A MODEL FOR SUSTAINABLE DEVELOPMENT-
THE NEWCASTLE, UTAH GEOTHERMAL RESOURCE

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ABSTRACT

Development of the Newcastle, Utah geothermal resource has proceeded slowly since its discovery in 1975. In 1993, a third commercial greenhouse operator completed construction of a 1.62 hectare (ha) greenhouse and drilled production and injection wells. Thermal fluid produced from the 155-meter production well passes through a heat exchanger and is sent to the injection well located down-gradient from the production area. The company plans to expand their facility, possibly enclosing more than 8 ha, in the near future. Future demands on the geothermal aquifer could stress the long-term productivity of the resource. Monthly temperature monitoring, in available observation holes during the 1993-94 heating season, shows small but measurable temperature changes in the thermal aquifer. Detailed geohydrologic information, including monitored flow tests, is necessary to complete a three-dimensional model of coupled fluid-flow and heat transfer. Such a model is needed to guide development of the thermal aquifer and to insure the long-term, sustainable use of the Newcastle geothermal system.

INTRODUCTION

Newcastle is a rural farming community located along the southeastern edge of the Escalante Desert, 48 km west of Cedar City, Utah (Figure 1). In 1975 during aquifer testing at a newly drilled irrigation well, a local farming cooperative - the Christensen Brothers - accidentally discovered a concealed hydrothermal system. Subsequent studies by the University of Utah (Chapman et al., 1981), the Utah Geological Survey (Blackett and Shubat, 1992) and other organizations have defined a covered upflow zone along the Antelope Range fault and a shallow thermal aquifer which channels the outflow plume of the hydrothermal system. One important result of the Blackett and Shubat (1992) study is that the anomalous heat loss of the system exceeds 12.4 MW.

Development of this resource proceeded slowly until 1993. In 1988, three relatively small greenhouses and a church were producing thermal fluids from the aquifer for space heating. The greenhouses disposed of the cooled fluids in shallow (0-5 m) evaporation/infiltration pits dug in the surface soils. No substantial change in the fluid temperatures or depths to warm water have been reported by the operators. In 1993,

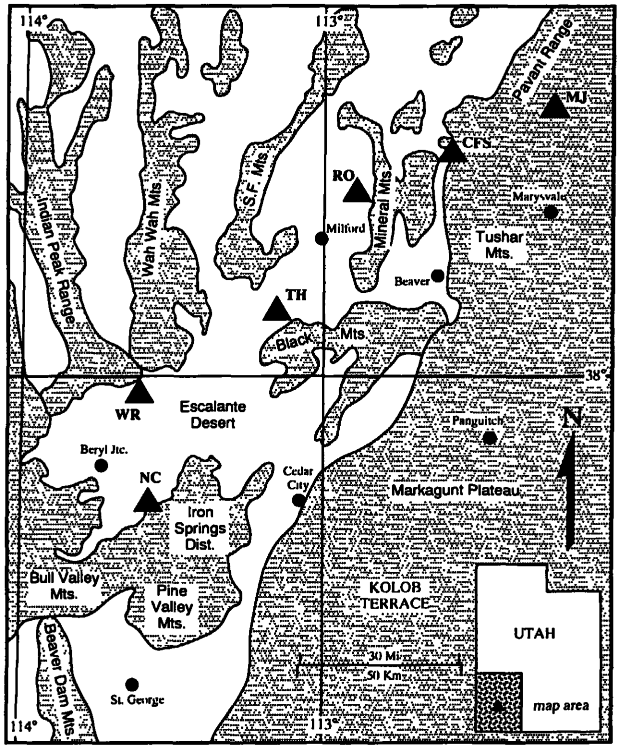

Figure 1. Geothermal areas and physiography in southwestern Utah. Newcastle (NC), Woods' Ranch (WR), Thermo Hot Springs (TH), Roosevelt Hot Springs (RO), Cove Fort-Sulphurdale (CFS) and Monroe-Joseph (MJ) geothermal systems.

