXCHANGE FLOW [M^3/D]	DIRECT RECHARGE
1	98.00752	98.00665	0.1709097	0
2	98.00754	98.00546	0.4071127	2.279375
3	98.00752	98.00644	0.2115511	0
4	98.00752	98.00644	0.211549	0
5	98.00752	98.00589	1.278394	0

Table 5.11

TUBE	B	E	FLOW	Q [M^3/D]	DIAM.[M]	LEN.[M]	Re	RESIDENCE TIME [D]
1	1	5	turb.	-0.17089	0.1	25	28.19792	1.14896
2	2	5	turb.	1.87228	0.1	25	308.93173	0.10487
3	3	5	turb.	-0.21153	0.1	25	34.90388	0.92821
4	4	5	turb.	-0.21153	0.1	25	34.90353	0.92822

```
    BUDGET OF THE PIPE SYSTEM OF TIMESTEP  180 IN STRESS PERIOD    1
------------------------------------------------------------------------

  TOTAL SIMULATION TIME   180.000000000000      s

       CUMULATIVE VALUES (L**3)           RATES THIS TIME STEP (L**3/T)

            IN:                                IN:
     CONSTANT HEAD =   0.0000000          CONSTANT HEAD =   0.0000000
     PIPE RECHARGE =   37131.019          PIPE RECHARGE =   2.2793750
   MATRIX EXCHANGE =   0.0000000        MATRIX EXCHANGE =   0.0000000
           STORAGE =   0.0000000                STORAGE =   0.0000000
                                               TOTAL IN =   2.2793750

           OUT:                                OUT:
     CONSTANT HEAD =   0.0000000          CONSTANT HEAD =   0.0000000
   MATRIX EXCHANGE =   37131.920        MATRIX EXCHANGE =   2.2795170
           STORAGE =   0.0000000                STORAGE =   0.0000000
                                              TOTAL OUT =   2.2795170

          IN - OUT = -0.90079754               IN - OUT = -0.14195382E-03
     PERCENT ERROR = -0.12129840E-02      PERCENT ERROR = -0.31137791E-02



 ------------------------NODE WATER BUDGET-----------------------
  STRESS PERIOD           1  TIME STEP         180
 TOTAL SIMULATION TIME   180.000000000000

 FLOW TO THE NODE IN M^3/d
```

Table 5.12

NODE	FIXED H.	RECHARGE	MATRIX	STORAGE	TUBE_IN	TUBE_OUT	IN - OUT
1	0	0	-0.17090973	0	0.17089333	0	-1.64E-05
2	0	2.279375	-0.40711271	0	0	-1.8722787	-1.64E-05
3	0	0	-0.21155114	0	0.21153474	0	-1.64E-05
4	0	0	-0.211549	0	0.2115326	0	-1.64E-05
5	0	0	-1.2783944	0	1.8722787	-0.59396067	-7.64E-05

```
HEAD IN LAYER   1 AT END OF TIME STEP 180 IN STRESS PERIOD    1
  ---------------------------------------------------------------------------

           1       2       3
 ...........................
   1    98.02   97.94   98.00
   2    97.94   97.58   97.87
   3    98.02   97.94   98.00
1
              HEAD IN LAYER   2 AT END OF TIME STEP 180 IN STRESS PERIOD    1
  ---------------------------------------------------------------------------

           1       2       3
 ...........................
   1    98.01   98.01   98.01
   2    98.01   98.01   98.01
   3    98.01   98.01   98.01

 HEAD WILL BE SAVED ON UNIT   58 AT END OF TIME STEP 180, STRESS PERIOD    1
1
          DRAWDOWN IN LAYER   1 AT END OF TIME STEP 180 IN STRESS PERIOD    1
  ---------------------------------------------------------------------------

            1           2           3
 ....................................
   1  -1.7750E-02  6.4199E-02  6.8519E-06
   2   5.8738E-02  0.4217      0.1281
   3  -1.7751E-02  6.4199E-02  6.7312E-06
1
          DRAWDOWN IN LAYER   2 AT END OF TIME STEP 180 IN STRESS PERIOD    1
  ---------------------------------------------------------------------------

            1           2           3
 ....................................
   1  -7.8153E-03 -6.4438E-03 -5.2802E-03
   2  -6.6509E-03 -5.8940E-03 -5.4623E-03
   3  -7.8159E-03 -6.4438E-03 -5.2802E-03

 DRAWDOWN WILL BE SAVED ON UNIT   36 AT END OF TIME STEP 180, STRESS PERIOD    1
1
```

```
 VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP180 IN STRESS PERIOD   1
  ------------------------------------------------------------------------------

     CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
     ------------------                 ------------------------

           IN:                                      IN:
           ---                                      ---
             STORAGE =         159.1391               STORAGE =      5.3331E-02
       CONSTANT HEAD =           0.0000         CONSTANT HEAD =          0.0000
               WELLS =           0.0000                 WELLS =          0.0000
            RECHARGE =        3282.3000              RECHARGE =         18.2350
         ET SEGMENTS =           0.0000           ET SEGMENTS =          0.0000
               PIPES =         410.2939                 PIPES =          2.2795

            TOTAL IN =        3851.7330              TOTAL IN =         20.5678

          OUT:                                     OUT:
          ----                                     ----
             STORAGE =          36.4205               STORAGE =          0.0000
       CONSTANT HEAD =           0.0000         CONSTANT HEAD =          0.0000
               WELLS =        3600.0000                 WELLS =         20.0000
            RECHARGE =           0.0000              RECHARGE =          0.0000
         ET SEGMENTS =         248.2486           ET SEGMENTS =          0.7100
               PIPES =           0.0000                 PIPES =          0.0000

           TOTAL OUT =        3884.6691             TOTAL OUT =         20.7100

            IN - OUT =         -32.9361              IN - OUT =         -0.1422

 PERCENT  DISCREPANCY  =                    -0.85           PERCENT  DISCREPANCY  =                    -0.69
```

5.2.3.3 Conclusion: From the results of the sensitivity analysis, it can be seen that the output from using CFP Mode 2 only in layer 2 (Case A) is different than applying Mode 2 to the whole layer (Mode 3 is the combination of Mode 1 and Mode 2. So when we say simulation using Mode 3, we are applying Mode 1 and Mode 2 together). In case B, the flow is totally in the opposite direction, i.e., from nodes to the porous media because the calculated head for each of the node is greater than the head of the porous media.

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