LUMPFIT

Automated simulation of pressure changes in hydrological reservoirs

Version 3.1

USER'S GUIDE

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1. INTRODUCTION

Modeling of geothermal systems, as well as other hydrological reservoirs, is used extensively as a tool for resource assessment. Rapid advances are being made in the development of numerical simulators for detailed and complex modeling of such systems. Yet detailed numerical modeling of complex fluid/rock systems is both time consuming and costly and requires large amounts of data on the nature of a system as well as powerful computers. However, various simple methods of modeling, mostly analytical, are available as cost effective alternatives.

Lumped parameter modeling of pressure changes in hydrological reservoirs is probably the most powerful of the simple modeling methods. Lumped models are simply models where the hydrological properties of a reservoir, or the major parts of a reservoir, are lumped together in one or two quantities for each part. This is analogous to methods used in electrical engineering. Simple lumped parameter models can be used to predict responses of a reservoir to different future production schemes. In addition a lumped model gives some insight into the properties of the reservoir being simulated.

This guide is designed to give instructions on how to use the program LUMPFIT, which is a very powerful program for lumped modeling of pressure changes in geothermal as well as other hydrological reservoirs. In addition to this introduction, chapter 2 decribes installation procedures for the program and preparations for its execution. Chapter 3 describes LUMPFIT and it's options in more detail. Chapter 4 gives a comprehensive example of how LUMPFIT may be used. The user should repeat that example in order to familiarize himself with the program before actually using it on real data. A listing of the error messages and warnings issued by LUMPFIT is given in chapter 5. The theoretical background and methodology for LUMPFIT is presented by Axelsson (1985, 1989).

Lumped models consist of a few capacitors or tanks that are connected by conductors or resistors. Examples of two simple lumped models are presented in Figure 1. The tanks simulate the storage of different parts of the reservoir in question, whereas the resistors simulate the permeability. A tank in a lumped model has the mass storage coefficient κ when it responds to a load of liquid mass m with a pressure increase given by $p = m/\kappa$. The mass conductance of a resistor in a lumped model is σ when it transfers $q = \sigma\Delta p$ units of liquid mass per unit time (e.g. kg/s) at the impressed pressure differential Δp. The pressure (water level) in the tanks simulates

the pressure in different parts of the reservoir, whereas production from the reservoir is simulated by withdrawal of water from one of the tanks.

Lumped models can either be open or closed. When open, they are connected by a resistor to an infinitely large imaginary reservoir, which maintains a constant pressure. When closed, lumped models are isolated from any external reservoirs. Actual reservoirs may be represented by a few tank closed or open lumped parameter models, a one tank closed model being the most simple.

The pressure response (p) of the open one tank model in Figure 1 to a constant production (Q) since time t=0 is given by the following equation:

$$p(t) = -(Q/\sigma_1)\,(1-e^{-\sigma_1 t/\kappa_1}) \tag{1}$$

The pressure response (p) of a more general open lumped model with N tanks, to a constant production (Q) since time t=0, is given by the equation:

$$p(t) = -\sum_{j=1}^{N} Q\frac{A_j}{L_j}\left[1-e^{-L_j t}\right] \tag{2}$$

The pressure response of an equivalent N tank closed model is given by the equation:

$$p(t) = -\sum_{j=1}^{N-1} Q\frac{A_j}{L_j}\left[1-e^{-L_j t}\right] + QBt \tag{3}$$

The coefficients A_j, L_j and B are functions of the storage coefficients of the tanks (κ_j) and the conductance coefficients of resistors (σ_j) of the model (compare equations (1) and (2) for the case of an open one tank model). The A_j's may be termed amplitude coefficients, whereas the L_j's are eigenvalues of the problem or decay rate coefficients.

Lumped modeling is appropriate in cases where data on the production (injection) from (into) a reservoir and the resulting pressure changes are available and when one or more of the following conditions apply:

- Data on the nature of a reservoir are limited and detailed numerical modeling is therefore not appropriate or justified.
- The time available for a particular modeling study is limited or a simple method is required as the first stage in the modeling study.
- Funds available for modeling are minimal and/or a powerful computer is not available.

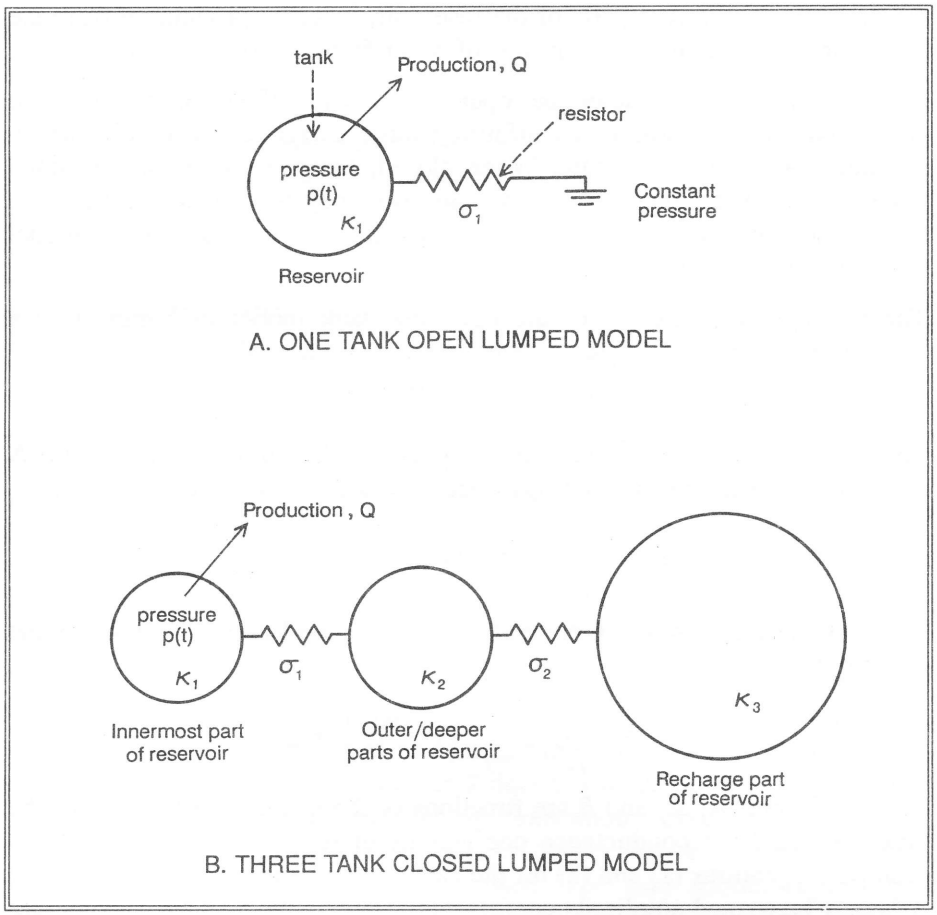

Figure 1. Examples of lumped models of hydrological reservoirs.

- An independent check on the results of more complex modeling techniques is required.

LUMPFIT tackles the modeling/simulation problem as an inverse problem. It automatically fits the analytical response functions of the lumped models to the observed data by using a non-linear iterative least-squares technique for estimating the reservoir parameters (Axelsson, 1989). LUMPFIT only requires an access to a PC-computer. The user needs to supply the following:

- A time series of the data to be simulated (production and pressure or water level changes).

- Information on units and the data set in general.
- A selection of the kind of lumped model to be used (one, two or three tanks; open or closed).
- An adequate first guess for the model coefficients before the program iterates for better values. This may require some skills and insight by the user; the non-linear inverse method may not converge for a poorly chosen first guess.

