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Reliability of Lumped Parameter Modeling of Pressure Changes in Geothermal Reservoirs

Gudni Axelsson[1)], Grímur Björnsson[1)] and Julio E. Quijano[2)]

1) ISOR, Iceland GeoSurvey, Grensasvegur 9, IS-108 Reykjavik, Iceland
2) LaGeo, km 11 ½ Carr. Puerto La Libertad, Apto Postal No. 2669, Santa Tecla, La Libertad, El Salvador

E-mail addresses: gax@isor.is, grb@isor.is, jquijano@lageo.com.sv

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ABSTRACT

Lumped parameter models have been used extensively to simulate data on pressure changes in geothermal systems in Iceland as well as in the P.R. of China, Central America, Eastern Europe, The Philippines, Turkey and other countries. Lumped models can simulate such data very accurately, if the data-quality is sufficient. The properties of the lumped models provide information on the corresponding properties of the geothermal system in question. Yet the principal purpose of such modeling is, of course, to estimate the production potential of geothermal systems through pressure response predictions and to estimate the effects of different management options. Because of how simple the lumped parameter models are, their reliability is sometimes doubted. Experience has shown that they are quite reliable, however, as examples presented demonstrate. The examples involve comparing pressure responses of geothermal systems, calculated by lumped parameter models, developed some years ago on basis of production histories available at the time, with the pressure responses observed since then. In addition, examples are presented of predictions for the same geothermal systems, calculated by open and closed lumped models, which demonstrate the precision, or sensitivity, of lumped modeling. Future pressure changes are expected to lie somewhere between the predictions of open and closed models and it is argued that the differences between these predictions do not demonstrate the unreliability of lumped parameter modeling, but simply the inherent uncertainty in all such predictions.

1. INTRODUCTION

Modeling plays an essential role in geothermal resource management and numerous examples are available on its successful application (Axelsson and Gunnlaugsson, 2000; O'Sullivan *et al.*, 2001). This ranges from simple analytical modeling of results of short well tests to detailed numerical modeling of complex geothermal systems, simulating an intricate pattern of changes resulting from long-term production. The purpose of geothermal modeling is, firstly, to obtain information on the physical conditions in a geothermal system as well as on its nature and properties. This leads to proper understanding of its characteristics and successful management of the resource. Secondly, the purpose of modeling is to predict the response of a reservoir to future production and estimate the production potential of a system, as well as to estimate the outcome of different management actions.

Various modeling approaches are currently in use by geothermal reservoir scientists, which in essence all involve a mathematical model being developed that simulates some, or most, of the data available on the geothermal system involved. These can be simple analytical models, lumped parameter models or detailed numerical models. A reliable model will provide information on the conditions in, and the properties of the actual geothermal system. But it must be kept in mind that this information is not unique, but model-dependent. Consequently the model is used to predict the future changes in the reservoir involved and estimate its production potential.

In simple models, the real structure and spatially variable properties of a geothermal system are greatly simplified, such that analytical mathematical equations, describing the response of the model to energy production may be derived. These models, in fact, often only simulate one aspect of a geothermal system's response. Detailed and complex numerical models, on the other hand, can accurately simulate most aspects of a geothermal systems structure, conditions and response to production. Simple modeling takes relatively little time and only requires limited data on a geothermal system and its response, whereas numerical modeling takes a long time and requires powerful computers as well as comprehensive and detailed data on the system in question.

Numerical modeling, which is increasingly being used to simulate geothermal systems in different parts of the world, is extremely powerful when based on comprehensive and detailed data. For a thorough review the reader is referred to O'Sullivan et al. (2001). Without good data, however, detailed numerical modeling can only be considered speculative, at best.

Simple modeling has also been used extensively to study and manage geothermal resources worldwide. Lumped parameter modeling of pressure change data constitutes an efficient method of simple modeling. It has for example been the principal modeling tool applied to low-temperature geothermal systems utilized in Iceland, in particular to model their long-term response to production (Axelsson and Gunnlaugsson, 2000). The method used tackles the simulation as an inverse problem and automatically fits the response functions of the lumped models to observed data. Lumped models can simulate pressure change data very accurately, even very long data sets (several decades). Today, lumped models have also been developed by this method for a few high-temperature geothermal systems in Iceland, as well as geothermal systems in the P.R. of China, Turkey, Eastern Europe, Central America and The Philippines, as examples.

In principle, it may be stated that the complexity of a model should be determined by the purpose of a study as well as the data available. In fact, simple modeling, such as lumped parameter modeling, is often a cost-effective and timesaving alternative. It may be applied in situations when available data are limited, when funds are restricted or as parts of more comprehensive studies, such as to validate results of numerical modeling studies.

