Research Technical Completion Report

ANALYSIS OF HISTORICAL AND CURRENT DRAWDOWN AND PRODUCTION DATA FROM THE BOISE GEOTHERMAL SYSTEM

by

C.J. Waag
S.H. Wood

Department of Geology/Geophysics
Boise State University

Idaho Water Resources Research Institute
University of Idaho
Moscow, Idaho 83843

August, 1987

Research Technical Completion Report

ANALYSIS OF HISTORICAL AND CURRENT DRAWDOWN AND PRODUCTION DATA FROM THE BOISE GEOTHERMAL SYSTEM

by

C.J. Waag
S.H. Wood

Department of Geology/Geophysics
Boise State University

Idaho Water Resources Research Institute
University of Idaho
Moscow, Idaho 83843

August, 1987

The research on which this report is based was financed in part by the United States Department of the Interior as authorized by the Water Research and Development Act of 1978 (P.L. 95-467).

Contents of this publication do not necessarily reflect the views and policies of the United States Department of the Interior nor does mention of trade names or commercial products constitute their endorsement by the U.S. Government.

Research Technical Completion Report

14-08-0001-G1222-02

ANALYSIS OF HISTORICAL AND CURRENT DRAWDOWN AND PRODUCTION DATA FROM THE BOISE GEOTHERMAL SYSTEM

by

C.J. Waag
Professor

S.H. Wood
Associate Professor

Department of Geology/Geophysics
Boise State University

Submitted to:
U.S. Geological Survey
United States Department of the Interior
Washington, D.C. 20242

Idaho Water Resources Research Institute
University of Idaho
Moscow, Idaho 83843

August, 1987

ACKNOWLEDGEMENTS

We wish to thank Mr. Robert Griffiths, Boise Warm Springs District Water Engineer; Mr. Robin Finch, Senior Environmental Specialist, City of Boise; and John Carlson, Idaho Department of Water Resources for supplying data on their operations.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Since 1982 withdrawals from the Boise Geothermal aquifer system have increased from less than 300 million to over 600 million gals/yr. Prior to 1983 the system appears to have been in or near equilibrium. Current production levels exceed the ability of the system to recover on an annual basis. Potentiometric levels within the aquifer are declining at increasing rates and a new equilibrium level is not evident.

INTRODUCTION

Warm geothermal water produced from three well fields (Fig. 1) is currently used to heat about 2,000,000 square feet of office building and residential housing in downtown Boise. The Boise Warm Springs Water District (BSWSD) no. 1 and 2 wells have been in use since 1892 and have typically produced between 235 and 300 million gallons/year of approximately 165°F water for space heating and domestic use. The State of Idaho Capitol Mall no. 2 well has produced water at an average rate of about 196 million gallons/year and temperature of 157°F since the winter of 1982. The Boise Geothermal, Ltd. wells have withdrawn 166.7, 121.4, and 176.8 million gallons of 165°F water annually in the three years since October 1983. Demand for the hot water generally increases from the beginning of the heating season in September to a peak in January, then begins to decline again through May. In response to this demand, water levels within the artesian aquifer system currently decline from their peak recovery in September to their lowest levels in late February and early March when the recovery portion of the cycle begins. Approximately 30 days lag time exists between the peak in the production cycle and the greatest drawdown created by the production. Of the three major producers from the system, only Capitol Mall (CM) reinjects its geothermal water. After heating use, Boise Geothermal Limited regathers its effluent into a single pipeline and discharges it into the Boise River. BWSWD waters are discharged into canals or into the sewage system by the individual domestic users.

Expansion of demand on the aquifer system began in 1982-83 when production increased from between 250 and 300 million gallons/year by the Boise Warm Springs Water District (BWSWD) to over 600 million gallons/year, that expansion currently continues. The Veterans Administration production and reinjection well system is projected to go on line in the winter of 1987, and the City of Boise will increase its production in 1988 to provide geothermal water to Boise State University.

Owing to the success of recent efforts to complete large capacity wells within the geothermal aquifer and in marketing the resource it was recognized that demands on the system may have increased beyond the capacity of the natural system to recharge or repressurize the aquifer. Evidence of declining water levels and delays in the recovery peaks have focused attention on a need for base-line data to determine the aquifer system's response to present and future withdrawals. Concern for prudent development of this important natural resource has led to efforts to monitor water production and water pressure in available wells. This study sponsored by Idaho Water Resources Institute is an ensuing effort at base-line data collection and interpretation. Our initiation of systematic data collection began in 1984 under a grant from the Institute and continued throughout 1985 under a grant form the State of Idaho Department of Water Resources.

GEOLOGIC FRAMEWORK OF THE BOISE GEOTHERMAL AQUIFER
AND
THE OVERLYING COLD WATER SYSTEMS

All wells producing water in excess of 150°F are completed in layered rhyolite at depths ranging from 450 to 3,000 feet (Figs. 1, 2). The rhyolite and minor intercalated sandstone and conglomerate appear to have well developed fracture permeability. Yields from both pumped and flowing wells are in the range of 300-1500 gallons/min. Of the 12 exploratory and production wells drilled since 1980, only two are considered unsuccessful. In these wells pumping at 50-100 gpm caused large drawdowns to occur.

Successful wells have been completed in two geologic settings (Figs. 2, 3). The most widespread and predictable setting is for wells drilled in the Boise River Valley within one mile of the base of the foothills. Wells drilled in this area are in a downdropped fault block or blocks, within which the strata dip approximately 6° to the southwest (Fig. 3). Production is primarily from the fractured upper 200 feet of rhyolite. Overlying and confining the rhyolite aquifer are 200-to-600-feet of volcaniclastic sediments and basaltic tuff. These are in turn overlain by 200 to 1000 feet of claystone, siltstone, and minor sand units of the lower Idaho Group. Examination of rhyolite outcrops in the foothills, indicates that of all the rocks in the geologic section, the rhyolites are the only units with abundant, open, unhealed fractures. The origin and nature of the fractures has not been determined. A study of the fractures would be useful to determine if they are widespread features of the upper parts of

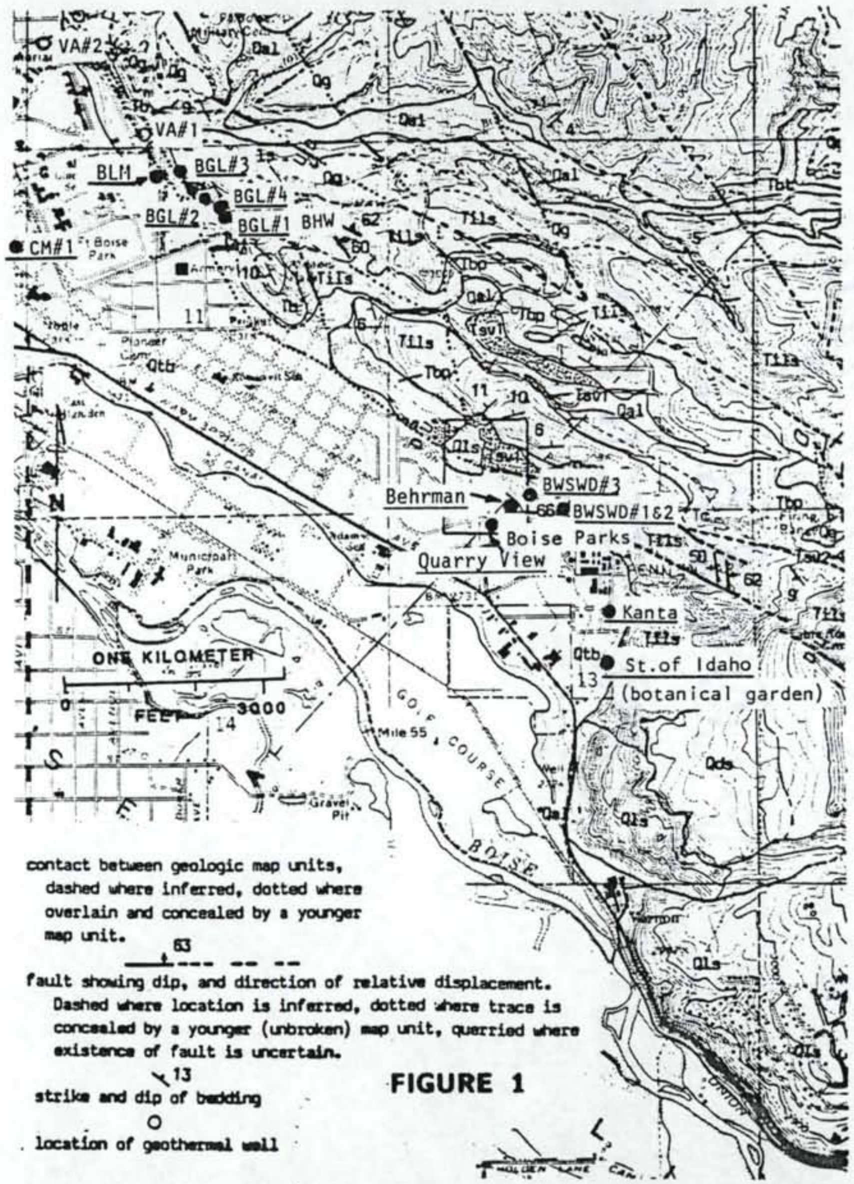

FIGURE 1

Qal	Alluvial deposits within floodplain of modern streams.
Qtb	Alluvial deposits of a late Quaternary terrace of the Boise River.
Qls	Landslide deposits ranging in age from late Quaternary to active in historic time.
Qds	Sandstone layers, folded and disturbed by shallow landsliding prior to the Warm Springs Mesa landslide.
Qg	Gravel deposits of stream terraces generally 16 m (50 ft) above modern streams
QTs	Sandstone, sand, gravel high in the stratigraphic section, but considered part of the lower Idaho Group.
Tils	Sandstone and minor silt layers of the lower Idaho Group.
Tb	Basalt within sediment of the lower Idaho Group.
Tbt	Basaltic tuff, brown in color with interbedded basalt flows.
Tc	Clay, maroon and light green in color with interbedded thin arkosic sand.
Tpb	Basalt, typically contains one or more flows with large plagioclase phenocrysts.
Tsv1	Rhyolite of "Castle Rock"
Tsv2	Rhyolite of Rocky Canyon.
Ki	Granitic rocks of the Idaho batholith.

Geothermal wells in northeast Boise. Geology after Burnham and Wood (1985). BWSWD #1 and 2 are producing wells. BWSWD #3, Kanta, and BLM were used as observation wells in this study. State of Idaho (botanical gardens) and Boise Parks are irrigation wells using geothermal water. BGL #2, 3 & 4 are producing wells. BGL #1, VA #1 & 2, & BHW are not producing at the present time. CM #1 is a reinjection well for the Capital Mall system.