Consequently the program changes the parameters by the automatic iterative process until a best fit (in the least squares sense) for the model selected is obtained. This usually takes a very short time. Direct or forward modeling, where the iterations are done manually, takes much longer. After the best fit is obtained by LUMPFIT the parameters of the model may be used to estimate the properties of the reservoir in question and to predict the pressure changes in the reservoir in the future for given production scenarios.

The data required for the simulation can either be data from short-term tests involving only one well, data from longer tests involving the reservoir as a whole or monitoring data collected during long-term production from the reservoir. In the latter two cases the production data used should be the total production (less any possible reinjection) from the reservoir. LUMPFIT accepts either pressure or water level data. This data should preferably be data from a centrally located observation well, but data from production wells is also acceptable.

2. *INSTALLATION OF THE PROGRAM*

2.1 The Floppy Disk Containing LUMPFIT

On the inside back cover of this manual there should be a folder with a floppy disk containing the following files:

LUMPFIT.EXE	The executable version of LUMPFIT.
LUMPFIT.FON	A font file necessary for graphics.
SAM1.DAT	A sample data file.
SAM2.DAT	Future prediction file.

2.2 A Setup Procedure

It is possible to run the program from the floppy disk. However, we recommend that you copy all the files to your hard disk and keep the disk as a backup in the back folder. If you have no special preferences as to how you want to store the program on your hard disk, here is a suggestion:

Copy all the files to a new directory called "LUMP" on your hard disk and define the full path name into your "AUTOEXEC.BAT" file ("PATH C:\LUMP"). To make this path definition active you need to restart the computer. Then you can execute LUMPFIT from any directory of your PC. It may be convenient to copy the file LUMPFIT.FON to your working directory or give the path "C:\LUMP" to this file when asked by the program.

2.3 To Set Graphics Mode

To draw plots on a Hercules graphics monitor, you will need to set the graphics mode of your computer prior to executing LUMPFIT. For instance if the command file MSHERC.COM is available the graphics mode is set by the command "MSHERC".

2.4 To Print Graphs

To print graphics from your screen on a printer, which is connected to your PC, it should be possible to use the [PRINT-SCREEN] button on your keyboard. You should suppress colors in the screen plot before printing, unless you have a color printer. You may need to consult your DOS manual before printing, but the three following setups are the most common:

1. Dot matrix printer connected to a PC with Hercules graphics: Execute a screen dump program such as the program HPRINT prior to executing LUMPFIT and print by [SHIFT/PRINT-SCREEN][0].

2. Dot matrix printer connected to a higher level PC: Give the DOS command "GRAPHICS GRAPHICS" prior to executing LUMPFIT and print by [PRINT-SCREEN] or [SHIFT/PRINT-SCREEN].

3. Laser printer (e.g. a HP Laserjet II) connected to a higher level PC (DOS Version 5 required): Give the DOS command "GRAPHICS LASERJETII" prior to executing LUMPFIT and print by [PRINT-SCREEN] or [SHIFT/PRINT-SCREEN].

3. PROGRAM DESCRIPTION

3.1 The Input Data File

The time series of production data and pressure data, or water level data, is arranged into a file. An example of a short data file is given in Figure 2. The first line is a text line which may be used to identify the data. The following lines should each contain three numbers, i.e. (time, pressure, production) or (time, water level, production). The numbers are separated by spaces or commas (free format). These numbers can be in any units, but they must be decimal. For instance, time can be the number of hours or months from a certain starting time, but not a regular date. Note that the time value has to be monotonically increasing. The pressure or water level value is for the given time point. However, the production value represents the average production from the last time point to the time value of the current line. The pressure or water level data may be unknown for periods at the beginning and/or the end of a time series and should be entered into the data file as numbers out of bounds of ordinary values (for example -999.0 m in the case of water level data). A maximum of 900 lines is allowed in the data file.

3.2 Finding a Simple Reservoir Model that Fits the Data

We suggest a certain procedure for finding an adequate model that fits the observed data which can consequently be used to predict future pressure changes in the reservoir. The procedure is based on increasing the model size (i.e. complexity) incrementally and finding the best fitting model during each step. This procedure also gives statistics for comparing the different sized models. It should be mentioned that LUMPFIT makes suggestions on the initial guesses of the model coefficients (the A_j's, L_j's and B), which in many cases are adequate.

The suggested procedure is as follows:

1. First, we let LUMPFIT find the best fitting model coefficient for a single tank closed model (B). The theoretical response of this model to a constant production Q is simply given by $p(t) = -QBt$. The initial guess at this stage is usually not important.
2. Then we turn to an open one tank model, which is defined by two coefficients; A_1 and L_1 and equation (2) with N=1 (see also equation (1)). We use the best fitting coefficient for the single closed tank model (step 1) as our initial guess for the coefficient A_1. The initial guess for L_1 should be a very low positive value.

```
Sample 1 for the program LUMPFIT: Time(mon)  Water level(m)  Production(l/s)
   1.  -999.0     8.0
   2.  -999.0     8.0
   3.  -999.0     8.0
   4.  -999.0     8.0
   5.  -999.0     8.0
   6.  -999.0     8.0
   7.  -999.0     8.0
   8.  -999.0     8.0
   9.  -999.0    25.0
  10.  -999.0    20.0
  11.  -999.0    11.0
  12.  -999.0    15.0
  13.  -999.0    18.3
  14.  -999.0    20.6
  15.    84.4    22.1
  16.    85.5    21.4
  17.    84.3    19.6
  18.    80.9    19.4
  19.    90.6    20.7
  20.    98.0    22.5
  21.    96.5    21.5
  22.    98.3    21.2
  23.    97.1    21.0
  24.    98.2    20.4
  25.    92.7    20.4
  26.    84.8    19.4
  27.    87.2    16.4
  28.    77.0    13.6
  29.    68.1    15.0
  30.    81.1    16.4
  31.    96.1    20.3
  32.   103.7    21.5
  33.   119.7    23.6
  34.   133.6    27.3
  35.   128.3    24.2
  36.   134.7    25.5
  37.   123.9    23.0
  38.   110.4    19.2
  39.   100.9    17.5
  40.    91.7    17.5
  41.    86.3    16.4
  42.    90.8    17.7
  43.   120.5    24.5
  44.   130.0    24.4
  45.   142.3    24.6
  46.   143.6    23.6
  47.   138.7    22.1
  48.   140.6    22.9
  49.   131.7    21.4
  50.   121.1    19.0
  51.   110.6    16.8
  52.   101.1    17.8
  53.   103.6    17.8
  54.   114.1    18.9
  55.   126.2    23.5
  56.   143.5    24.0
  57.   149.8    25.0
```

Figure 2. The sample input data file SAM1.DAT.

3. After finding the best open one tank model, we expand to a three coefficient model; a two tank closed model (equation (3) with N=2). Such a model is defined by the coefficients A_1, L_1 and B. We suggest using the results of the open one tank model as the initial guesses for A_1 and L_1 and to use either an order of magnitude higher or lower value than A_1 as the initial guess for B.

4. This way we may continue step by step until we have expanded to a three tank open model, which is the most complex model allowed by LUMPFIT.

As it turns out, this method of slowly expanding the model size usually keeps the initial guess values for the model coefficients, made by LUMPFIT, within reasonable bounds. Furthermore, the statistics for each sized model should be monitored, because a simple model that gives nearly as good a fit as a more complicated model is usually a better choice.