Because of how simple the lumped parameter models are, their reliability is sometimes questioned. The purpose of this paper is to discuss this issue. At first the basics of lumped parameter modeling are reviewed and some examples presented. Consequently, the reliability of lumped parameter modeling is evaluated through a few examples that involve comparing pressure responses of geothermal systems, calculated by lumped parameter models developed some years ago on basis of production histories available at the time, with the pressure responses observed since then. In addition the possibility of using lumped parameter models to assess the inherent uncertainty in pressure predictions is presented.

2. LUMPED PARAMETER MODELING

The background of lumped parameter modeling, according to a technique presented by Axelsson (1989), is described in this chapter. Some field examples are also presented along with the specific approach to employing this modeling technique, which has evolved in Iceland during the last decade.

Several examples of lumped modeling of geothermal resources that don't employ this specific technique can be found in the literature (Grant *et al.*, 1982; Bodvarsson *et al.*, 1986). The works of Kjaran *et al.* (1979), Fradkin *et al.* (1981), Westwood and Castanier (1981), Gudmundsson and Olsen (1987) and Zimmerman *et al.* (1995) can also be named as examples. Recently Sarak *et al.* (2003a and b) presented a revision of the method discussed here and applied it to some of the same data, with comparable results.

2.1 Model description

Axelsson (1989) has described an efficient method that tackles pressure change simulation with lumped parameter models as an inverse problem and can simulate such data very accurately, if the data quality is sufficient, even very long data sets (several decades). It automatically fits the analytical response functions of the lumped models to observed data by using a non-linear iterative least-squares technique for estimating the model parameters.

The theoretical basis of this automatic method of lumped parameter modeling is presented by Axelsson (1985 and 1989), and in fact Bodvarsson (1966) discussed the usefulness of lumped methods of interpreting geophysical exploration data. The computer code *LUMPFIT* has been used since 1986 in the lumped modeling studies carried out in Iceland (Axelsson and Arason, 1992).

A general lumped model is shown in Fig. 1. It consists of a few tanks and flow resistors. The tanks simulate the storage capacity of different parts of a geothermal system and the water level or pressure in the tanks simulates the water level or pressure in corresponding parts of the system. A tank has a storage coefficient (capacitance) κ when it responds to a load of liquid mass m with a pressure increase $p = m/\kappa$. The resistors (conductors) simulate the flow resistance in the reservoir, controlled by the permeability of its rocks. The mass conductance (inverse of resistance) of a resistor is σ when it transfers $q = \sigma \Delta p$ units of liquid mass, per unit time, at the impressed pressure differential Δp.

The first tank in the model in Fig. 1 can be looked upon as simulating the innermost (production) part of the geothermal reservoir, and the second and third tanks simulate the outer parts of the system. The third tank is connected by a resistor to a constant pressure source, which supplies recharge to the geothermal system. The model in Fig. 1 is, therefore, open. Without the connection to the constant pressure source the model would be closed. An open model may be considered optimistic, since equilibrium between production and recharge is eventually reached during long-term production, causing the water level draw-down to stabilize. In contrast, a closed model may be considered pessimistic, since no recharge is allowed for such a model and the water level declines steadily with time, during long-term production. In addition, the model presented in Fig. 1 is composed of three tanks; in many instances models with only two tanks have been used.

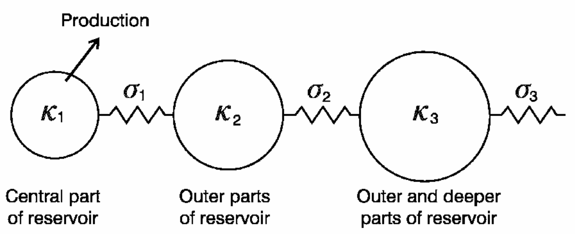

Figure 1: A general lumped parameter model used to simulate water level or pressure changes in geothermal systems.

Axelsson (1989) presents the system of basic equations describing the behavior of a general lumped parameter model in matrix form as well as a general solution for the pressure response to variable production. The iterative non-linear inversion technique employed by *LUMPFIT* to fit a corresponding solution to observed pressure- or water level data is, furthermore, presented by Axelsson (1989).

Hot water is pumped out of the first tank, which causes the pressure and water level in the model to decline. This in turn simulates the decline of pressure and water level in the real geothermal system. When using this method of lumped parameter modeling, the data fitted (simulated) are the pressure or water level data for an observation well inside the well-field, while the input for the model is the production history of the geothermal field in question.