Figure 1. Geothermal wells in northeast Boise.

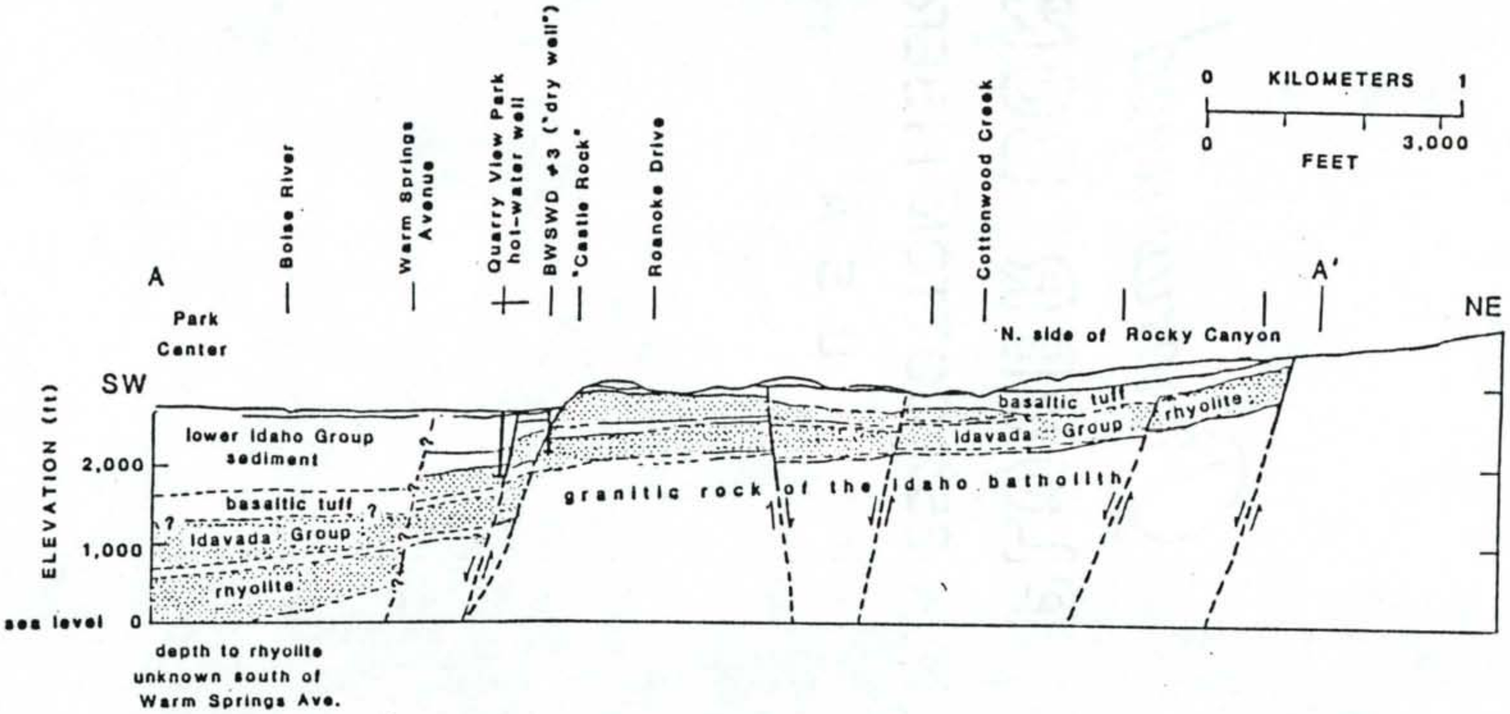

Figure 2. Geologic cross-section through the Boise Warm Springs area.

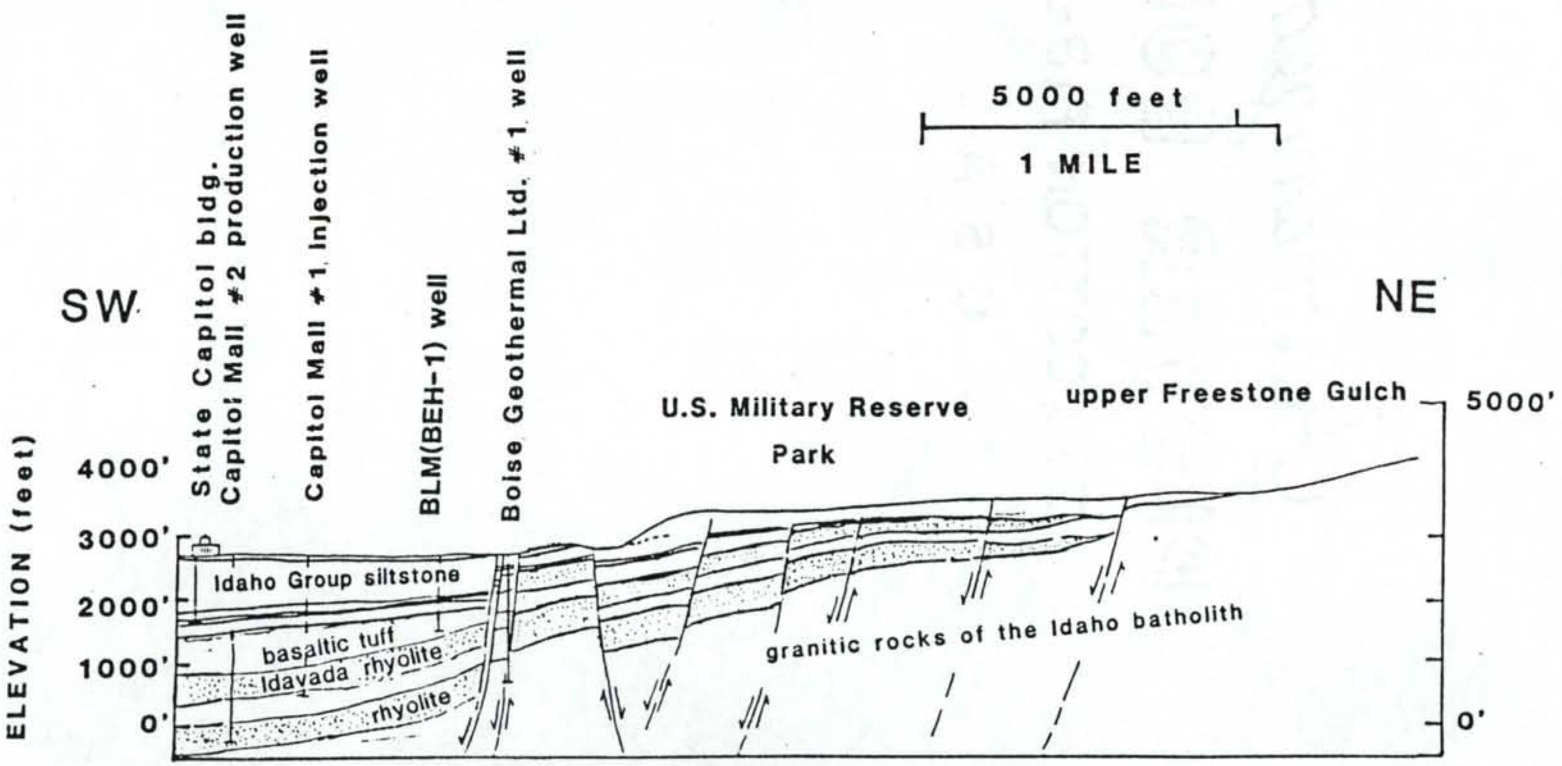

Figure 3. Geologic cross-section through the Boise Geothermal, Ltd. wells and the Capitol Mall wells.

the rhyolite layers such as the original cooling fractures, or if they are confined to fracture zones such as would be expected of tectonic fractures. Wells of this geologic setting are not associated with faults identified by surface geologic mapping or by subsurface correlation of well logs, and include the Capitol Mall, Kanta, Quarry View Park, and the BLM (BEH-1) wells. Of these wells, only the BLM well was unsuccessful. It experienced a drawdown of 169 feet with a pumpage of 120 gpm for 30 hours (Nelson and others, 1980). We do not have an accurate log of the well, but it appears the well did not penetrate the rhyolite. If it did, it is likely that only the uppermost part of the rhyolite was penetrated, thus explaining the poor production.

The other geologic setting for successful geothermal-well completion is within fractures of a northwest-trending major fault zone near the edge of the Boise foothills. This fault zone apparently controlled natural discharge from the system in the late 19th Century manifested as seeps and springs of warm water (Lindgren, 1898; Wells, 1971). Most of these springs have ceased to flow over the years since production from the Boise Warm Springs wells began in 1892. In this setting along the base of the foothills, most large production wells derive their principal flow from fractures in rhyolite, but in this case the fractures are more clearly related to faulting. Wells in this fault-zone setting are the Boise Warm Springs Water District Wells, the Boise Geothermal Limited well field, and the Veteran's Administration wells. Two of the recently drilled wells in the footwall did not yield enough water to justify completion. These are the Boise

Warm Springs No. 3 and the Boise Geothermal Ltd. No. 1. In both cases, the wells were drilled through the normal fault zone and into the footwall without encountering sufficient fracture permeability. Most successful wells are located southwest of the surface trace of the target fault zone in the hanging wall. Wells should be designed to penetrate a significant section of rhyolite in the fractured hanging wall. This concept of greater abundance and openness of fractures in the hanging wall is illustrated in the literature on tunnel geology. Tunnels entering a fracture zone from the footwall side have experienced catastrophic inflows of groundwater when the tunnel advances from the impermeable footwall into the fractured hanging wall, whereas tunnels driven from the hanging wall side encounter more gradual increase in fracture density, and consequently more gradual inflow as the tunnel is advanced (Thompson, 1966; Freeze and Cherry, 1979, p.490).

The lateral and vertical extent of the rhyolite section is of interest if we are to eventually understand the nature of groundwater storage and recharge to the system. The rhyolite aquifers seem to be a sequence of tabular rock layers. Two rhyolite layers, each about 200-300 feet thick appear to be widespread units in the subsurface. Total thickness of the rhyolite sequence is not known. It is suspected that much of the production from the Capitol Mall No. 2 well is from the upper part of the uppermost rhyolite. However, some production may be derived from the underlying 200 feet of sandstone and conglomerate, and the lower 300 feet drilled into the lower rhyolite. The rhyolite units thin to the northeast where the section laps upon granitic rock of the Idaho batholith. Seismic reflection sections of the valley 3 miles east of the geothermal field show that the entire section of Miocene-Pliocene rocks dips about 6° to the west-southwest. Because of this structural tilting toward the center of the plain, and because of down faulting to the southwest, the rhyolite layers lie at greater depth to the west and southwest. The Capitol Mall wells are the most westerly exploration into the subsurface rhyolite section.