3.3 The Central Menu of LUMPFIT

The program revolves about a central main menu of ten options, of which the user has to select one at a time. The central menu is shown in Figure 3. After completing a chosen task, the program returns to the central menu, and the user can select the next operation. The options are selected by typing one letter and pressing the [RETURN] or [ENTER] button. Each option can be selected as often as needed and in the order the user finds most convenient. Following is a brief description of the ten commands.

The ABOUT-command is selected by typing "A" (About the program LUMPFIT). This command lists some information about the program on the screen as well as information on the authors and relevant literature. It does not interfere with any of the calculations performed by the program. Figure 4 shows the listings given when the ABOUT-command is selected.

The OPEN-command is selected by typing "O" (Open input data file). This option is used to read production and pressure (water level) data from a data file into the program. The user must know the file name of the data file. This is usually the first operation selected when running LUMPFIT. Figure 5 shows a sample of the screen when the OPEN-command has been selected.

The SAVE-command is selected by typing "S" (Save calculated values). After a successful run of the program, the user should save the

```
                    L U M P F I T   V 3.1



                A     About the program LUMPFIT

                O     Open input data file
                S     Save calculated values
                V     View data
                M     Define model
                P     Set parameters
                F     Forward calculations and statistics
                I     Inverse calculations
                D     Draw graph

                Q     Quit

    Selection:
```

Figure 3. The central menu of the program.

calculated results into a file. Figure 6 shows a sample of the screen after selecting the SAVE-command.

The VIEW-command is selected by typing "V" (View data). At any time after reading in the data, the user can view the current time, pressure, and production data as a numerical table. Furthermore, the calculated pressure and residual (difference between the observed and calculated pressure) for a current model are also shown. Figure 7 shows a sample of such a listing.

The MODEL-command is selected by typing "M" (Define model). This operation is selected to view the current working reservoir model and/or to alter the model. This operation is usually used quite frequently when a user is trying to find a good model that adequately simulates the observed pressure changes in a natural reservoir. Figure 8 shows a sample of the screens following the MODEL-command, where the model size is increased from a three coefficient model to a four coefficient model, and the user adjusts a model coefficient manually. The first screen presents the model coefficients A_j, L_j and B as well as the mass storage and conductance coefficients, κ_j and σ_j of the model (Kappa and Sigma in Figure 8).

Note that there is a fundamental difference between the long term behavior of an open or a closed reservoir. For a constant non-zero

```
 X      X   X  X   X  XXXX   XXXXX  XXX  XXXXX
 X      X   X  XX XX  X   X  X       X     X
 X      X   X  X X X  XXXX   XXXX    X     X
 X      X   X  X   X  X      X       X     X
 XXXXX   XXX   X   X  X      X      XXX    X

Lumped parameter modeling of geothermal reservoirs

Version 3.1 , August 1992

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Disclaimer: Neither the National Energy Authority of Iceland nor the authors
  of this program assume any responsibility for the accuracy, completeness,
    usefulness or consequential damages of this program and its results.

======================(Next - About the method): [ENTER]

L U M P F I T
Version 3.1 , August 1992

The program LUMPFIT simulates pressure response data from liquid-dominated
geothermal reservoirs by simple lumped parameter models. The program is based
on an automatic non-linear least-squares iterative inverse technique.

Literature:
  Axelsson, G., 1985, Hydrology and thermomechanics of liquid-dominated
    hydrothermal systems in Iceland, Ph.D. Thesis, Oregon State University,
    Corvallis, Oregon, U.S.A., 291 pp.
  Axelsson, G., 1989, Simulation of pressure response data from geothermal
    reservoirs by lumped parameter models, paper SGP-TR-122, Proceedings,
    Fourteenth Workshop on Geothermal Reservoir Engineering, Stanford
    University, Stanford, California, U.S.A., p. 257-263.

=====================(Next - About the program): [ENTER]

L U M P F I T  V 3.1

It should be OK to experiment with the program LUMPFIT, without endangering
the source code or other files on the disk. The program revolves about a
central menu which offers ten operations. The program returns to the main
menu after execution of each operation. The operations are:
ABOUT - gives this information, OPEN - to open an input data file and read
the data, VIEW - to list the current data and also some calculated values,
PARAMETERS - to adjust several constants used in the calculations,
MODEL - to select size of the model and to adjust the model parameters,
FORWARD - to calculate the forward problem and some statistics,
INVERSE - to let the program adjust the model parameters to minimize misfit
between the observed and calculated pressure data, DRAW - to draw a graph,
SAVE - to save into a file the data and some calculated values,
QUIT - to exit the program.

Along with each question the program usually shows a {default} value in braces.
The user can either type in a new value or choose the default value by pressing
the <RETURN> or <ENTER> button. The user supplied value becomes the default
value next time this question is asked. Through this feature the user can
easily view the current setting of the parameters.

========================(Next - The main menu):
```

Figure 4. The ABOUT-screens.

```
                Data vectors have been initialized

        Initial (I) or current (C) settings (C): [ENTER]

 Input file name: SAM1.DAT

 Data title:
 Sample 1 for the program LUMPFIT: Time(mon) Water level(m) Production(l/s)

                      First and last four data lines
                 -------------------------------------------------
                   1:   1.00000       -999.000        8.00000
                   2:   2.00000       -999.000        8.00000
                   3:   3.00000       -999.000        8.00000
                   4:   4.00000       -999.000        8.00000
                  ...:
                  54:   54.0000        114.100        18.9000
                  55:   55.0000        126.200        23.5000
                  56:   56.0000        143.500        24.0000
                  57:   57.0000        149.800        25.0000
                 -------------------------------------------------

 ========================(Next - The main menu):
```

Figure 5. The OPEN-screen.

```
                              Saving data and results

      Output file name: SAM1.OUT

      The data have been successfully saved to the output file

      ============================(Next - The main menu):
```

Figure 6. The SAVE-screen.

production a closed reservoir will eventually respond by a constant pressure decline versus time, whereas an open reservoir will eventually reach an equilibrium at a fixed pressure level because of its connection to a constant pressure reservoir (infinitely large). This difference should be kept in mind when making future predictions. For a cautious prediction we recommend using a closed model.

The PARAMETERS-command is selected by typing "P" (Set parameters). There are a number of parameters that affect the calculations of the program and these should be set by the user before attempting to fit a model to the data. The user can adjust or view the parameters at any time. A sample of the three parameter screens is shown in Figure 9. The first part defines conversion factors from input data units into SI units.

Line	Time	Production	Obs-W.Level	Calc-W.Level	Residual
1:	1.00000	8.00000	-999.000	-34.8797	1034.78
2:	2.00000	8.00000	-999.000	-20.8853	1020.79
3:	3.00000	8.00000	-999.000	-14.2657	1014.17
4:	4.00000	8.00000	-999.000	-11.0187	1010.92
5:	5.00000	8.00000	-999.000	-9.31409	1009.21
6:	6.00000	8.00000	-999.000	-8.31487	1008.21
7:	7.00000	8.00000	-999.000	-7.63822	1007.54
8:	8.00000	8.00000	-999.000	-7.10910	1007.01
9:	9.00000	25.0000	-999.000	57.3583	942.542
10:	10.0000	20.0000	-999.000	68.7019	931.198
11:	11.0000	11.0000	-999.000	40.5534	959.347
12:	12.0000	15.0000	-999.000	43.0427	956.857
13:	13.0000	18.3000	-999.000	57.0177	942.882
14:	14.0000	20.6000	-999.000	72.5709	927.329
15:	15.0000	22.1000	84.4000	85.8969	-1.49691
16:	16.0000	21.4000	85.5000	89.9625	-4.46253
17:	17.0000	19.6000	84.3000	85.6324	-1.33239
18:	18.0000	19.4000	80.9000	83.4373	-2.53733
19:	19.0000	20.7000	90.6000	87.8608	2.73925
20:	20.0000	22.5000	98.0000	97.2292	.770824
21:	21.0000	21.5000	96.5000	98.3664	-1.86637
22:	22.0000	21.2000	98.3000	98.3473	-.472986E-01