Milgro Nurseries completed construction of a 1.62 hectare (1 ha = $10^4 m^2$ = 2.47 acre) greenhouse (the first of seven planned). Thermal fluids of 89°C are produced from a 155 m well, heat is extracted through a heat exchanger, and the cooled fluids are injected into the unconfined aquifer 610 m down-gradient from the production well. Because of uncertainties about the reservoir, increased fluid production could eventually stress the aquifer and/or present problems to developers with facilities already in place.

The expanded greenhouse development provides desirable, year-round employment well suited to this rural area, and provides an expanded tax base and economic boost to the southwestern Utah economy. It is important to improve our understanding of the hydrothermal system and to plan for sustainable (long-term) development which will provide continued employment and protect the capital already invested. This paper describes some preliminary monitoring efforts, discusses problems which may arise during future development, and presents a conceptual model for integrated, sustainable development of the resource.

GEOTHERMAL SYSTEM

The Newcastle area is located at the southern margin of the Escalante Valley (Figure 1), an elliptical basin approximately 70 by 45 km that includes much of the southern portion of the Sevier thermal area. The valley is situated near the Basin and Range-Colorado Plateau transition zone. It is surrounded by mountains and hills composed primarily of Tertiary ash-flow tuffs ranging in age from 32 to 19 Ma and 13 to 8.5 Ma rhyolite and dacite flows and domes. The Antelope Range fault marks the southeastern margin of the Escalante Valley. Blackett and Shubat (1992) completed detailed geologic studies and summarized previous geoscientific work in their case study of the Newcastle system. Geologic, geophysical and temperature data indicate that thermal fluids rise beneath alluvial cover at the intersection of a northwest-oriented fault and fracture zone and the northeast-oriented Antelope Range fault.

Exposed bedrock units southeast of Newcastle (described in detail by Siders et al., 1990) range in age from upper Cretaceous to upper Miocene, and consist of upper Cretaceous and lower Tertiary sedimentary rocks overlain by a series of mid-Tertiary ash-flow tuffs of regional extent (Figure 2). Local rhyolite and dacite flows cap these units. The oldest unit exposed is the Upper Cretaceous Iron Springs Formation, which consists of sandstone, carbonaceous shale, and limestone of fluvial and paludal origin with a thickness of 427 m. The Iron Springs Formation is unconformably overlain by the Eocene Claron Formation which consists of about 210 m of fluvial and lacustrine sediments (Blackett and Shubat, 1992). Mid-Tertiary (26 Ma to 19 Ma) volcanic units overlying the Claron Formation consist mostly of a series of dacitic to rhyodacitic ash-flow tuff units with source areas in the eastern Great Basin. Aerially extensive volcaniclastic rocks, that probably represent alluvial deposits shed from the flanks of composite volcanoes, lie above these units (Blackett and Shubat, 1992).

A variety of unconsolidated to semi-consolidated deposits overlie the bedrock units and constitute much of the Escalante Desert valley-fill. These units include moderately consolidated upper Miocene to Pliocene coarse fluvial material deposited at the margin of the Escalante Valley, and Pliocene to lower Pleistocene piedmont-slope alluvium (Siders et al., 1990). Pleistocene and Holocene alluvial units of the Escalante Valley generally terminate at the Antelope Range fault (Figure 2). This structure is a major north-northeast-trending, range-bounding normal fault that defines the south-