Similar rhyolite layers crop out in the foothills immediately northeast of the geothermal field (Wood and Burnham, 1985) and in the vicinity of Pearl, 15 miles northwest of Boise (Anderson, 1934). It seems likely that an extensive section of rhyolite may be buried under the northern part of the Boise River Valley; however, insufficient data exists to evaluate the extent of the rhyolite in the subsurface.

The nature of the aquifers that supplied 118°F water to the Silkey, Ryan, Edwards, and Tiegs wells, about 3 miles west of the Capitol is not known. Testimony during the 1931 Supreme Court hearing of the <u>Silkey vs. Tiegs</u> water rights dispute indicates that the hot water was encountered in "lava rock" or "hard rock" about 1200 ft deep in all of the wells (Case No.5651, in the archives of the Idaho Supreme Court). Such descriptions are given by drillers to both rhyolite and basalt, and without cuttings or geophysical logs, the type of volcanic rocks cannot be ascertained.

The Harris well drilled in 1986 is the most easterly hot water well of the system. The water pumped from the well is also the hottest water known from the system. It produces 180°F water from fractures in sandstone and granite near the site of a former warm springs. No rhyolite was encountered in that 890-ft well, indicating that the well is fractured granite along the foothills fault zone (interpretation by S. Wood, based on examination of cuttings). Success of the Harris well indicates that open fractures may be encountered in faulted granitic rocks, as well as the rhyolite.

Although part of the rhyolite sequence is clearly an important aquifer inclined fault zones in the granitic, sedimentary and volcanic rocks are also a part of the groundwater storage and circulation system. Fault zones having significant vertical permeability, serve as conduits for deeply circulating ground water , whereas the tabular rhyolite layers and fracture zones appear to provide the system with lateral hydraulic conductivity, and interconnections within the system.

Location of the Major Faults

Major faults have been determined by surface geologic mapping and from subsurface studies using well and geophysical data (Wood and Burnham, 1983). A geologic map of the northeast Boise area prepared by Burnham and Wood (1985) is shown in Figure 1. Location of faults is currently being revised in the light of a new mapping compilation of the Boise area by Will Burnham, Kurt Othberg, and Spencer Wood, which will be released by the Idaho Geological Survey in 1987. Orientation of faults varies from

N60°W to north-south. Faults are of different ages, in that some faults offsetting older units, do not cut younger units. Measured attitudes of surface outcrops of fault planes of the foothills fault zone trend N70°W to N45°W, and dip 55° to 70°. Many of the faults mapped in the foothills probably project under the Boise River Valley, but their exact position and degree of interconnection is not well known.

The volcanic section is faulted against granite in several places in the foothills by northwest-southeast trending fractures. Faults certainly exist within the granitic rocks, but they have not been documented by detailed mapping in the batholith. Numerous warm springs elsewhere in the batholith are evidence that deep groundwater circulation occurs in fracture zones in the granitic rocks, but as yet we know little of their geometry or if they may be related to the Boise Geothermal System.

For purposes of discussion it is useful to classify the groundwater systems beneath the Boise River Valley into three somewhat separate systems. The classification is based mostly on depth of the aquifer units; however, water use and geologic framework are similar within each system.

The principal geothermal system is considered to be waters in excess of 120°F derived either from the deep rhyolite aquifers or from wells near fault zones along the Boise foothills. Other occurrences of warm waters in deep wells occur in the area, but they are not yet widely exploited and little is known of their aquifer systems (Wood and Anderson, 1981).

The "deep groundwater system" as defined by Dion (1972), Nace and others (1957), Ralston and Chapman (1970), Young (1977), and Burnham (1979), is from a depth of 200 feet to 800 feet. The stratigraphic section is mostly silty claystone, and siltstone of low permeability, but which contains several important beds of sand and sandy gravel. As the stratigraphy of the valley is presently understood, most of these sediments are within the lower part of the Idaho Group (Wood and Burnham, 1983) and not part of the Glenns Ferry Formation as originally reported by Dion (1972). The Glenns Ferry Formation should be regarded as the upper Idaho Group and is recognized by Wood and Burnham (1983) as a sand facies capping the western Boise Foothills. Geologic formations within the Idaho Group beneath the Boise River Valley have not been studied in sufficient detail to use formation subdivisions at this point. Burnham (1979) describes the deep system as overlain by a clayey sequence of low permeability which restricts water movement rather than forming an absolute separation. Sand aquifers within this clayey sequence are the source of the major drinking water supply for the City of Boise and other municipalities in the area. The "deep groundwater system" is thought to recharge near the Boise River, east of Boise, and to discharge to deep wells and to the Snake River toward the south and southwest (Ralston and Chapman, 1970; Young, 1979). The recharge characteristics have never been examined in detail. The extent to which the deep part of this system may interconnect along faults with the geothermal system is not known. Most wells deeper than 500 feet are warm, 60-80^{o}F, but that may be due entirely to the local geothermal gradient, and not to intermixing with water from the geothermal system. Mixed water would clearly be indicated by anomalous fluoride-ion content ($F^- > 1.0$ mg/liter) because waters from the principal geothermal wells exceed 15 mg/liter fluoride. Fluoride content of deep wells in the valley needs to be examined, and that is a problem for additional research.

The shallow groundwater system as defined by Dion (1972) and discussed by Burnham (1979) is that continuous body of groundwater that lies within the upper 100 to 300 feet of sediments of the Idaho Group, fluvial sediments of the Boise River, and basaltic lavas of the Snake River Group. This ground water system is under essentially water table conditions and responds seasonally to recharge by precipitation and mostly to imported irrigation water. The water-level map for October, 1970, constructed by Dion (1972) shows the New York Canal as a major source of recharge. The water table slopes to the west-northwest about 20 ft per mile. More recently, septic tank and sewage treatment effluent are a component of recharge. Water from the shallow groundwater system discharges in west Boise to individual irrigation and domestic wells and by drainage ditches and springs to the Boise River. The water table of this shallow system rose rapidly in the 1912-1915 interval as new irrigation waters were supplied by canals of the Boise Project. The water table is as deep as 300 feet beneath the upper terraces in the southeast Boise area, but is very near the surface in west Boise. Local perched tables occur within this upper section and are discussed most recently by Burnham (1979).

PRODUCTION FROM THE GEOTHERMAL SYSTEM

Three principal producers withdraw hot water from the aquifer system; Boise Warm Springs Water District (BWSWD), Boise Geothermal Limited (BGL) which is presently operated by the City of Boise, and Capitol Mall (CM), the State of Idaho system. A fourth, the Veterans Administration, is planning to come on-line during the winter heating season of 1987-1988.

Boise Warm Springs Water District, one of the oldest commercially utilized geothermal systems in the United States, has been producing hot water for residential heating and domestic use since 1892. However, production and water-level data are available only from 1978 through the present. The data have been systematically recorded, but are only partially complete and are summarized in Table I.

Until 1982 BWSWD was the only large producer from the system, but late in the winter of 1982 the State of Idaho began production from their Capitol Mall No. 2 well. Water produced by the No. 2 well is reinjected by the Capitol Mall No. 1 well after use for heating the state office buildings. Production figures from CM No. 2 are presented in Table II.

In October 1983 the third major producer BGL began production from their well field in the vicinity of reserve park. BGL production is used for heating office building, regathered into one line and discharged into the Boise River. Production by BGL shows an increasing trend as more users are connected onto the system. BGL production data are tabulated in Table III.

TABLE I
PRODUCTION
BOISE WARM SPRINGS WATER DISTRICT

PERIOD	MONTHLY PRODUCTION (M GALLONS)	ANNUAL SEPT. 1 - AUG 31. (M GALLONS)
April '78	21,927	
May	14,753	
June	9,577	
July	5,838	
August '78	3,366	1977-1978 55,461
September '78	3,717	
October	5,799	
November	31,948	
December	40,740	
January '79	48,331	
February	49,295	
March	42,799	
April	29,587	
May	19,653	
June	12,778	
July	8,751	
August '79	9,321	1978-1979 302,719
September '79	11,199	
October	21,405	
November	36,143	
December	39,193	
January '80	49,230	
February	39,842	
March	35,372	
April	22,306	
May	18,779	
June	15,101	
July	7,421	
August '80	9,109	1979-1980 305,100

Table I (cont'd)

PERIOD	MONTHLY PRODUCTION (M GALLONS)	ANNUAL SEPT. 1 - AUG 31. (M GALLONS)
September '80	14,140	
October	22,678	
November	30,418	
December	36,151	
January '81	37,241	
February	32,811	
March	20,315	
April	13,782	
May	10,324	
June	5,868	
July	6,200	
August '81	6,634	1980-1981 236,562
September '81	13,151	
October	26,008	
November	30,548	
December	35,667	
January '82	46,778	
February	38,050	
March	------	
April	------	
May	------	
June	------	
July	------	
August '82	5,892	1981-1982 196,094
September '82	13,288	
October	23,612	
November	35,496	
December	40,744	
January '83	37,122	
February	29,038	
March	30,059	
April	26,641	
May	19,530	
June	10,038	
July	9,269	
August '83	7,048	1982-1983 281,885

Table I (Cont'd)

PERIOD	PRODUCTION (M GALLONS)	ANNUAL SEPT. 1 - AUG. 31 (M GALLONS)
September '83	15,890	
October	24,859	
November	31,763	
December	41,336	
January '84	41,438	
February	34,021	
March	32,908	
April	28,796	
May	19,534	
June	8,392	
July	------	
August '84	------	1983-1984 278,937
September '84	------	
October	29,467	
November	31,250	
December	36,842	
January '85	37,557	
February	32,714	
March	34,055	
April	16,367	
May	------	
June	------	
July	------	
August '85	8,791	1984-1985 227,043
September '85	21,264	
October	29,314	
November	36,322	
December	36,808	
January '86	32,882	
February	25,310	
March	23,140	
April	20,150	
May	15,507	
June	6,638	
July	6,893	
August '86	5,628	1985-1986 259,856

Table I (cont'd)