==========(Next - Another page): **[ENTER]**

Line	Time	Production	Obs-W.Level	Calc-W.Level	Residual
23:	23.0000	21.0000	97.1000	98.1677	-1.06772
24:	24.0000	20.4000	98.2000	96.4032	1.79678
25:	25.0000	20.4000	92.7000	96.1565	-3.45645
26:	26.0000	19.4000	84.8000	92.8387	-8.03874
27:	27.0000	16.4000	87.2000	80.5591	6.64094
28:	28.0000	13.6000	77.0000	64.8515	12.1485
29:	29.0000	15.0000	68.1000	63.3126	4.78738
30:	30.0000	16.4000	81.1000	68.2918	12.8082
31:	31.0000	20.3000	96.1000	85.7029	10.3971
32:	32.0000	21.5000	103.700	98.7409	4.95913
33:	33.0000	23.6000	119.700	113.200	6.49960
34:	34.0000	27.3000	133.600	134.392	-.791770
35:	35.0000	24.2000	128.300	133.161	-4.86107
36:	36.0000	25.5000	134.700	138.157	-3.45733
37:	37.0000	23.0000	123.900	131.730	-7.82984
38:	38.0000	19.2000	110.400	115.115	-4.71482
39:	39.0000	17.5000	100.900	101.643	-.743057
40:	40.0000	17.5000	91.7000	95.9627	-4.26267
41:	41.0000	16.4000	86.3000	89.7039	-3.40390
42:	42.0000	17.7000	90.8000	92.1865	-1.38652
43:	43.0000	24.5000	120.500	119.410	1.08979
44:	44.0000	24.4000	130.000	132.156	-2.15646

==========(Next - Another page): **[ENTER]**

Line	Time	Production	Obs-W.Level	Calc-W.Level	Residual
45:	45.0000	24.6000	142.300	139.409	2.89136
46:	46.0000	23.6000	143.600	139.636	3.96432
47:	47.0000	22.1000	138.700	134.740	3.96000
48:	48.0000	22.9000	140.600	136.120	4.48001
49:	49.0000	21.4000	131.700	131.732	-.323557E-01
50:	50.0000	19.0000	121.100	121.277	-.177328
51:	51.0000	16.8000	110.600	108.735	1.86535
52:	52.0000	17.8000	101.100	107.225	-6.12498
53:	53.0000	17.8000	103.600	107.023	-3.42335
54:	54.0000	18.9000	114.100	111.561	2.53852
55:	55.0000	23.5000	126.200	131.475	-5.27505
56:	56.0000	24.0000	143.500	143.110	.390209
57:	57.0000	25.0000	149.800	152.855	-3.05469

==========(Next - The main menu):

Figure 7. The VIEW-screens.

Note that default values are always given in braces, e.g. {1.000}, and the default value can be selected by pressing the [ENTER] button. If the value is changed, the new value becomes the default value next time this question is asked.

The second parameter screen deals with initial values for time, pressure or water level, and production. If the observed water level is measured in a producing well (instead of an observation well) then the water level in that well needs to be corrected for turbulence pressure losses. One can also select to use only part of the data from the input file in the inversion (e.g. if pressure data is not available). To find the appropriate line numbers you should use the VIEW-command.

The last parameter screen allows scaling of the graph LUMPFIT can draw of the data and simulation results. For instance in the sample data file the time is in months, but a plot with the time-axis in years may be desired. Furthermore the axes labels can be adjusted.

The FORWARD-command is selected by typing "F" (Forward calculations and statistics). For a given model and production data this operation calculates the pressure response, or water level response, of the reservoir. This operation is chosen automatically after inverting for new model coefficients. This option can also be selected to calculate the response of a user defined model and to predict the response to a future production for a known reservoir model.

The forward calculations are followed by a list of statistics describing the fit. The coefficient of determination describes how much of the variance about the mean of the observed data is explained by the model. Note that the estimate of standard deviation is slightly higher than the root mean square misfit, since it takes the degrees of freedom also into account. A sample of the screen followed by the FORWARD-command is shown in Figure 10.

The INVERSE-command is selected by typing "I" (Inverse calculations). This operation is at the core of the program and is used to find the best model coefficients so that the resulting response of the selected reservoir model fits the observed data. It is the most time consuming part of the program. A sample screen is shown in Figure 11. The INVERSE-command is automatically followed by forward calculations and statistics.

```
                    Model of the geothermal reservoir

                              Number of tanks : 2
                                Closed model : C

A unit step change in production at t=0 results in the pressure response
P(t) = sum[ A(i)*(1-exp{-L(i)*t})/L(i) ] + B*t
where the model parameters A(i), L(i) and B are
                                          A(1) :  5.35503
                                          L(1) :  .782367
                                          B    :  .506005E-01
Kappa: 49.7440            5264.40
       ----------         ----------
       |        |         |        |
       |        |VVVVVVVVVV|        |
       |        |         |        |
       ----------         ----------
Sigma:          .146303E-04

     Do you want to change the model (Y/N) {N}: Y

-------------------------------------------------------------------------------

                    Definition of reservoir model

                          Number of tanks {2}: [ENTER]

               Open (O) or Closed (C) model {C}: O

A unit step change in production at t=0 results in the pressure response
P(t) = sum[ A(i)*(1-exp{-L(i)*t})/L(i) ] + B*t
Guess of the model parameters A(i), L(i) and B
                          A(1) { 5.35503    }: [ENTER]
                          L(1) { .782367    }: [ENTER]
                          A(2) { .506005E-01}: [ENTER]
                          L(2) { .782367E-01}: 0.78E-02

-------------------------------------------------------------------------------

                    Model of the geothermal reservoir

                              Number of tanks : 2
                                Open model : O

A unit step change in production at t=0 results in the pressure response
P(t) = sum[ A(i)*(1-exp{-L(i)*t})/L(i) ] + B*t
where the model parameters A(i), L(i) and B are
                                          A(1) :  5.35503
                                          L(1) :  .782367
                                          A(2) :  .506005E-01
                                          L(2) :  .780000E-02
                                          B    :  .000000
Kappa: 49.7440            5371.97
       ----------         ----------
       |        |         |        |
       |        |VVVVVVVVVV|        |VVVVVVVVVV
       |        |         |        |         V
       ----------         ----------         V
Sigma:          .146317E-04          .160494E-04

     Do you want to change the model (Y/N) {N}:
```

Figure 8. The MODEL-screens.

```
                Scaling of data from input file into SI units

          Scaling time unit to (s) { 1.00000    }: 2635200

    Pressure data (P) or water level data (W) {P}: W

        Scaling water level to (m) { 1.00000    }: [ENTER]

      Scaling production to (kg/s) { 1.00000    }: 0.958

      Density of the water (kg/m3) { 1000.00    }: 958

SIGN CONVENTIONS:  Pumping OUT OF reservoir leads to
  higher (+1) or lower (-1) pressure values
  higher (+1) or lower (-1) water level values
  positive (+1) or negative (-1) production values

              Water level sign convention {-1.0}: +1
               Production sign convention { 1.0}: [ENTER]

========================(Next - Data parameters): [ENTER]

                       Definition of data parameters
                         in input data file units


                    Starting time { 1.00000    }: 0
              Initial water level { -999.00    }: -65
          Average past production { 8.00000    }: 0

           Turbulence coefficient { .000000    }: [ENTER]


                Part of water level data used in inversion

       First water level data point number {  1}: 15
        Last water level data point number { 57}: [ENTER]

===========================(Next - Graph scales): [ENTER]

                Scale from input data units to graph units


             Scale for time units { 1.00000    }: 0.08333333
       Scale for water level units { 1.00000    }: [ENTER]
        Scale for production units { 1.00000    }: [ENTER]

                           Text by axes on graph

                            {Time (s)                                    }
         Label by time-axis: Time(years)
                            {Water level (m)                             }
  Label by water level-axis: [ENTER]
                            {Production (kg/s)                           }
   Label by production-axis: Production(l/s)

========================(Next - The main menu):
```

Figure 9. The PARAMETERS-screens.