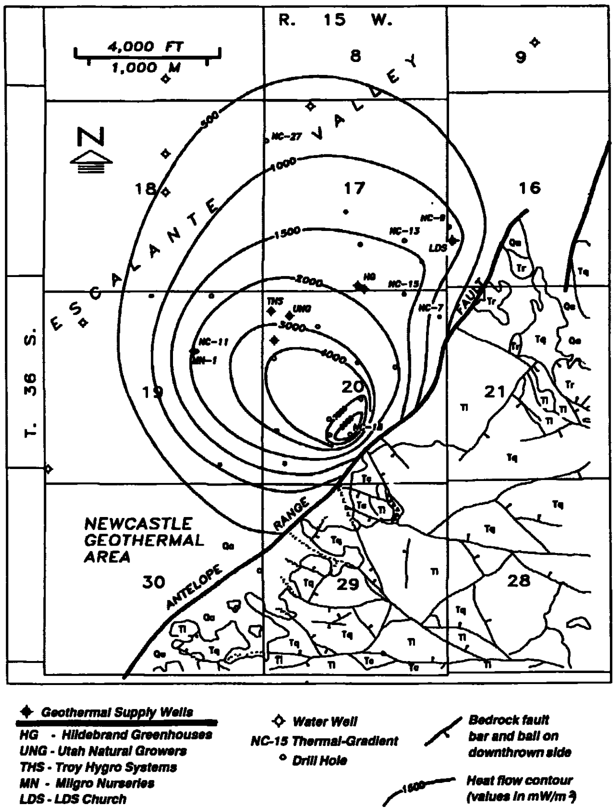

Figure 2. Revised heat-flow map for the Newcastle geothermal area (contour values in mW/m^2). Bedrock units (modified from Siders et al., 1990), faults (heavy lines, bar and ball on downthrown side), and locations of temperature-gradient holes are also shown. Tc: Eocene Claron Formation. Ti: Oligocene Isom Formation. Tq: Oligocene and Miocene volcanic rocks mainly of the Quichapa Group. Tr: Miocene Racer Canyon Tuff. Qa: Quaternary valley-fill units. Triangles in the north half of section 29 denote coarse fault breccia.

eastern side of the Newcastle graben, a feature first suggested by the regional gravity work of Pe and Cook (1980). Detailed gravity surveys by C.M. Schlinger (in Blackett and Shubat, 1992) suggest that valley-fill deposits within the Newcastle graben may be 1.6 km thick. Scarp morphology along the Antelope Range fault indicates a middle-to late-Pleistocene age for the last surface-rupturing event (Anderson and Christenson, 1989).

Geologic mapping of the volcanic units near Newcastle to determine fault locations, displacements and attitudes revealed that the greatest stratigraphic separation on bedrock faults (600 to 900 m) occurs along northwest-striking structures (Shubat and Siders, 1988; Blackett and Shubat, 1992). Several of these structures, when projected beneath the valley fill and onto the footwall of the Antelope Range fault, appear to intersect the Antelope Range fault near the center of the mapped thermal anomaly (Figure 2).

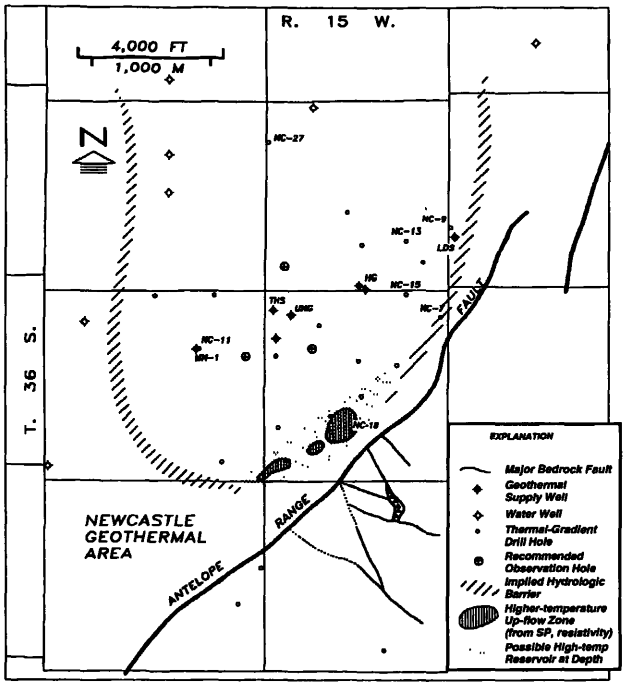

Figure 3. Principal elements of the Newcastle geothermal system from geologic and geophysical data. Arrows show flow.