PERIOD	PRODUCTION (M GALLONS)	ANNUAL SEPT. 1 - AUG. 31 (M GALLONS)	ANNUAL SEPT. 1- AUG. 31 (ACRE FEET)
September '86	14,344		
October	19,832		
November	24,305		
December	28,557		
January '87	28,693		
February	24,526		
March	16,274		
April	26,274	1986-1987 182,805	

TABLE II
CAPITOL MALL PRODUCTION
(Millions of Gallons)

1983	79.1
1984	204.8
1985	196.4
1986	188.6
1987 to 3/31/87	75.4

TABLE III

MONTHLY SUMMARY OF GEOTHERMAL WATER PUMPED BY BOISE GEOTHERMAL LIMITED WELLS*

PERIOD	TOTAL GALLONS PUMPED	YEARLY TOTAL (GALLONS)
October 1983	12,894,700	
November	17,565,300	
December	23,306,400	
January 1984	32,091,300	
February	16,187,700	
March	12,646,000	
April	13,226,810	
May	13,543,570	
June	7,367,020	
July	5,527,710	
August 1984	5,898,120	160,254,630
September 1984	6,441,750	
October	9,971,100	
November	15,237,220	
December	15,136,520	
January 1985	18,188,710	
February	17,822,100	
March	12,071,100	
April	8,308,450	
May	7,384,000	
June	3,752,000	
July	2,746,000	
August 1985	4,897,000	121,955,950
September 1985	5,869,000	
October	11,894,000	
November	15,477,000	
December	20,739,000	
January 1986	25,295,000	
February	21,459,000	
March	20,318,000	
April	20,752,000	
May	18,751,000	
June	8,730,600	
July	1,279,350	
August 1986	861,380	171,425,330

PERIOD	TOTAL GALLONS PUMPED	YEARLY TOTAL (GALLONS)
September 1986	11,267,070	
October	19,685,600	
November	20,558,550	
December	29,991,500	
January 1987	34,236,350	
February	27,911,380	
March	21,680,110	
April	17,407,460	182,638,020

ANALYSIS OF WATER-LEVELS RELATED TO PRODUCTION

In the late 19th Century, natural seeps and springs of warm water flowed along the surface trace of the fracture system at the base of the Boise foot hills (Lindgren, 1898; Wells, 1971). The discharge from those geothermal seeps and springs was probably small. The largest spring flow seems to have been that mentioned by Lindgren (1898) as coming from the west side of Squaw Creek (now renamed Warm Springs Creek). Lindgren, however, gives no estimate of the volumetric flow. Lindgren does estimate the elevation of the highest flow of warm springs as approximately 2850 feet. This was probably in the Warm Springs Creek area and is interpreted to reflect the level of the potentiometric surface during the late 19th Century. In 1896 or early 1897, Lindgren noted that the water from the Boise Warm Springs wells was under moderate pressure and would rise not more than 50 feet above the mouth of the Boise Warm Springs Water district well or wells. The ground surface of the well site is 2764.9 feet; thus the potentiometric surface at that time must have been at approximately 2815 feet. Until 1983 artesian flow at the Boise Warm Springs Water District well house was a rather common occurrence during the summer. The exact number of days that surface flows occurred is difficult to determine because the records are sketchy; however, flows specifically noted in the records are shown below.

TABLE IV

Maximum Recovery of Potentiometric Surface BWSWD Wells 1 and 2

1986	25 feet below surface	No surface flow
1985	15 feet below surface	No surface flow
1984	10 feet below surface	No surface flow
1983	At surface	Flow 14 days
1982	At surface	Flow 7 days
1981	At surface	Flow 50 days
1980	At surface	Flow 36 days
1979	At surface	Flow 38 days
1978	At surface	Flow 6 days

Typically water-levels within the aquifer system reach their peak recovery during the summer when demand for heat is low. As the winter heating season ensues, water-levels decline to a low in late February or early March. Production demand is commonly greatest in January, but there is a month to six-week lag time between maximum production and the lowest water level in the aquifer. Recovery continues from March into summer and the cycle begins again. As production has increased, recovery within the aquifer has been delayed until later and later in the summer. Using surface flow as an indication of the water-level in 1983, the decline in water-level between 1897 and 1983, would be 50 feet or an average of .58 feet per year. After 1983 the decline in the recovery level is approximately 8.5 feet per year.

BWSWD produces from two wells which are completed in fractures of the frontal fault system. BWSWD Well No. 2 is the principal production well. Well No. 1 is pumped only when No. 2 cannot supply the demand on the distribution system. Both pumps are 150 feet below the well house floor and a 10 foot long tail pipe is installed below the pump. Water-level measurements are made using an airline in each well. Flow rate measurements are calculated from a Sparling cumulative flow meter installed in a common pipe served by both wells. Water-levels and the Sparling meter are read once per day, usually in the morning between 8 a.m. and 10 a.m., or occasionally in late morning or afternoon. The readings reflect the water level only at the time of reading and are somewhat skewed toward levels at a time of day when domestic demand is high. However, during the peak heating season, even random readings commonly reflect a maximum drawdown.

Sparling meter readings are averaged over the period since the previous reading was taken (approximately 24 hours) to determine the pumpage in gallons per minute; thus, they reflect an average flow rate for that period. Unfortunately, gaps exist in the flow-rate data when the meter was not functioning.

Computer plots of BWSWD production and water-level data versus time for the years 1978 through 1987 are shown in Fig. 4. Water-levels are shown in the upper curve and production in gallons/minute are shown in the lower curve. The graphs illustrate rather succinctly the substantial declines occurring in the aquifer, and indicate that since 1983 the district has been

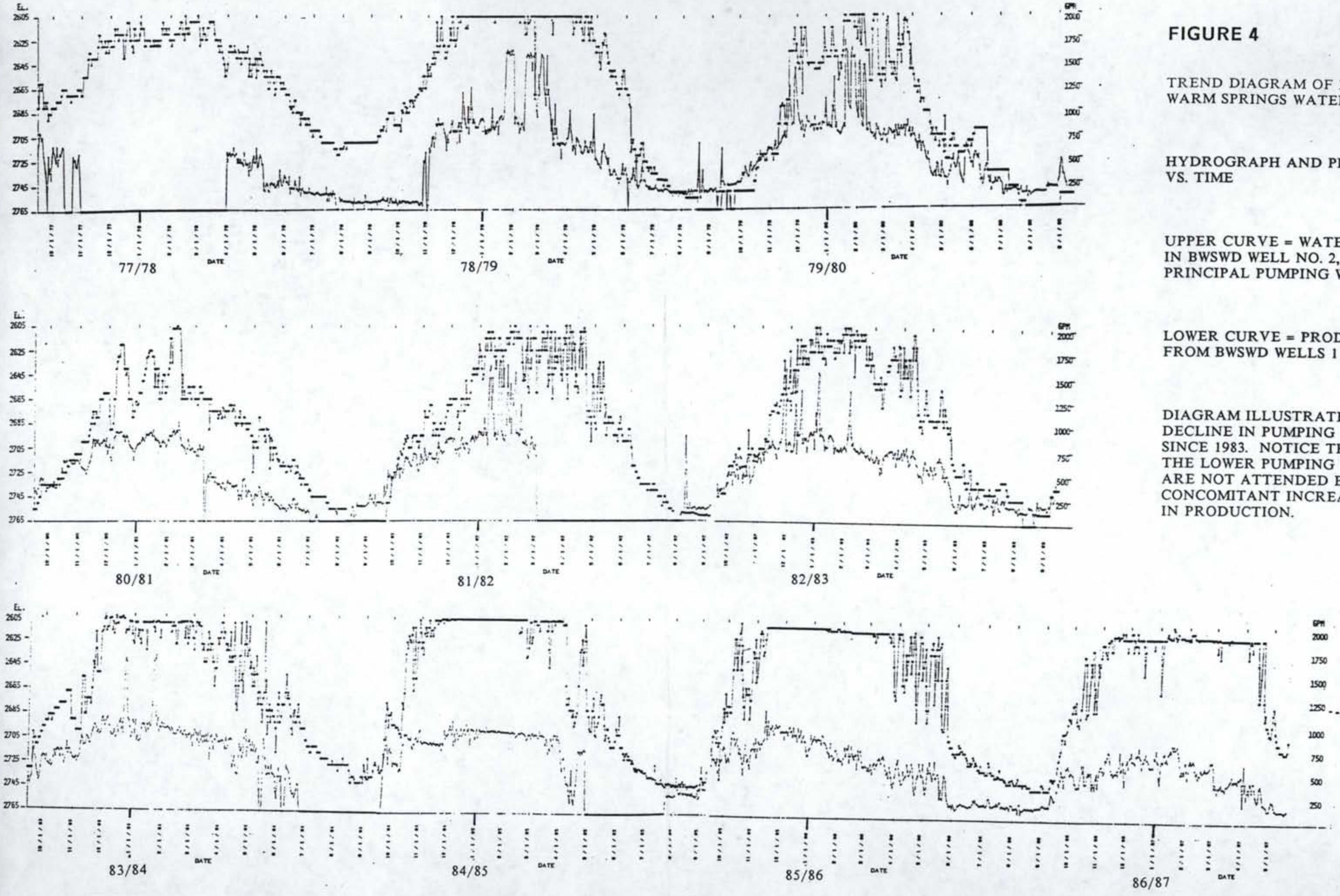

FIGURE 4

TREND DIAGRAM OF BOISE WARM SPRINGS WATER DISTRICT

HYDROGRAPH AND PRODUCTION VS. TIME

UPPER CURVE = WATER LEVEL IN BWSWD WELL NO. 2, THE PRINCIPAL PUMPING WELL

LOWER CURVE = PRODUCTION FROM BWSWD WELLS 1 AND 2

DIAGRAM ILLUSTRATES THE DECLINE IN PUMPING LEVELS SINCE 1983. NOTICE THAT THE LOWER PUMPING LEVELS ARE NOT ATTENDED BY A CONCOMITANT INCREASE IN PRODUCTION.

pumping from greater depths for longer and longer periods to obtain less production. Drawdowns within the production wells during the heating season have reached the levels of the tail pipes and the pumps for substantial periods causing cavitation in the pumping wells.

The yearly average pumping levels for Well No. 2, the principal pumping well, are also summarized in Table V.