2.2 Examples

Lumped parameter models have been used extensively, via the method described above (employing *LUMPFIT*), during the last two decades, to simulate data on pressure (water level) changes in geothermal systems in Iceland as well as for several geothermal systems in China, The Philippines, Turkey, Eastern Europe and Central America, as already mentioned. A list of some of these systems is presented in Table 1. This list should not be looked upon as complete, but rather as indicative of the extent to which this technique has been employed. The table only includes studies known to the author at the time of writing.

Figures 2 – 4 show representative examples of long and detailed water level and pressure histories simulated by this lumped parameter modeling technique. Fig. 2 shows the simulated water level history of the Ytri-Tjarnir low-temperature field in central N-Iceland from 1980 up to 1999 (Axelsson *et al.*, 1999). Utilization of the field started in 1978. Ytri-Tjarnir is a typical low-temperature system located in an older and less permeable segment of the basaltic crust of Iceland. The reservoir temperature at Ytri-Tjarnir is about 80°C and in recent years the average yearly production from the field has amounted to about 31 kg/s through one production well.

Fig. 3 shows the simulated water level history of the Urban geothermal system under Beijing, the capital of the P.R. of China, for the period 1979-2002 (Liu *et al.*, 2002; Axelsson *et al.*, 2005). Utilization of this system started in the 1970s'. It is associated with the vast geothermal resources found in the deep sedimentary basin under the city. About 70 geothermal wells have presently been drilled into the Urban system, which is mostly composed of limestone and dolomite with a reservoir temperature of up to 90°C. In recent years the average yearly production from the Urban field has been of the order of 110 kg/s.

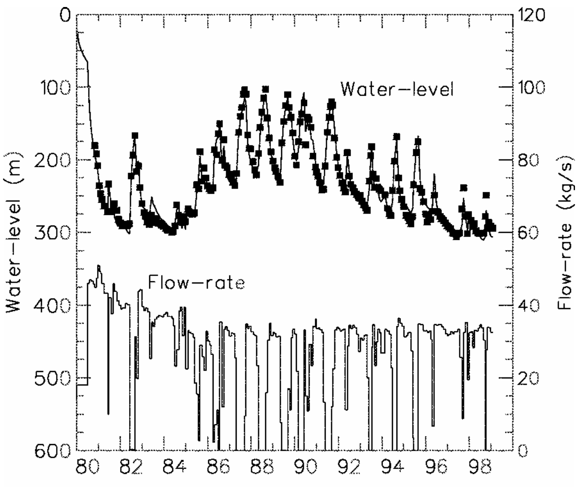

Figure 2: Production and water level history of the Ytri-Tjarnir low-temperature geothermal system in central N-Iceland 1980-1999. The water level history has been simulated by a lumped parameter model (squares = observed data, line = simulated data).

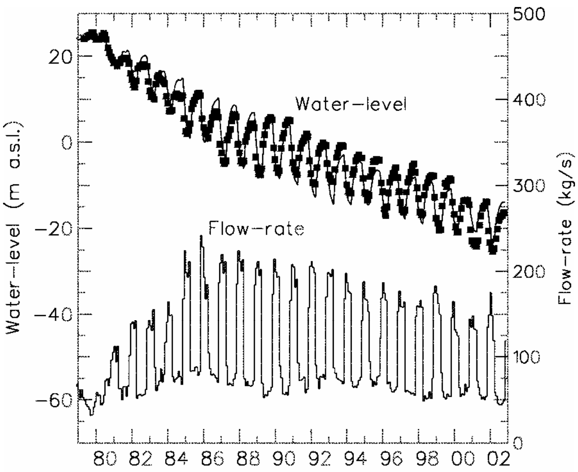

Figure 3: Production and water level history of the Urban sedimentary geothermal system in Beijing 1979-2002. The water level history has been simulated by a lumped parameter model (squares = observed data, line = simulated data; from Axelsson *et al.*, 2005).

The final example is presented in Fig. 4, which shows the simulated pressure decline history of the Ahuachapan high-temperature geothermal system in El Salvador from 1975 through 2001 (Quijano, 1994; Montalvo *et al.*, 1997). The fields' utilization started in the late 1960s'. About 35 wells have been drilled into the Ahuachapan system, which is composed of andesitic and other volcanic rocks with a reservoir temperature of the order of 250°C. In recent years the average yearly mass extraction at Ahuachapan has amounted to about 450-500 kg/s and electricity production been of the order of 50-60 MW_e.