The DRAW-command is selected by typing "D" (Draw graph). This option is used to draw a graph of the observed production and pressure profiles as well as the calculated pressure changes of the current reservoir model. This operation should be used frequently. A sample screen is

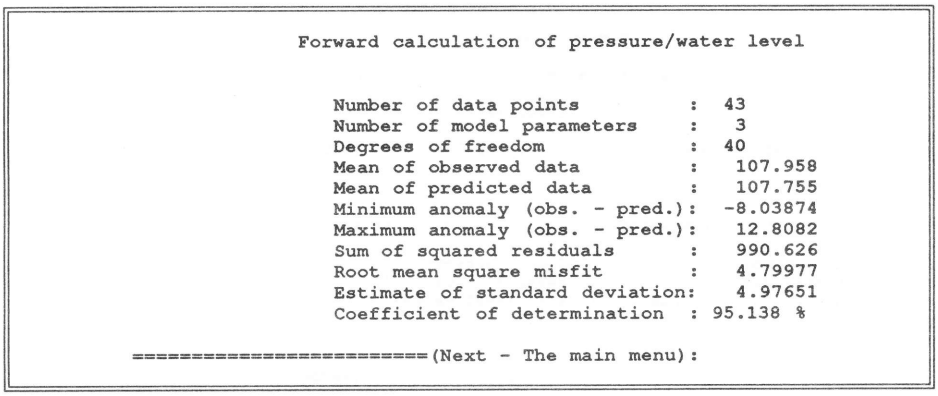

Figure 10. The FORWARD-screen.

shown in Figure 12.

The QUIT-command is selected by typing "Q" (Quit). This option is used to exit LUMPFIT to DOS.

To this list we add the CANCEL-command, which is selected by typing "C". In between screens there is a line similar to:

========== (Next - ...):

and by pressing the [ENTER] button results in clearing the screen and giving the next screenful. At these turning points it is possible to give the CANCEL-command which causes LUMPFIT to jump back to the central menu.

4. EXAMPLE OF USAGE

In this chapter an example is given of how LUMPFIT is used to simulate water level data. You should try to repeat and understand this example, that finds an adequate reservoir model for the data in the file SAM1.DAT. The file contains data on the water level in a certain liquid dominated geothermal reservoir during the first five years of its exploitation. In the file SAM1.DAT time is given as the number of months since the exploitation of the field started. The water level was not monitored for the first 14 months. The initial pressure in the reservoir, prior to exploitation, has been estimated as equivalent to a water level head of 65 m.

4.1 Lumped Modeling

First one sets the graphics mode and printer settings if needed (see chapters 2.3 and 2.4). Then to start the program the operating system is given the command:

```
LUMPFIT
```

The first question of the program should be answered with a "Y" (yes). This leads to the central menu.

Step 1 - The OPEN-command: Read the input data from the file SAM1.DAT into the program (see Figure 5).

Step 2 - The PARAMETERS-command: After the program has read the input data the parameter settings need to be adjusted. The three parameter screens are shown in Figure 9. The first part gives conversion factors for converting the data into SI units. The time in the input data file is in months and there are about 2635200 seconds in a month. The production data is in l/s in the input data file, the temperature of the water about 100°C and the density is therefore 958 kg/m^3. To convert l/s into kg/s one should multiply by 0.958. Water level is defined positive downward in the data file and therefore the water level sign conversion is positive. Similarly, production is defined positive in the input file and the default value (+1) can be used for the sign conversion.

The second parameter screen deals with initial values for time, water level, and production. It is assumed that nothing was produced from the reservoir before time 0 and the initial water level is entered as -65 m, in agreement with the estimated initial water level head mentioned earlier. Next, one selects to use only the part of the water level data from line 15 to line 57 in the inversion (remember: the water level was not measured

```
                Inversion to find better model parameters

                          Number of iterations {10}: [ENTER]
 Iter    RMS-misfit      A(1)          A(2)          L(1)          L(2)
    0    6.71694       5.35503       .506005E-01   .782367       .780000E-02
    1    6.05842       5.49604       .771504E-01   .837780       .210958E-01
    2    4.58619       5.73289       .118131       .928214       .325678E-01
    3    4.33317       5.80854       .124761       .953505       .317673E-01
    4    4.33242       5.80807       .124314       .953163       .316813E-01
    5    4.33242       5.80791       .124279       .953091       .316700E-01
    6    4.33242       5.80789       .124274       .953082       .316685E-01
    7    4.33242       5.80789       .124274       .953080       .316683E-01
    8    4.33242       5.80789       .124274       .953080       .316683E-01
    9    4.33242       5.80789       .124274       .953080       .316683E-01
   10    4.33242       5.80789       .124274       .953080       .316683E-01

==================(Next - Forward calculations): [ENTER]

             Forward calculation of pressure/water level


                Number of data points          :  43
                Number of model parameters     :   4
                Degrees of freedom             :  39
                Mean of observed data          :   107.958
                Mean of predicted data         :   107.856
                Minimum anomaly (obs. - pred.):  -9.24192
                Maximum anomaly (obs. - pred.):   9.96188
                Sum of squared residuals       :   807.103
                Root mean square misfit        :   4.33242
                Estimate of standard deviation:   4.54917
                Coefficient of determination   : 96.039 %

=========================(Next - The main menu):
```

Figure 11. The INVERSE-screens.

during the first 14 months).

The last parameter screen enables scaling of the graph drawn by LUMPFIT. Time is in months, but a plot in years is required, so months are scaled to years by the conversion factor 1/12 = 0.08333. Furthermore, axes labels are changed so that they correspond with the units used (see Figure 9). Now the parameters should be set and the current settings are now default values and can be viewed by selecting the PARAMETERS-command again.

Step 3 - The VIEW-command: View the data (similar to Figure 7).

Step 4 - The MODEL-command: View the first model, which is a closed one tank model. The model coefficient is the initial guess made by LUMPFIT (no adjustments at this time).

```
                        Graph settings

 Do you want to adjust graph settings (Y/N) {N}: Y

 ------------------------------------------------------------------

                    Definition of graph settings

 Scaled range of time values                    .833333E-01   4.75000
 Scaled range of observed water level data      68.1000       149.800
 Scaled range of calculated water levels       -63.0365       196.372
 Scaled range of production data                8.00000       27.3000

      Starting value on time-axis { .000000    }: -0.2
        Ending value on time-axis { 4.83333    }: 5
  Starting value for water level { 150.617     }: 170
    Ending value for water level { 64.0150     }: -80
       Starting production value { .000000     }: [ENTER]
         Ending production value { 27.5730     }: 30

   Portion of figure for production curve { .30}: [ENTER]
                  Data label size (cm) {  .12}: .1

              Do you want full colors (Y/N) {Y}: [ENTER]

 ========================(Next - Drawing graph):
```

Figure 12. The DRAW-screens.