TABLE V

Yearly Average Depth to Water Level
(pumping level)
(September 15-September 14)

YEAR	WELL NO. 2
1985-1986	104.5
1984-1985	100.5
1983-1984	102.2
1982-1983	83.5
1981-1982	82.2
1980-1981	72.5
1979-1980	79.8
1978-1979	111.1
1977-1978	107.7

The deep pumping levels for the years 1978-1979 and 1977-1978 are interesting and anomalous. Obviously, they cannot be attributed to effects caused by other producers since CM and BGL did not begin production until 1982 and 1983. The BWSWD Engineer, Mr. Robert Griffiths, states that those data predate his tenure and he could not vouch for their accuracy. If the data are accurate, it may be that the deep pumping levels are somehow related to a drought period experienced in Idaho during those or previous years. Whatever the reason, it is interesting to note that inspite of the large average drawdown values, the aquifer recovered to flow at the surface during the summers of 1978 and 1979. This has not been the case attendant to the large drawdowns after 1983.

The principal observation well in the vicinity of the BGL well field is the BLM (BEH) well, (Fig. 1). Figure 5 includes a hydrograph of the BLM well for the period September 1981 to October 1986. The hydrograph for the period September 1983 to August 1984 is a composite record of water-levels in the BLM well and the Veterans Administration well. Those data and water-level data prior to our monitoring beginning in June 1985, are replotted from graphs in the <u>Phase II Proposal</u> - Boise City Geothermal Project (p.29).

The data from 1981-1982 are regarded as base-line data. Interestingly, the base-line data indicate that the water-level in the BLM fluctuated on an annual cycle prior to Capitol Mall and BGL production from the system. Similar to the effects in the BWSWD wells imposed by their own pumpage, the water-level in the BLM well reaches its lowest levels in March and its highest levels in September. These same cyclical fluctuations are evident in some BLM well data from 1976-1977 and 1978 published by Nelson and others (1980). Attempting to explain these similar cyclical fluctuations in the BLM water-level during 1976-1978, Nelson and others (1980, p.23) state "An obvious conclusion would be to suspect the water level drops that occur after December of each year are the result of increased water usage by the Warm Springs wells for the winter heating months." (Referring to the BWSWD wells 1 and 2 as Warm Springs wells). However, Nelson & others then chose to explain the fluctuations not as effects of BWSWD pumpage but by either loading of the geothermal aquifer by cold irrigation water or by leakage downward from the overlying cold water aquifers. They suggest that the increases in water-level in the cold water reservoir resulting from the influx of irrigation waters beginning in the spring, continuing throughout the summer and declining after irrigation ceases in the fall, create a cyclical load on the geothermal system. Such an affect would be similar to tidal effects in coastal confined aquifers where the weight of the incoming tidal waters load and compress the confined aquifer to some extent and cause an increase in water levels in wells penetrating the confined aquifer. Under those conditions, the water-level rise in a well divided by the water-level rise in the tide is termed the aquifer's tidal efficiency (TE) and is a reflection of the rigidity or elasticity of the aquifer.

Fracture system aquifers such as the Boise Geothermal system, commonly have a high rigidity and a correspondingly low tidal efficiency. Tidal efficiency (TE) is also related to barometric efficiency (BE) by the relationship TE + BE = 1 (Ferris, et.al., 1962). Our preliminary calculations of the barometric efficiency of the aquifer in the vicinity of the Kanta well indicate an efficiency on the order of .9 or 90%. This value compares favorably with a published barometric efficiency for BGL well No. 3 (Kelly, J.E., 1986). If we accept these values as approximately an average for the entire system, then the tidal efficiency of the aquifer would be approximately 10% or .1.

Figure 5 shows a water-level fluctuation of approximately 10-11 feet between September 1981 and mid-February 1982. Using a tidal efficiency of 10%, a cold-water table fluctuation of a minimum of 100 feet would be required to induce the potentiometric surface fluctuations recorded in the geothermal aquifer between September and late February or early March. This assumes that one would be adding the weight of the 100 feet of water and not just filling the pore spaces of the material. Nelson and others (1980, p.24) for the years of record 1934-77, show a maximum range of annual fluctuation of approximately 10 feet for the free water table near Meridian. This is less than 1/10 of the annual head charge that would be required to cause the fluctuations observed in the geothermal system. Or, conversely, the geothermal aquifer and all of the overlying confining layers would have to have a tidal efficiency exceeding 100%, perfect elasticity, for the phreatic reservoir to provide the required load changes.

The tidal concept is generally attractive theoretically and the timing of loading and unloading appears to be close enough. However, the indication of the rigid nature of the geothermal aquifer requires cold water-table fluctuations which are much larger than observed. Perhaps such loading and unloading contributes to the observed fluctuation, and is integrated with other causes, but it is not at all likely to be the principal cause. We must look elsewhere for the explanation for the annual fluctuations.

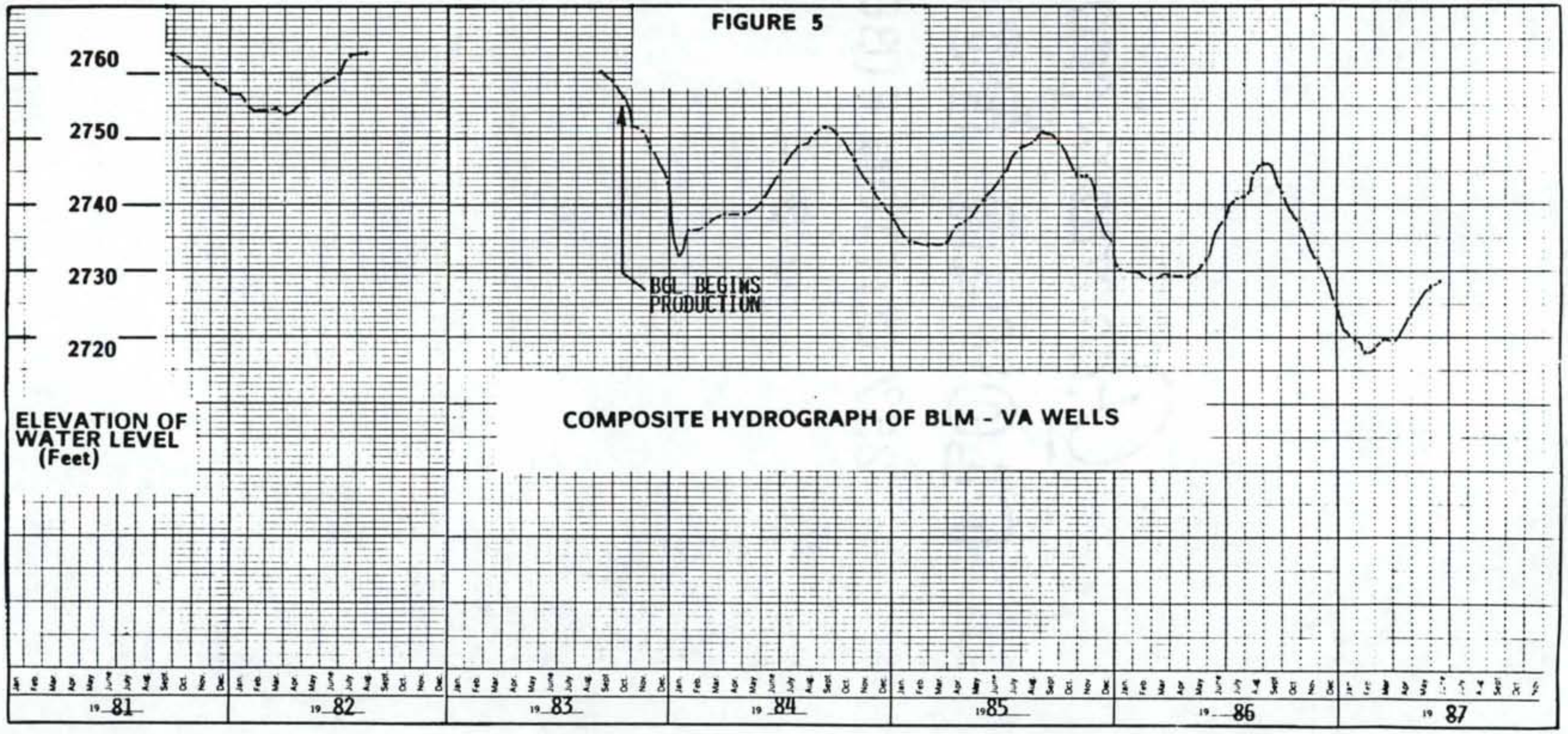

Figure 5. Composite hydrograph of BLM-VA wells.

The cyclicity of fluctuations may reflect, to some degree, annual changes in the balance of recharge and natural discharge within the system. Nelson and others (1980, p.23) also suggest that the annual geothermal fluctuation in the BLM well may be caused by vertical leakage from the cold water aquifer. Admittedly, we know very little about how and where the geothermal system becomes recharged. However, recharge from the cold water aquifer in the Snake River Plain is not likely. More likely, the geothermal system waters are leaking upward into the cold water system. Abnormally warm groundwaters observed in wells in the Boise vicinity probably reflect this leakage. The Boise Geothermal system waters have a high fluoride content that is quite consistent throughout the geothermal aquifer. A study designed to determine fluoride contents within the cold water aquifer would delineate areas and amounts of discharge by dilution of the hot waters upward into the cold water aquifers.

Having the benefit of additional data and knowledge gained from our monitoring of the system for the past three years, it seems more likely that all or certainly the largest part of those cyclical fluctuations in the BLM well are, indeed, due to the influence of pumpage by the BWSWD wells 1 and 2. The Warm Springs wells were the only wells making very large withdrawals from the geothermal system until the winter of 1982. We have complete pumpage data for the period from 9/1/81 to 3/1/82, the decline period, when approximately 190 million gallons were withdrawn by the Warm Springs wells. Although the aquifer system is apparently faulted into blocks, it seems unlikely that an essentially impermeable barrier or series of impermeable barriers separate the Warm Springs portion of the system from the BLM-BGL-CM portion. Thus, large drawdowns for prolonged periods such as those created by Warm Springs pumpage would be expected to cause or at least contribute significantly to the measured fluctuations in the BLM well.

Unfortunately, only estimates of the drawdown effects that one might expect as a result of Warm Springs pumpage are possible from the data we currently have available. Nevertheless, by using what information we have, and by making what seem to be reasonable assumptions we can suggest, at least, a range of drawdown effects. Such estimates require values of transmissivity (T) and storativity (S) of the aquifer. Because the aquifer is a fracture-controlled system, T and S values are difficult to determine and are variable throughout the aquifer depending largely on the abundance, openness, and continuity of the fractures.

The mathematical models applied in this estimate are designed for a porous media aquifer rather than fracture systems. However, all presently available transmissivity and storativity estimates for the aquifer were also made using porous media models. Wood and Burnham (1986) report on data gathered from discharge-drawdown tests of several types, from artesian head response to barometric pressure change, and from long-term response of artesian head to variable annual discharge rates. Their analyses have been strictly for engineering-design purposes. In spite of that, they suggest that within time limits of a few hours to a few days, the system responds to a measured discharge-drawdown stress as though the average transmissivity is of the order of 240,000 gal/day/ft and storativity is of the order of 5 x 10 EXP -4. Although these values have been useful for design of wells, they should not be applied to the aquifer system as a whole.