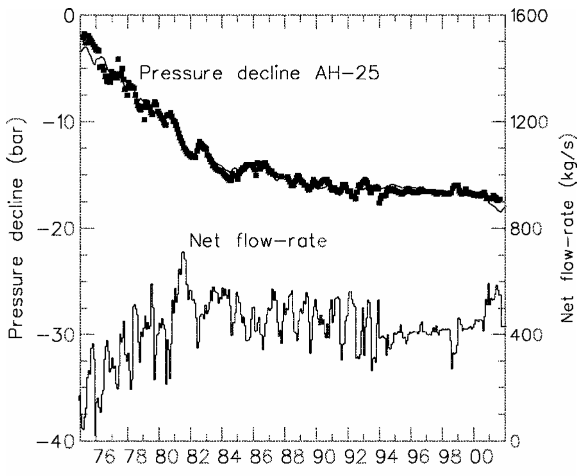

Figure 4: Production and pressure decline history of the Ahuachapan high-temperature geothermal field in El Salvador 1975-2001. The pressure history has been simulated by a lumped parameter model (squares = observed data, line = simulated data) based on the net production (mass extraction – infield reinjection).

These figures all show a very good agreement between the observed and simulated data, in spite of long data sets. This reflects the efficiency and flexibility of the method of lumped parameter modeling reviewed here. The reason for this is the diffusive nature of the pressure response of geothermal systems. Comparable results have been obtained for most other geothermal fields, simulated by this method (see also Axelsson, 1989; Axelsson and Gunnlaugsson, 2000). Of the three simulations presented the one for the Urban field in Beijing appears to be the least satisfactory, even though it is quite good. The reason is, most likely, the fact that production is distributed over several tens of production well, with considerable spatial and temporal variations in the production pattern. In contrast, production at Ytri-Tjarnir, where the best fit has been achieved, is just from one well, which is better suited for lumped parameter modeling.

It should also be mentioned that isothermal and single phase conditions are assumed in the theoretical basis of the method reviewed here (Axelsson, 1989). This is not fully valid in high-temperature situations, such as for the Ahuachapan system. Significant changes in two-phase conditions, such as growing two-phase zones, as well as temperature transients, will reduce the reliability of predictions calculated by lumped parameter models. In addition, lumped modeling is normally based on the net mass extraction when reinjection is applied. This may be inaccurate in fields where reinjection is partially, or fully, far-away from the main production area.

2.3 Methodology

The methodology, or specific approach, applied during lumped parameter modeling in Iceland, which has evolved during the last two decades, may be summarized as follows:

(1) The modeling is usually based on the whole production history of a geothermal system. The production is estimated during periods when data are scarce (such as at the beginning of the history). If reinjection is applied the net production is used.

Subsequently, *LUMPFIT* is used to simulate the available pressure (or water level) decline history, preferably from a centrally located observation well. If only data from active production wells are available these are corrected for turbulence pressure losses and skin effect. The input data are finally digitized with a time interval of days, weeks or months (not necessarily constant), such that the time series contains from a few tens to a few hundred data points.

(2) One usually starts out with the most simple one-tank model. Following that the model is made more complex in steps, i.e. two-tank closed and/or open followed by a three-tank model, if that turns out to be possible. In general the complexity of the lumped parameter model used is determined by the length of the data set available and the data quality. The aim is to end up with two models, one open and the other closed, that simulate the data well.

(3) The properties of the lumped models provide information on the corresponding properties of the geothermal system in question. The storage coefficients of the tanks (κ) provide information on the size of the geothermal system and on the controlling storage mechanism while the conductance (σ) of the resistors provide information on reservoir permeability. The model properties provide, furthermore, information on the boundary conditions in effect. Axelsson (1989) provides more information on this while some examples of reservoir properties inferred on the basis of lumped model properties can be found in Axelsson *et al.* (2005).

(4) The principal purpose of lumped parameter modeling is, of course, to estimate the production potential of geothermal systems through pressure response predictions and to estimate the effects of different management options. Predictions are, therefore, calculated by both an open and a closed lumped model, which constitute an optimistic and a pessimistic prediction, respectively. Future pressure changes are, in fact, expected to lie somewhere between the predictions of open and closed models. The divergence in the predictions actually demonstrates the precision, or sensitivity, of the particular lumped parameter predictions. This will be demonstrated with later examples.

3. RELIABILITY OF LUMPED MODELING

Because of how simple lumped parameter models are, their reliability is sometimes doubted. In addition, the accuracy, or precision, of predictions calculated by lumped models has been questioned. Experience has shown that lumped parameter models are quite reliable, however. It can also be stated that their predictions are just as accurate as predictions of other reservoir models, which are based on the same data, simulating it equally well.