Step 5 - The INVERSE-command: Iterate twice for a better model coefficient. Write down the final model coefficient and some of the statistical parameters, at least the coefficient of determination and the root mean square misfit or estimate of standard deviation.

Step 6 - The DRAW-command: In this first drawing you should adjust the graph settings as shown in Figure 12. In later drawings you don't need to adjust the graph settings. Now you should get a graph similar to that on Figure 13a, but not a particularly impressive fit, which is due to a model that is too simple. Press [ENTER] to exit the graph and return to the main menu.

Step 7 - The MODEL-command: Adjust the model to a one tank open model. Use the suggested model coefficients.

Step 8 - The INVERSE-command: Iterate 10 times. Write down model coefficients and the statistical parameters.

Step 9 - The DRAW-command: No need to adjust graph settings. Note a considerably better fit (see Figure 13b).

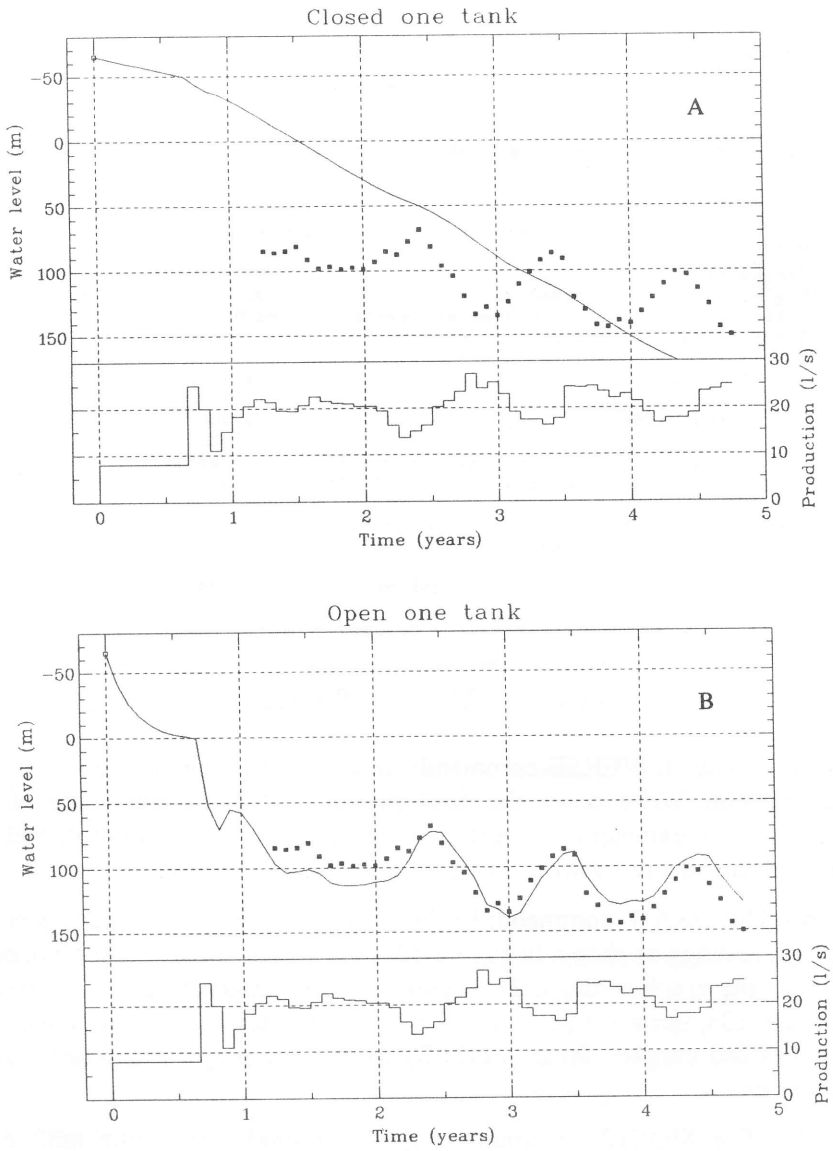

Figure 13. Graphs drawn by LUMPFIT for different sized models. Each graph is composed of two panels. The upper panel shows the observed water level data as small squares, and the calculated water level as a continuous curve. The lower panel shows the production data.

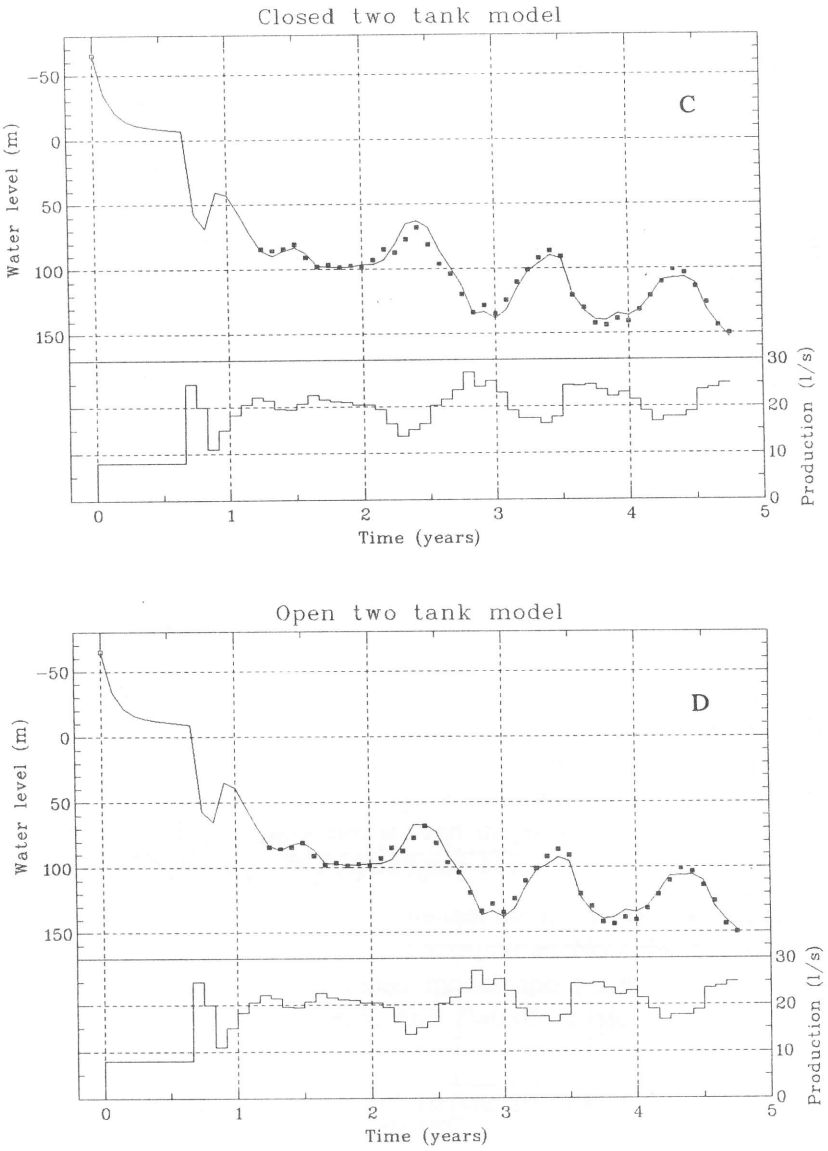

Figure 13. cont.