Waag and Wood (1985) published estimates of transmissivity in the vicinity of the BWSWD and Kanta wells of 3500 gal/day/ft, 13,000 gal/day/ft and 25,000 gal/day/ft. These variations in transmissivities are interpreted to reflect segmentation or compartmentalization of the aquifer by faulting. Portions of the fracture zones separating the segments apparently range from nearly open conduits such as that of BWSWD wells 1 and 2 and the BGL wells to portions which are partially or nearly filled with secondary deposits including zeolites, clay, silica, etc. The open fracture zones have the largest transmissivities (highest permeabilities); whereas, partially cemented fracture zones and the interfracture zone "block" or segments have a wide range of transmissivities (permeabilities).

Our estimate of 25,000 gal/day/ft. was based on the longest term sample. Recognizing that the limiting assumptions for strict use of the porous media mathematical models cannot be met in the Boise Geothermal System, it, nevertheless, seems worthwhile to make a few qualified estimates of the possible drawdowns that might be expected in the BLM well as a result of pumpage by Warm Springs wells.

Considering then the period 9/1/81 to 3/1/82 when the BLM hydrograph in Figure 5 shows a 10-11 ft. decline and when BWSWD pumpage was 190 million gallons averaging 730 gpm and using the following forms of the Theis equation:

$$u = 1.87 \frac{r^2 S}{Tt} \text{ and } s = \frac{114.6\ Q}{T} W(u) \text{ where}$$

$W(u)$ = Exponential integral

r = Distance in feet, from the discharging well to the point of observation

S = Storativity

T = Transmissivity

t = Time in days since pumping started

s = Drawdown, in feet, at any point of observation (r) in the vicinity of a well discharging at a constant rate

Q = Discharge of a well in gallons per minute

Using values of:

$T = 25{,}000$ gal/day/ft and
$S = .5\text{x}10^{-4}$
$Q = 730$ gpm
$r = 7580$ feet (approximate map distance from BWSWD No. 2 to the BLM well)
$t = 181$ days - 9/1/81 to 3/1/82 and obtaining values of the well functions of u (Wu) from standard tables (Ferris et.al., 1962, p.96-97)

a value of $s = 12.9$ ft. is obtained.

Using a $T = 240{,}000$ gal/day/ft
$S = 5\text{x}10^{-4}$

and other values as above, the estimated drawdown decreases to 2.1 ft.

These estimated drawdown values between 12.9 and 2.1 feet are probably reasonable for the range of effects that might be expected at the radius of the BLM well owing to BWSWD pumpage for the 181 day period. The transmissivity value of 240,000 gpd was obtained from pump testing in the BGL portion of the system. Quite likely it is valid for that vicinity, but it is nearly an order of magnitude greater than our largest estimate of T in the Warm Springs portion of the aquifer using longer term, but not as well controlled, pumpage data. A transmissivity of 240,000 gal/day/ft is probably too large to apply to the whole portion of the aquifer system between the BWSWD wells and the BLM well. Thus for the period during 1981-82 under consideration, if the BLM well did, indeed, experience drawdown as a result of pumping by the Warm Springs wells the water level declines would have to exceed 2.1 feet. Lower values of transmissivity would shift the estimated drawdown toward the upper side of the range of 12.9 feet calculated above, perhaps, to drawdown values similar to those shown in Figure 5 for the period 9/1/81 to 3/1/82.

The declining potentiometric surface in the Warm Springs area since 1983 is clearly manifested in the water-level data graphed in Figure 4. Although continued monitoring and analysis of the system is necessary before the details of the relationship between the BGL-CM withdrawals and the declining water-levels in the Warm Springs area are well understood, the evidence that interconnection between those two portions of the system exists is clear. Opinions to the contrary, (Nelson and Others, and Boise City Geothermal Project, Phase II Proposal) should be reconsidered. Drawdown effects created in the Warm Springs area by pump testing in the BLM and BGL well for relatively shorter times were probably too subtle or too overprinted by other effects closer to the observation well to be recognized. Our review of the longer term production and drawdown data from both portions of the system, indicates that a pattern of evidence of interconnection and interference is clearly emerging.

It must be noted again, however, that it is obvious from the data that other factors also influence recovery and pumping levels within the system. For instance, during the period 1978-1979 and 1977-1978, the pumping levels in well No. 2 averaged 111 feet and 107 feet respectively (Table V). These are pumping depths equal to or exceeding those experienced since 1983. Those periods were, however, succeeded by recoveries which caused artesian flow; phenomena which have not been observed in the Warm Springs wells since the summer of 1983. It appears that in addition to the obvious annual cycles, other multi-year cycles exist. Our data base is still too short to evaluate that possibility. However, whether a correlation exists between regional drought and water-levels within the geothermal aquifer is an important consideration. What is the role of precipitation and snow accumulation, if any, in recharge to the aquifer? Such a study is the next logical step in a comprehensive study of the system.

To see if the recent lowering of average pumping levels and declining recovery levels in the Warm Springs area are simply related to increased extractions by the Warm Springs system itself, we have estimated the production by the pumping wells. Monthly and annual production data for the Boise Warm Springs Water District are in Table IV. Although some gaps in the data exist, it is apparent that production by the District has not increased since the fall of 1983. Indeed, the data indicate that the District has experienced a decline in production since 1980. In fact, in recent years wells 1 and 2 have had to pump from greater average depths to obtain equal or smaller quantities of water.

Other wells in the vicinity of the Warm Springs pumping wells also show signs of decline in recent years. Data from Warm Springs Water District well No. 3 are shown in Figure 6. It is informative to note that the maximum recovery in No. 3 during August of 1981, reached 2758.5 feet, approximately 16.0 feet above its 1986 recovery. That is an average decline of 3 feet per year. Some caution must be expressed concerning attaching too much significance to a few feet of difference in the recovery levels in well No. 3 on a short-term basis. BWSWD well No. 3 is only 645 feet northwest of wells 1 and 2 and intersects the same fracture zone. The interconnection between No. 3 and the pumping wells is well developed, therefore, No. 3 responds quickly to pumpage by wells 1 and 2 and the water-level fluctuates several feet on a short term basis. However, the longer term decline in the maximum recovery certainly cannot be explained as short-term pumping effects.

Figure 7 is a hydrograph of the Kanta well for the period August 1984 through June 15, 1987. The Kanta Well is approximately 1675 feet south 10° east of the BWSWD pumping wells (Figure 1) and serves as an observation well. Although the period of record is short, it clearly shows an increase in the maximum drawdown and an accelerated decline in the maximum recovery within the past two years. The maximum drawdown in February 1987 was 5

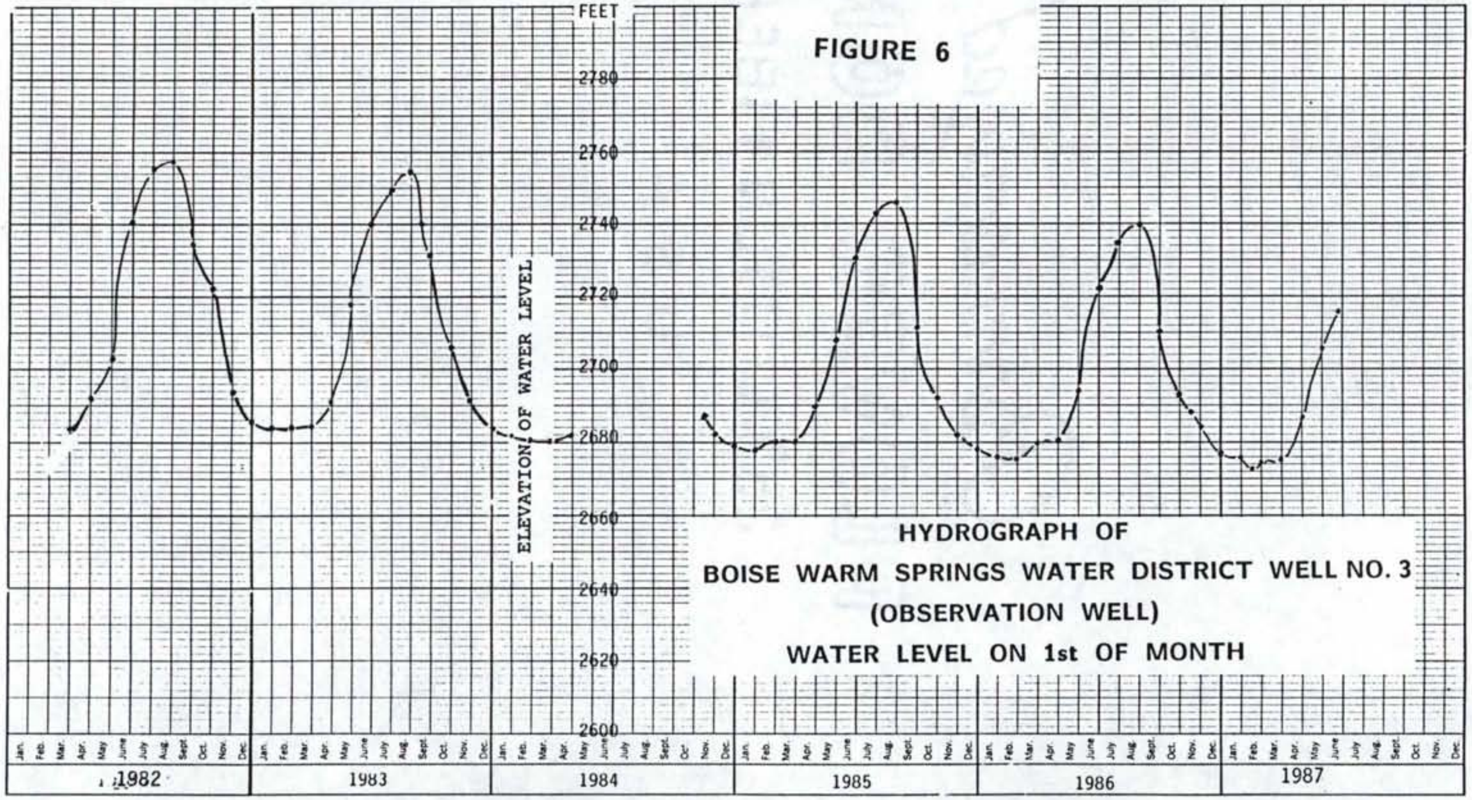

Figure 6. Hydrograph of Boise Warm Springs Water District well #3, (Observation Well) water level on 1st month.