To demonstrate this and discuss further the examples in figures 6 – 11 are presented. They concern lumped parameter modeling of pressure response data from three low-temperature systems in Iceland. These examples have not been specifically selected for the purpose of this paper, but involve typical modeling case histories based on long and detailed data sets. Such comprehensive case histories abound for low-temperature systems in Iceland. Firstly, these examples involve comparing the pressure response histories of the corresponding geothermal systems, calculated by lumped parameter models, developed some years ago on basis of production histories available at the time, with the pressure responses observed since then. Secondly, the examples selected include pressure response predictions calculated by open and closed lumped parameter models with the divergence between the open and closed predictions demonstrating the precision, or accuracy, of lumped parameter model predictions.

The low-temperature geothermal systems selected are: Hamar in Central N-Iceland, Hofstadir in W-Iceland and Gata in Central S-Iceland (see Fig. 5). The Hamar system is discussed by Axelsson *et al.* (2005a). It is embedded in a region of the basaltic lava-pile of N-Iceland, which is relatively permeable because of recent tectonic activity, and has a reservoir temperature of about 65°C. The Hamar system has been utilized for space heating in the near-by town of Dalvik since 1969. In recent years the average yearly production from the field has been about 30 kg/s through one main production well. The Hofstadir system, which is discussed by Axelsson *et al.* (2005b), is located in the basaltic bedrock of the Snaefellsnes peninsula of W-Iceland. It has a reservoir temperature of 85-90°C, but appears to be unusually small in volume and have abnormally closed boundaries, if compared with other low-temperature systems in Iceland. This is attributed to an unusual tectonic setting. The Hofstadir system has been utilized since late 1999 at an average yearly rate of about 19 kg/s through a single production well. The Gata (or Laugaland) system has been discussed briefly by Axelsson *et al.* (1995) and Zhang (2003). It is located a few km south of the highly active S-Iceland seismic zone, yet the permeability of the Gata system is unusually low. It has a reservoir temperature of 100-105°C and has been utilized since the end of 1982, at an average yearly rate of 10 – 22 kg/s, through one main production well.

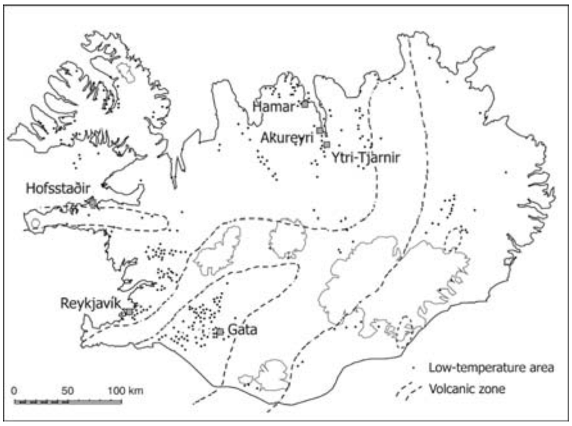

Figure 5: Locations of the low-temperature geothermal areas in Iceland, presented as examples here, relative to the distribution of other low-temperature areas and the volcanic zone.

Fig. 6 shows two decades of the water level history of the Hamar geothermal system simulated by a lumped parameter model developed in early 1993 (Axelsson and Sverrisdottir, 1993). The observed data are presented by boxes while the simulated water level is depicted by solid lines. The simulation is based on water level data from 1982 up to 1993 (filled boxes in the figure) and production data until the end of 2001. The simulation is calculated by an open and closed version of the model. This way it is possible to compare the measured water level changes since 1993 (open boxes in the figure) with the changes calculated by the 1993 model and thus assess the reliability of that model. This will be discussed later.

Fig. 7 shows water level changes in the Hamar geothermal system for a 200-year production history predicted by a lumped parameter model based on data up to 2001 (Axelsson *et al.*, 2005). The model used is a revision of the 1993 model used in Fig. 6. The figure shows optimistic predictions by an open version of the model as well as pessimistic predictions by a closed version of the model. Thus the divergence/uncertainty inherent in such predictions can be assessed.