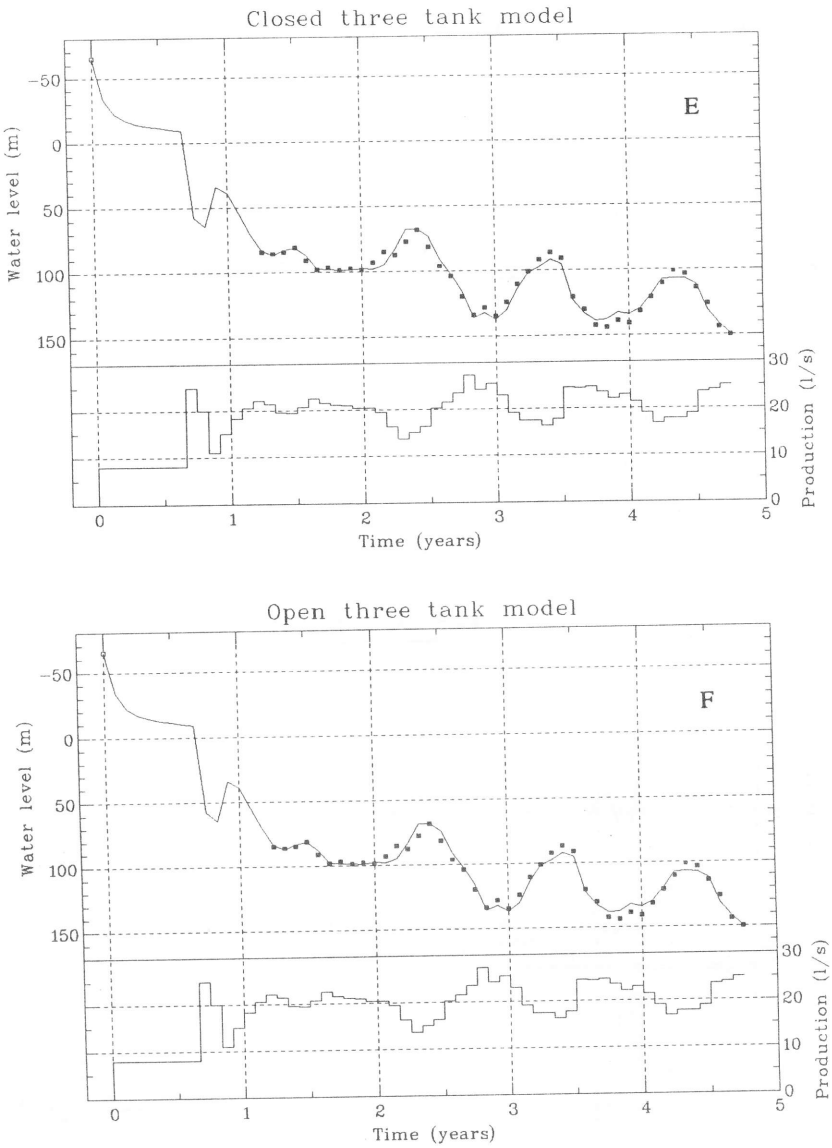

Figure 13. cont.

Step 10 - The MODEL-command: Adjust the model to a two tank closed model. Use the suggested model coefficients.

Step 11 - The INVERSE-command: Iterate 10 times. Write down model coefficients and the statistical parameters.

Step 12 - The DRAW-command: No need to adjust graph settings. Note a very good fit (see Figure 13c). See chapter 2.4 for instructions on how to obtain a hard copy of the figure.

Step 13 - The VIEW-command: Notice the observed and calculated water level values and the residuals (see Figure 7).

Step 14 - The MODEL-command: Although you have now found a simple model that fits the data very well, you may continue to increase the model size to see how much better the fit may get. Therefore, increase the model next to a two tank open model, and use the suggested model coefficients.

Step 15 - The INVERSE-command: Iterate 10 times. Note that this time the iterations result in a non-convergence. In our experience this happens often. The reason is that the initial guess for the model coefficients (actually you used LUMPFIT's suggestions) was not close enough to a stable solution. At this point the model coefficients are all messed up and you have to try to recover the model coefficients you had obtained after step 11. If you have not written them down you can obtain them from the zero iteration line (see Figure 11).

Step 16 - The MODEL-command: Note that the L_2 model coefficient is now negative, which is physically not acceptable. Now decrease the model size back to a two tank closed model and manually set the model coefficients to A_1=5, L_1=0.8, and B=0.05 (close to the best values obtained in step 11).

Step 17 - The INVERSE-command: Iterate 10 times. You should now be back to where you were after step 11.

Step 18 - The MODEL-command: Increase the model size to a two tank open model. You know that in this case you can not trust LUMPFIT's suggested model coefficients and you must guess the values yourself. Here we try to lower L_2 by an order of magnitude (see Figure 8).

Step 19 - The INVERSE-command: Iterate 10 times. Write down model coefficients and the statistical parameters (see Figure 11).

Step 20 - The DRAW-command: No need to adjust graph settings. Note that the fit is not improving significantly (see Figure 13d).

Step 21 - The MODEL-command: Increase the model size to a three tank closed model (use the suggested model coefficients).

Step 22 - The INVERSE-command: Iterate 10 times. Note that 10 iterations are not enough to stabilize the model coefficients.

Step 23 - The INVERSE-command again: Iterate 30 times. The iteration starts where the last iteration ended.

Step 24 - You may try to increase the model size to a three tank open model, but a stable solution is difficult to find.

Step 25 - Repeat steps 18 and 19

Step 26 - The SAVE-command: Save the results of the simpler two tank open model into a file (see Figure 6). You have now completed a simulation.

By analyzing the statistics for the different sized models, which you should have written down (presented here in Table 1), you should be able to select a model by which you can predict the future response of the reservoir. The best choice is the most simple model which gives approximately the best fit attainable. In the example that has been presented here the best choice is the two tank open model (see Table 1.). However, as has been mentioned earlier, a closed lumped model should be used for a cautious prediction, in this case a closed three tank lumped model.

4.2 Future Predictions

Once a simple model for the reservoir has been defined, you are able to predict water level changes for a given future production scheme. The future production time series is appended to the input data file, along with unspecified water level values. For instance adding the lines shown in Figure 14 to the file SAM1.DAT results in the file SAM2.DAT. The prediction is then performed in the following manner where the FORWARD-command is used to calculate the predicted response of the reservoir.

Step 27 - The OPEN-command: Read in the file SAM2.DAT, which is identical to SAM1.DAT except that there are five extra lines at the bottom as shown in Figure 14.

Table 1. Results of simulating the sample data with variable sized models.

Model number	1	2	3	4	5	6
Number of tanks	1	1	2	2	3	3
Model type	Closed	Open	Closed	Open	Closed	Open
A_1		3.657	5.355	5.808	5.901	5.861
L_1		0.433	0.782	0.953	1.041	1.028
A_2				0.124	0.190	0.200
L_2				0.032	0.105	.0737
A_3						.0064
L_3						−.0365*)
B	0.245		0.051		0.0356	
κ_1 (Kappa, ms^2)	1100	73.5	49.7	45.3	43.9	44.3
κ_2			5260	2270	1380	1460
κ_3					6130	16200
σ_1 (Sigma, $10^{-6}ms$)		12.1	14.6	16.1	16.8	16.7
σ_2				27.8	46.1	39.7
σ_3						−238*)
Coeff. of determ. (%)	0.0	63.1	95.1	96.0	96.2	96.2
R.m.s. misfit (m)	54.0	13.2	4.80	4.33	4.23	4.22
Standard deviation (m)	54.7	13.5	4.98	4.55	4.50	4.55

*) A negative value indicates a physically impossible solution

```
 58.  -999.0   15.0
 59.  -999.0   15.0
 65.  -999.0   15.0
 90.  -999.0   15.0
119.  -999.0   15.0
```

Figure 14. The last five lines in the file SAM2.DAT, which were added to a file identical to file SAM1.DAT.