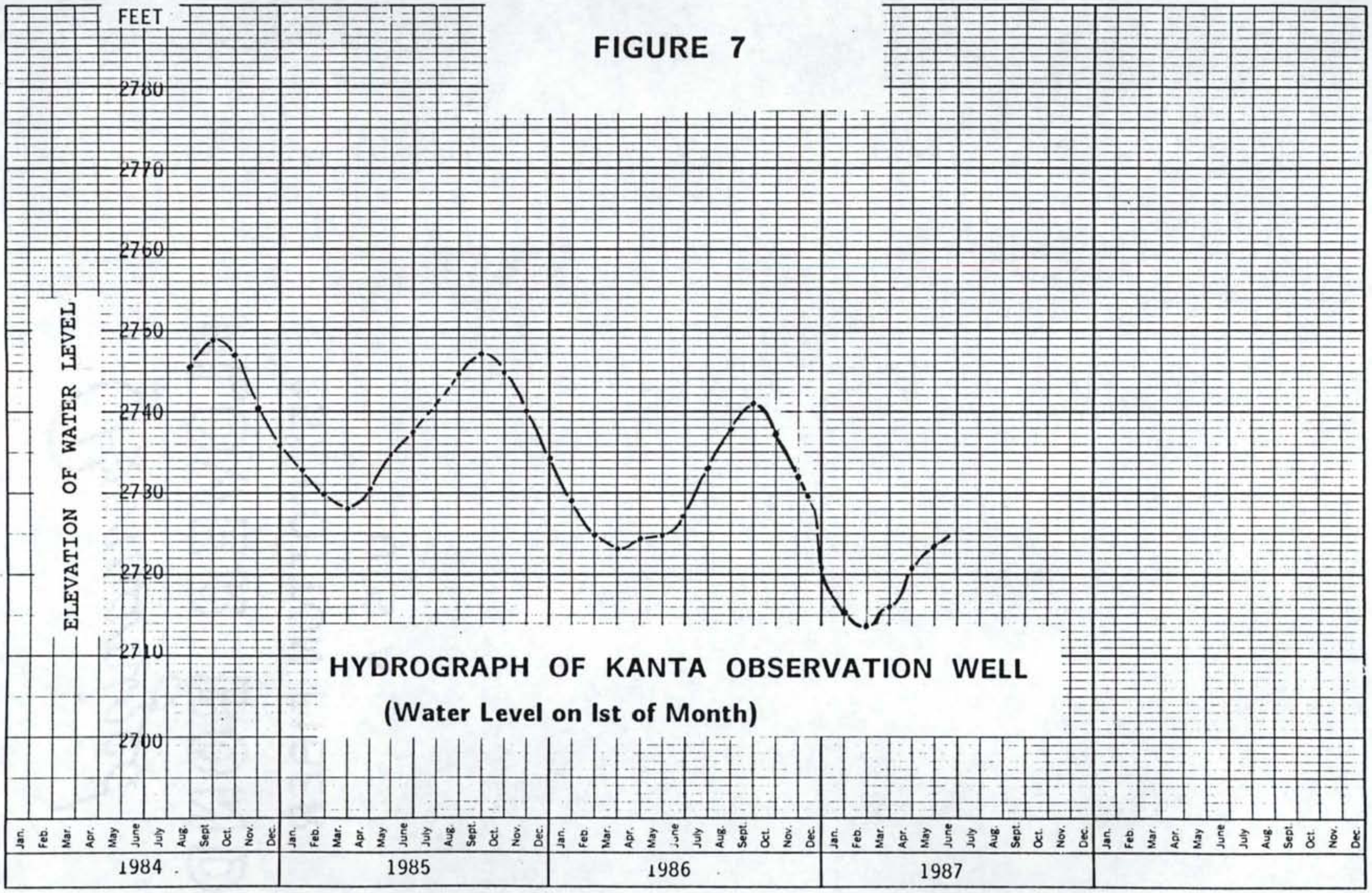

Figure 7. Hydrograph of Kanta Observation Well (water level on 1st month).

feet below the projected downward trend using the maximum drawdowns for 1985 and 1986. The Kanta well reflects the general trend within the aquifer system, but the drawdowns in the well may be exacerbated by extractions from the State of Idaho Penitentiary well which is approximately 675 feet, S 10^{o} E of the Kanta well. In the spring and summer of 1985, 1986, and 1987, the State well was pumped to provide irrigation water for the gardens of the Idaho Botanical Garden Society. The amount of pumpage from the well has not been measured, and we have not yet attempted to determine what effects, if any, the State well production might have upon the Kanta well and other wells in the system.

As a part of our 1984-85 study of the Warm Springs portion of the aquifer, we estimated a transmissivity value of 6800 gals/day/ft for the aquifer in the vicinity of the Kanta well (Waag and Wood, 1985). This value is considerably less than our estimate of approximately 25,000 gals/day/ft. for the transmissivity of the fracture system in which BWSWD wells 1 and 2 are completed. The Kanta well responds well to pumpage by BWSWD Wells 1 and 2 indicating good interconnection. However, the lower transmissivity and our knowledge of the structure in the area prompts the interpretation that the Kanta well is drilled in a down-thrown block of the fracture system in which wells 1 and 2 are completed (Waag and Wood, 1985).

The Kanta well was completed in January of 1983 and pump tested during February 1983. Static water-levels measured at that time were at depths of 23.5 and 31 feet or at elevations of 2760 and 2752 feet. Unfortunately, a large gap in the data exists between February 1983 and August 1984 when our monitoring began. As a result, we do not have a record of the 1983 recovery. However, if one compares February water-levels, the average decline is approximately 11.5 feet (3.5m). Declines within the first 2 years, average 13.5. This spans the time when BGL and CM came on line.

Although the annual fluctuations are clearly due to pumpage by the Warm Springs wells, it is logical to attribute a large portion of the declining trend in water-levels to increased withdrawals from the system by BGL. The effects of CM are considered to be much less important because of the increased distance and reinjection of their production. As noted earlier in discussing data from the BLM well, the system seems to have been in or near equilibrium prior to the winter of 1983 and the inception of BGL production. The evidence for interconnection between the Kanta Well and the Warm Springs Pumping wells is unequivocal (Wood and Waag 1985), and for interconnection between BGL-BLM-CM and BWSWD substantial. Considering these observations and interpretations, it is concluded that the declining water levels in the Kanta Well are probably the consequence of interference of BGL pumpage into the zone of influence of the Warm Springs Wells. Whereas prior to 1983, BWSWD received more water from the fractured aquifer to the northwest of its wells, much of that water may now be withdrawn by the BGL wells. AS a consequence, the BWSWD wells now receive proportionately more of their water supply from the fractured aquifer to the southeast of the wells in the direction of the Kanta Well.

CONCLUSIONS & SUGGESTIONS FOR FURTHER STUDY

Although our data base is short we have accumulated enough data to identify trends within the aquifer and to obtain an understanding of some of the inter-relationships between segments of the aquifer system. Data suggest that the aquifer system was at or near equilibrium prior to 1983. However the data since 1983 indicate that production from the Warm Springs and BLM-BGL-CM portions of the geothermal system exceeds the ability of those portions of the system to recover on an annual basis. Increased development and exploitation of the system since 1982 and 1983 has been attended by an annual decline in the level to which the potentiometric surface recovers during the summer period of low pumpage. Since 1983, maximum recovery levels in observation wells in the vicinity of the BWSWD pumping wells have declined an average of 3.5 feet per year, and an average of eight feet per year in the BWSWD pumping wells themselves. ALso, maximum recovery levels in the BLM (BEH) well which monitors the water-levels in the vicinity of the BGL pumping wells have declined an average of five feet per year since BGL withdrawals began in 1983.

Information on water-levels in the BLM well prior to 1983 are scanty; however, the data available indicate that although there were annual water-level fluctuations ranging through 8-12 feet, maximum recovery levels peaked at elevations near 2760 feet in 1978, 1981, and 1982. In addition, according to BWSWD data, surface flows consistently occurred at BWSWD wells 1 and 2 during maximum recovery in the years 1978 through 1983. These data allow the suggestion that prior to 1983-84, the BWSWD and BLM-BGL-CM portions of the aquifer were near equilibrium.

The data do not indicate a concomitant expansion of production by BWSWD after 1983. Therefore, the most obvious explanation for the increased declines in both portions of the aquifer system since 1983 are withdrawals by BGL which began in the fall of 1983, and to a lesser extent Capitol Mall which began withdrawals but also began reinjection in 1982. This interpretation requires that some degree of interconnection exists between the BLM-GBL-CM and BWSWD portions of the aquifer.

Geologically and hydraulically such interconnection is likely. Review and interpretation of the geologic and hydrologic data currently available to us allows us to suggest the following working aquifer model which requires testing, revision, and confirmation or rejection. The aquifer consists of interlayered sequences of rhyolites and sediments and granites which have been divided into major "blocks", sections, or segments by relatively large fracture zones. Portions of the fracture zones separating the segments apparently range from nearly open conduits such as that of BWSWD wells 1 and 2 and the BGL wells to portions which are partially or nearly filled with secondary deposits including zeolites, clay, silica, etc. The open fracture zones have the largest transmissivities (highest hydraulic conductivities); whereas, partially cemented fracture zones and the inter- fracture zone "blocks" or segments have a wide range of transmissivities (hydraulic conductivities). The broad variation in values of transmissivity that have been estimated by pump tests and long term withdrawals from the aquifer probably reflect this segmentation of the aquifer.

Although none of the aquifer segments or fracture zones are believed to be effectively impermeable, it is probable that some aquifer segments have permeabilities, or are bounded by permeabilities, that are so low that observation wells within the segment show little or no recognizable response to short-term aquifer tests performed outside of the segment. By contrast, essentially constant withdrawals by any of the large production wells in the system for prolonged periods such as those during the multi-month heating season would be expected to create drawdown effects within other aquifer "blocks" or segments even at distances of a mile or more.