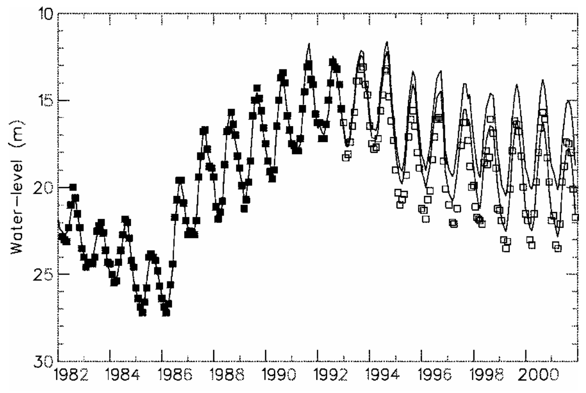

Figure 6: Water level history of the Hamar geothermal system, from 1982 through 2001, simulated by a lumped parameter model developed in early 1993. Observed data are shown as boxes (filled before 1993 and open after that) while simulated water level is depicted by solid lines. The simulation is based on water level data from 1982 up to 1993 and production data until the end of 2001. The upper curve is calculated by an open version of the model while the lower one is calculated by a closed version.

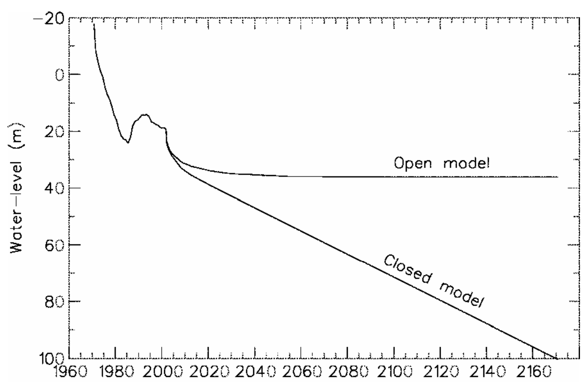

Figure 7: Predicted water level changes in the Hamar geothermal system for a 200-year production history calculated by a lumped parameter model based on data up to 2001 (revision of the model of Fig. 6). Predictions by an open (optimistic) and a closed (pessimistic) version of the model, for a 40 kg/s constant production, are presented.

Fig. 8 shows the water level history of the Hofstadir geothermal system, from late 1999 up to early 2002, simulated by a lumped parameter model developed in 1997 (Bjornsson *et al.*, 1997). That model was developed on the basis of data from a 5-month production test conducted earlier that same year. The simulation is based on water level data collected during the 1997 test (these data may be seen in the upper left hand corner of Fig. 9) and production data up to early 2002. The simulation is again calculated by open and closed versions of the lumped model. Fig. 8 makes it possible to compare the measured water level data (open boxes for the period from May 2000 through January 2002) with changes calculated by the 1997 model just as in the case of Fig. 6.

Fig. 9 shows predicted water level changes in the Hofsstadir geothermal system for a 10-year prediction period calculated by a lumped parameter model based on data up to 2002. The model used is a revision of the model used in Fig. 8). The figure shows predictions by an open and a closed version of the model, for a yearly production pattern replicating the pattern in 2001. Fig. 9 demonstrates the prediction uncertainty just as Fig. 7 did in the case of Hamar.

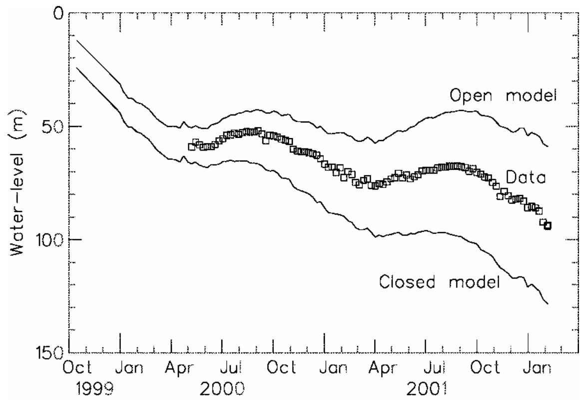

Figure 8: Water level history of the Hofstadir geothermal system, from late 1999 up to early 2002, simulated by a lumped parameter model developed in 1997 on the basis of data from a 5-month production test conducted that same year. The simulation is based on water level data collected during the 1997 test and production data up to early 2002. The simulated data are calculated by open and closed versions of the lumped model.

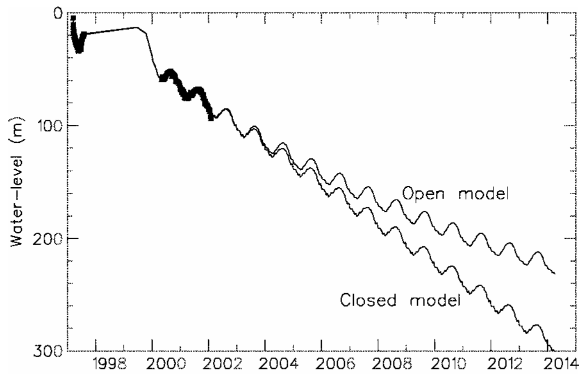

Figure 9: Predicted water level changes in the Hofsstadir geothermal system for a 10-year prediction period calculated by a lumped parameter model based on data up to 2002 (revision of the model of Fig. 8). Predictions by an open (optimistic) and a closed (pessimistic) version of the model, for a yearly production pattern as in 2001, are presented.