Step 28 - The MODEL-command: Verify that the model size and coefficients are correct (two tank open model).

Step 29 - The VIEW-command: Find the first and last line numbers of the water level data.

Step 30 - The PARAMETERS-command: You need to adjust the second parameter screen (Definition of data parameters), as shown in Figure 9, and you need to adjust the first and last water level data point numbers to 15 and 57.

Step 31 - The FORWARD-command: This operation will calculate the water level response of the model to the production in the file SAM2.DAT.

Step 32 - The DRAW-command: You need to adjust the graph settings, to increase the length of the time axis to 10 years. Figure 15a shows the result. Similarly by using the closed three tank model the prediction results in the response of figure 15b.

Step 33 - The QUIT-command: You have now made the future prediction for a constant production of 15 l/s. By varying the production in the input data file you can compare the effects of different production scenarios.

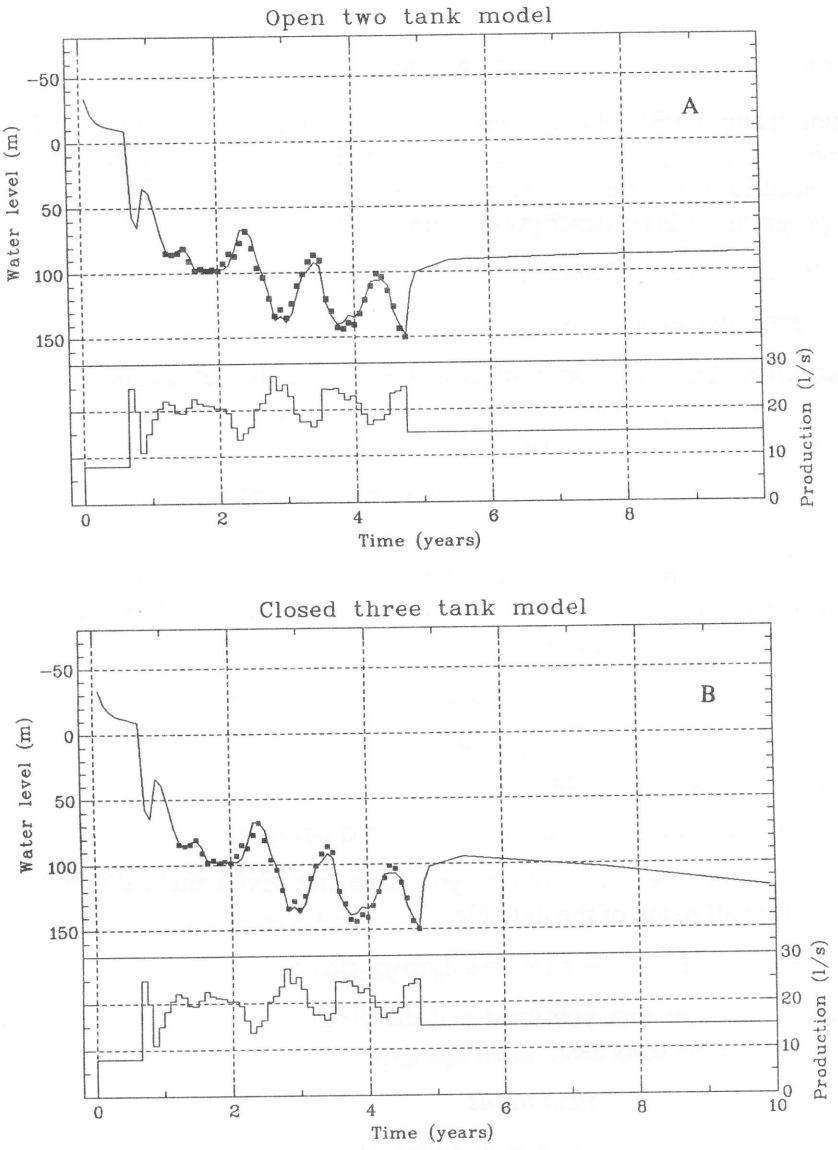

Figure 15. The predicted response to a 15 l/s future production. The predictions of two models are shown.

5. ERROR AND WARNING MESSAGES

When using LUMPFIT the user must set many parameters, and some combinations of parameter settings will lead to a run-time error and the user will need to restart the program. However, there are several error checks in the program. A brief description of these follows:

5.1 When opening a Data File.

```
ERROR: Reading error at line XXX
```

Unspecified type of error in reading a specified line of the input data file. Possibly a character (usually a typo) where the program expects a number. You need to exit the program and fix the file.

```
WARNING: Very short time step encountered
```

The input data file has at least one abnormally short time step. This may indicate a potential error and the data file should be checked. However, in some cases this may be done on purpose by the user, but may lead to unstability in the calculations.

```
ERROR: Inverted time in input data file
```

The time value in the input data file is not increasing monotonically. This is an error and the data file must be corrected.

```
ERROR: That file could not be opened
```

The file name does not exist or you have not given the path to the file. Check the full name of the data file.

```
ERROR: Please fix the input data file
```

General reminder that you must exit the program and fix some unspecified error in the input data file.

5.2 During Forward Calculations.

```
WARNING: parameters or model coefficients out
of range   Please use different values
```

This means that the current model coefficients or some user defined parameters result in a violent behavior of the calculated pressure and that the calculations are heading for an overflow. You have to reset the model coefficients manually.

5.3 When Inverting for Better Model Coefficients.

```
WARNING: Bad choice of parameters or model
coefficients   Please try different values

WARNING: Matrix inversion problem X
Please try a different initial guess for the
model coefficients

WARNING: Parameters or model coefficients out
of range   Please try different values
```

These three warnings come as results of non-convergence, because the initial guess of the model coefficients are not close enough to a stable solution. You need to manually adjust the model coefficients and you should inspect the parameter settings. It is also advisable to decrease the size of the model before continuing.

5.4 When Drawing a Graph.

```
ERROR: Unable to locate the file LUMPFIT.FON
```

In order to be able to draw a graph you must have this file in your working directory or be able to type its path.

```
ERROR: Unable to set graphics mode
```

This may happen on lower-end PC's. See Chapter 2.3 on how to set a graphics mode for the monitor.

5.5 When Saving Results to a File.

```
ERROR in opening output file
Please try a different output file name
```

This error may indicate that the output file name does already exist and you should use a different name.

Other run time errors will usually result in a program crash. You should write down the error message, and try to repeat the run leading to the crash, write down the parameter settings and find the most sensitive parameters. If no logical reason can be found for a crash, please send the input data file, parameter settings, and description of how the error resulted to the authors of this guide.

6. REFERENCES

Axelsson, G., 1985, Hydrology and thermomechanics of liquid-dominated hydrothermal systems in Iceland, Ph.D. Thesis, Oregon State University, Corvallis, Oregon, 291 pp.

Axelsson, G., 1989, Simulation of pressure response data from geothermal reservoirs by lumped parameter models, Fourteenth Workshop on Geothermal Reservoir Engineering, Jan. 1989, Stanford University, 257-263.