The aquifer seems to have been near or at equilibrium prior to production by the Capitol Mall and BGL wells; however, our current data base does not yet allow a prediction as to where a new equilibrium level will be established. It is interesting to note that the total annual production for BWSWD and BGL combined for 1983-84, 1984-85, 1985-86, and predicted for 1986-87 are 459.6, 380.4, 436.2, and 437 million gallons respectively. It is noteworthy that the total combined withdrawals by these two producers have not increased since 1983. Yet, water-levels within those portions of the system are declining at increasing rates with even greater increases in the rates evident from 1986-1987 data. The balance of production has shifted. In 1983-84, 63.7% of the withdrawals were by BWSWD. In 1986-87 BWSWD will produce only about 46% of the total. In addition to the BWSWD, BGL, and

CM withdrawals, an estimated 15-25 million gallons of geothermal water is being produced annually for irrigation by the Boise City Parks Quarry View Well, and by the Idaho Botanical Garden from the State Well. These withdrawals also commenced about 1983-1984.

If as planned, even greater production from the system occurs, water-levels within the system can be expected to decline more rapidly and a new potentiometric equilibrium level delayed. The increasing rates of decline in the recovery levels evident since 1983 and anticipated for 1986-87 without a significant corresponding increase in production by the principal producers is cause for pause and concern.

Exploitation of the geothermal aquifer is currently outstripping our knowledge and understanding of the aquifer; thus, our ability to prudently manage the system. It is time to give serious consideration to placing a temporary moratorium on further development and production from the system until we have a better understanding of its capacity. Serious consideration should also be given to requiring reinjection of produced waters where feasible. Although we have no data base to predict accurately the effects of reinjection, our current interpretation of the aquifer system and the apparent degree of interconnection that exists within it suggests that reinjection will significantly affect the economic productivity and extend the life of the resource. Expressed concerns for temperature declines within the system caused by reinjection are recognized and may be legitimate. However, the rather small difference between production and rejection temperatures in the Capitol Mall system is encouraging, and other producers should strive to design reinjection systems that would achieve similar or superior results.

REFERENCES

Anderson, A.L., 1934, Geology and ore deposits of the Pearl-Horseshoe Bend gold belt, Idaho: Idaho Bureau of Mines and Geology Pamphlet No. 41, 36 p.

Burnham, W.L., 1979, Southwest community waste management study: groundwater subtask, Ada County Council of Governments, Ada Planning Association, Boise, Idaho, 58 p.

Burnham, W.L., and Wood, S.H., 1983, Boise Front Geothermal Field Trip; 12 Annual Rocky Mountain Groundwater Conference, Boise, Idaho

Burnham, W.L. and Wood, S.H., 1983, Field trip guidebook - Boise Front geothermal system (12th Annual Rocky Mountain Ground Water Conference), Boise, Idaho, 36 p.

Burnham, W.L., and Wood, S.H., 1985, Field trip guide for geology of the Boise geothermal system: 38th annual meeting of the Rocky Mountain Section of the Geological Society of America, Boise State University, Boise, Idaho, 32 p.

Dion, N.P., 1972, Some effects of land-use change on the shallow groundwater system in the Boise Nampa area, Idaho: Idaho Department of Resources, Water Information Bulletin No. 26.

Ferris, J.G., Knowles, D.B., Brown, R.H., and Stallman, R.W., 1962, Theory of Aquifer Tests, Groundwater Hydraulics: Geological Survey Water Supply Paper, 1536-E, United States Government Printing Office, Washington

Freeze, R.A., and Cherry, J.A., 1979, Groundwater, Prentice-Hall, Englewood Cliffs, New Jersey, 604 p.

Kelly, J.E., 1986, Response of the Boise geothermal aquifer to earth tides; Proceedings of the 22nd Symposium on Engineering Geology and Soils Engineering, Idaho Department of Transportation, Boise, Idaho

Lindgren, W., 1898, Description of the Boise Quadrangle, Idaho: U.S. Geol. Surv. Geol. Atlas of the U.S. Folio 45, 7 p.

Mayo, A.L., Muller, A.B., and Mitchell, J.C., 1984, Geochemical and isotopic investigations of thermal water occurrences of the Boise front area, Ada County, Idaho: Water Information Bulletin No. 30, Geothermal Investigations in Idaho, Idaho Department of Water Resources, 55 p.

Nelson, L.B., Niemi, W.L., and Stoker, R.C., 1980 Geothermal Resource Exploration in Boise, Idaho: EG&G Report for U.S. Department of Energy DOE Contract No. DE AC 07-761D01570

Streltsova-Adams, T.D., 1978, Well hydraulics in heterogeneous aquifer formations, in Van Te Chow, ed., Advances in Hydraoscience, v.11, Academic Press, New York

Thompson, T.F., 1966, San Jacinto Tunnel, Engineering Geology in Southern California, Assoc. Eng. Geol. Spec. Publ., p.104-107

Waag, C.J., and Wood, S.H., 1985 Base line data analysis of a developing geothermal system, Boise, Idaho: Research Technical Completion Report, Idaho Water Resources Research Institute, University of Idaho, Moscow, Idaho

Wells, M.W., 1971, Early development of western geothermal resources: Journal of the West, 10, 53-71

Wood, S.H., 1984, Review of late Cenozoic tectonics, volcanism, and subsurface geology of the western Snake River Plain, in Beaver, P.C. ed., Geology, tectonics, and mineral resources of western and southern Idaho: Tobacco Root Geological Society, Dillon, Montana, p.48-60

Wood, S.H. and Anderson, J.E., 1981, Chapter 2 - Geology, in Geothermal Investigations in Idaho, Part II, geological hydrological, geochemical, and geophysical investigation of the Nampa-Caldwell and adjacent areas, southwestern Idaho: Water Information Bulletin No. 30, Idaho Department of Water Resources, p.9-31

Wood, S.H. and Burnham, W.L., 1983, Boise, Idaho geothermal system: Transactions of the Geothermal Research Council, v.7, p.215-225

Wood, S.H., and Burnham, W.L., 1986, Geologic Framework of the Boise Warm Springs Geothermal Area, Idaho: Decade of North American Geology, Rocky Mountain Section of the Geological Society of America, Centennial Field Guide, v.2

Young, H.W., 1985, Geochemistry and hydrology of thermal springs in the Idaho batholith and adjacent areas, central Idaho: U.S. Geological Survey Water Investigations Report 85-4172, 44p.

Young, H.W., Lewis, R.E., and Backsen, R.L., 1979, Thermal groundwater discharge and associated convective heat flux, Bruneau-Grand View area, Southwest Idaho: U.S. Geological Survey Water Resources Investigations, 79-62 (Open File Report) 17p.

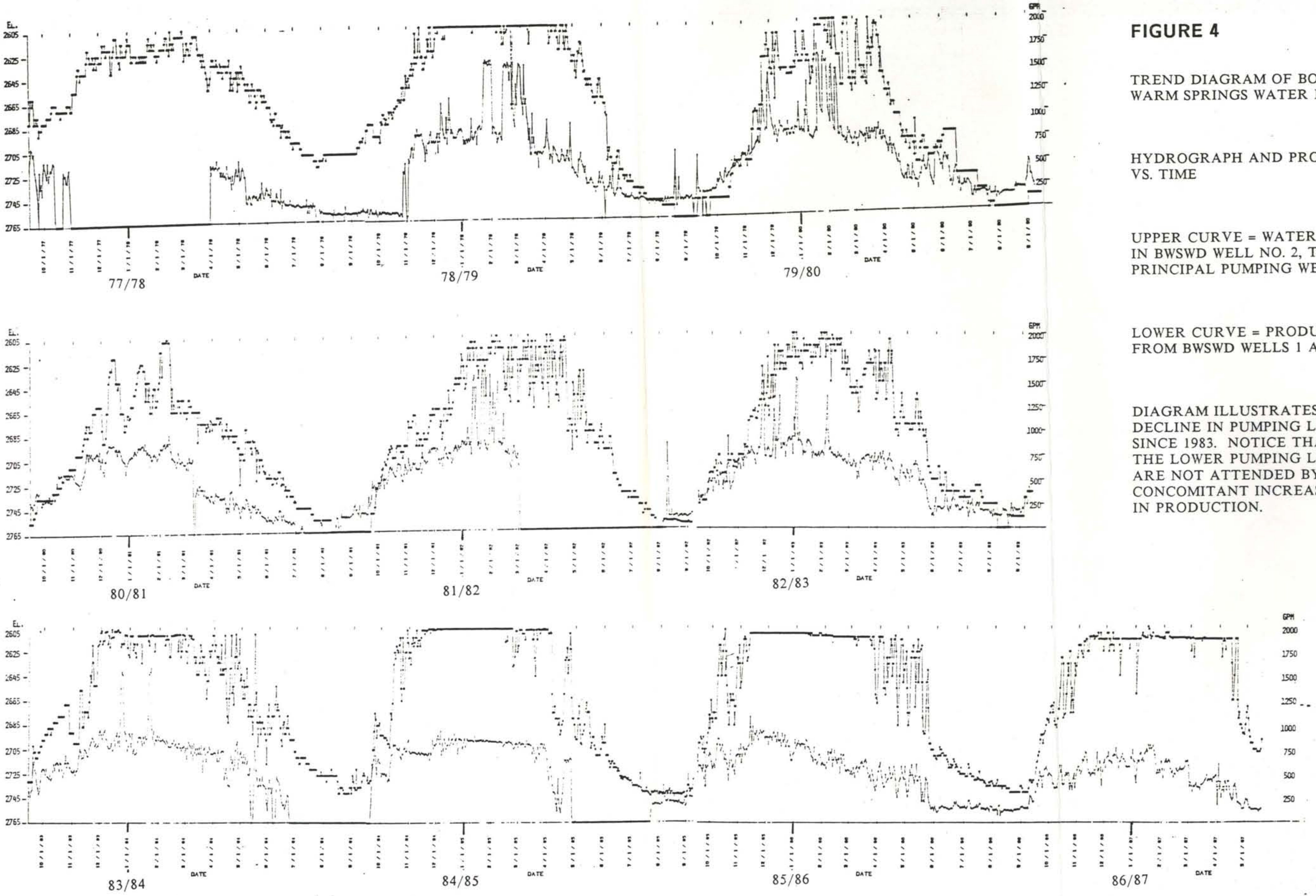

FIGURE 4

TREND DIAGRAM OF BOISE WARM SPRINGS WATER DISTRICT

HYDROGRAPH AND PRODUCTION VS. TIME

UPPER CURVE = WATER LEVEL IN BWSWD WELL NO. 2, THE PRINCIPAL PUMPING WELL

LOWER CURVE = PRODUCTION FROM BWSWD WELLS 1 AND 2

DIAGRAM ILLUSTRATES THE DECLINE IN PUMPING LEVELS SINCE 1983. NOTICE THAT THE LOWER PUMPING LEVELS ARE NOT ATTENDED BY A CONCOMITANT INCREASE IN PRODUCTION.