Fig 10 shows two decades of the water level history of the Gata geothermal system simulated by a lumped parameter model developed in early 1993 (Bjornsson *et al.*, 1993). The observed data are shown as boxes while the simulated water level is represented by solid lines. The simulation is based on water level data from 1983 up to 1993 (filled boxes in the figure) and production data up to the end of 2003. The simulation is calculated by an open and closed version of the model. Again Fig. 10 makes a comparison between observed and simulated data possible, as in the cases of figures 6 and 8.

Finally Fig. 11 shows predicted water level changes in the Gata geothermal system for a 13-year prediction period calculated by a lumped parameter model based on data up to the middle of 2000. The model is a revision of the model used in Fig. 10. The figure again shows predictions by an open and a closed version of the model, for a yearly production pattern with production ranging from 10 to 18 kg/s. It once more demonstrates prediction uncertainty just as figures 7 and 9.

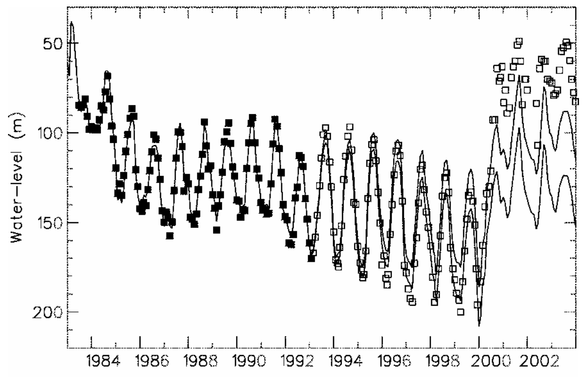

Figure 10: Water level history of the Gata geothermal system, from 1983 through 2003, simulated by a lumped parameter model developed in early 1993. Observed data are shown as boxes (filled before 1993 and open after that) while simulated water level is depicted by solid lines. The simulation is based on water level data from 1983 up to 1993 and production data until the end of 2003. The upper curve is calculated by an open version of the model while the lower one is calculated by a closed version.

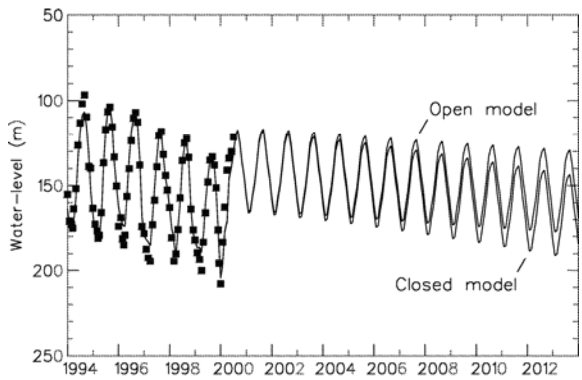

Figure 11: Predicted water level changes in the Gata geothermal system for a 13-year prediction period calculated by a lumped parameter model based on data up to the middle of 2000 (filled boxes, revision of the model of Fig. 10). Predictions by an open (optimistic) and a closed (pessimistic) version of the model, for a yearly production pattern with production ranging from 10 to 18 kg/s, are presented.

It should be noted that after June 2000 the fit between observed water level changes at Gata and those simulated by the 1993 model changes drastically. The observed water level is, in fact, 40 – 80 m higher than the simulated level. This is believed to be the result of drastic changes in reservoir conditions following a major earthquake in the region on June 17th 2000 (Jonsson *et al.*, 2003), not a model malfunction. Available data seem to indicate that reservoir permeability at Gata, as well as fluid recharge, may have increase considerably in conjunction with the earthquake (Axelsson and Hardardottir, 2004).

After studying figures 6 – 11 the following may be concluded:

(1) Figures 6 and 10 clearly demonstrate that lumped parameter simulations are quite reliable when based on long data sets (about one decade in these examples. The discrepancy between observed and simulated water level changes is slightly more in the case of Hamar, yet only a few % at the end of the simulation period.

(2) Figure 8, on the other hand, demonstrates that lumped models are less reliable when based on shorter data sets (5 months in the case of Hofstadir). This is not unexpected and simply applies to all such reservoir engineering predictions. Interestingly, the data in Fig. 8 falls right in-between the simulations by the open and closed versions of the Hofstadir 1997 model.

(3) The Gata case shows, however, that simulating internal changes in reservoir conditions is beyond the capacity of lumped parameter models. Such non-linear behavior is also beyond the powers of other conventional modeling methods.

(4) Future pressure or water level changes in geothermal systems are expected to lie somewhere between the predictions of open and closed versions of lumped parameter models. This is because these represent extreme kinds of boundary conditions. Therefore, the differences between these predictions do not demonstrate an inherent unreliability of lumped parameter modeling but simply the inherent uncertainty in all such predictions.

(5) The figures above demonstrate that the shorter the data period a simulation is based on is the more uncertain the predictions are. This can be seen by comparing figures 8, 9 and 11, for example.

(5) The figures also demonstrate that the uncertainty in the predictions increases with increasing length of the prediction period considered. Fig. 7, which presents an unusually long prediction period (170 years) clearly shows this.

4. CONCLUSIONS

An efficient method of lumped parameter modeling of pressure changes in geothermal systems presented by Axelsson (1989) is revisited in this paper. Numerous examples of its successful use in Iceland and other parts of the world are available, some of which have been presented above. The methodology for lumped parameter modeling, which has evolved in Iceland during the last two decades, is also reviewed. A key ingredient is to calculate future predictions by both open and closed versions of a specific model, which demonstrates the precision of the particular prediction. In addition the properties of the lumped models provide information on the corresponding properties of the geothermal system in question.

Because of how simple the lumped parameter models are, their reliability is sometimes questioned. Experience has shown that they are quite reliable, however, and a few examples presented involving repeated simulations, demonstrate this clearly. This applies, in particular, to simulations based on long data sets, which is in agreement with the general fact that the most important data on a geothermal reservoir are obtained through careful monitoring during long-term exploitation. Lumped parameter modeling is less reliable when based on shorter data sets, which is valid for all such reservoir engineering predictions.

Future pressure changes in geothermal systems are expected to lie somewhere between the predictions of open and closed versions of lumped parameter models, which represent extreme kinds of boundary conditions. The differences between these predictions simply reveal the inherent uncertainty in all such predictions. The examples presented above demonstrate that the shorter the data period a simulation is based on is the more uncertain the predictions are. They also demonstrate that the uncertainty in the predictions increases with increasing length of the prediction period.

Finally, it should be reiterated that even though lumped parameter models have been set up for high-temperature systems they are strictly developed for isothermal, single phase conditions. In addition, simulating internal changes in reservoir conditions and properties is beyond the capacity of lumped parameter models.

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Table 1. A list of geothermal systems in Iceland and in other parts of the world that have been simulated by the method of lumped parameter modeling presented in this paper via the simulation software *LUMPFIT*. Note that this list is not complete, it includes only studies known to the author at the present.

Country	Geothermal system	Reservoir Temperature (°C)	Year	Comments
Iceland	Gata	100-105	1987	Updated regularly
	Kaldárholt	65	2003, 2004	
	Ósabotnar	80-90	2001	
	Nesjavellir	280-340	2003	
	Svartsengi	240	1985	
	Laugarnes	125-130	1986	
	Ellidaardalur	85-95	1990	
	Mosfellssveit	70-95	1990, 1993	
	Hofstadir	85-90	1997, 2002	
	Reykjadalur	80-90	1994	
	Reykir	70	1992	
	Saudárkrókur	70	1992	
	Siglufjördur	75	1991	Updated regularly
	Laugarengi	65	1991	
	Hamar	65	1988	Updated regularly
	Hjalteyri	85-90	2003	
	Thelamörk	90-95	1993, 2002	Updated regularly
	Glerárdalur	60	1988	Updated regularly
	Botn	80-85	1988	Updated regularly
	Laugaland	95	1988	Updated regularly
	Ytrri-Tjarnir	80	1988	Updated regularly
	Krafla	210-340	1995	
	Eskifjördur	80	2003, 2004	
P.R. of China	Tanggu (Tianjin)	65-80	1996	
	Wuqing (Tianjin)	75-85	1998	
	Zhouliangzhuang (Tianjin)	60-100	2003	
	Shahe (Beijing)	80	2001, 2002	
	Urban (Beijing)	40-90	2002, 2004	
	Xian	40-105	2002	
	Qichun (Shanxi Province)	40-90	2003	
The Philippines	Bacon-Manito	~250	2000	
Turkey	Kizildere	190-210	1997	
Romania	Beius	75-85	2000	
Slovakia	Galanta	80	1995, 2000	
El Salvador	Ahuachapan	220-240	1994, 2001	Updated regularly
	Berlin	270-305	1999, 2001	
Costa Rica	Miravalles	220-250	1996	