Groundwater is present mainly within the unconsolidated and semiconsolidated valley-fill units of the Escalante Valley. The principal aquifer, described by Mower (1981), is tapped by numerous irrigation wells throughout the valley to the extent that groundwater no longer follows natural discharge paths northeastward toward Milford, but discharges to an artificial water-table depression near Beryl Junction. Near Newcastle, the potentiometric surface is higher relative to that in much of the Escalante Valley because the geothermal system discharges into the principal aquifer. The geothermal discharge originates in the shallow subsurface near the intersection of the range-bounding Antelope Range fault and high-angle bedrock faults (Figures 2,3). Thermal fluid spills from this discharge or upflow zone, into the principal aquifer of the Escalante Valley, and moves as an outflow plume northwestward down the hydrologic gradient.

Assuming a background heat flux of 100 mW/m^2, Blackett and Shubat (1992) reported an anomalous heat loss of 12.4 MW. A new calculation completed as part of this study, accounting for corrected well positions, and using the method of D.S. Chapman (in Blackett et al., 1990), yielded an anomalous heat loss of 13.8 MW (Table 1; Figure 2).

Ross et al. (1990) completed electrical resistivity and self-potential (SP) studies which provided independent evidence for the location of the thermal fluid upflow zone. A well-defined 108 mV SP minimum was mapped between the hottest shallow thermal gradient holes (NC-5,-14,-18,-19) and above the projected intersection of northwest-trending structures with the Antelope Range fault. Two lesser minima of -44 mV and -36 mV were later mapped to the southwest, also above the buried Antelope Range fault. Numerical models of dipole-dipole resistivity profiles resolve near-vertical low resistivity (4 ohm-m) bodies which are interpreted as upflow zones. They do not reach the surface, but form a low resistivity (4 ohm-m) layer at a depth of about 45 m within the alluvium that extends to the northwest. Figures 2 and 3 summarize the geologic, geophysical, and thermal results reported to date.

Heat flow contour interval (W/m^2)	Area(m^2) (10^6)	Average heat flow (W/m^2)	Heat Loss (MW)
0.5 - 1.0	3.01	0.75	2.26
1.0 - 1.5	1.95	1.25	2.44
1.5 - 2.0	1.36	1.75	2.38
2.0 - 3.0	1.06	2.50	2.65
3.0 - 7.5	0.87	4.75	4.13
7.5 - 9.0	0.053	8.25	0.44
> 9.0	0.035	9.00	0.32
Total	8.34		14.62
Background heat loss	8.34	0.10	0.83
Heat loss above background			13.8

Table 1. Revised heat loss for the Newcastle geothermal system.

DEVELOPMENT

In the late 1970's and early 1980's, developers drilled several water-supply wells to provide heat for a new greenhouse industry. Troy Hygro Systems, the Hildebrand Greenhouses, and Anzalone Greenhouses (later acquired by Utah Natural Growers) all developed water-supply wells in the thermal aquifer and disposed of spent fluids in shallow percolation pits or injection wells. The greenhouses of Troy Hygro Systems have been inactive since 1990. A well equipped with a downhole heat exchanger provides heat for an LDS church in the town of New Castle, and is reported to provide reliable heat for the building. Some local residents drilled wells and equipped them with downhole heat exchangers, but the recent construction of a natural gas pipeline through New Castle has displaced the use of geothermal fluids for home space heating.

In July 1993, Milgro Nurseries, Inc. began developing a state-of-the-art greenhouse facility with construction of a 1.62 ha greenhouse. Milgro drilled a 155 m production well (MN-1) near observation well NC-11. Geothermal fluids at 89°C are circulated through a heat exchanger and the cooled fluids (60°C) are sent to an injection well downgradient from the production well. The production well performed without problems throughout the 1993-94 heating season with no noticeable decline in temperature or water level (William Gordon, Milgro Nurseries, Inc., personal communication, 1994).

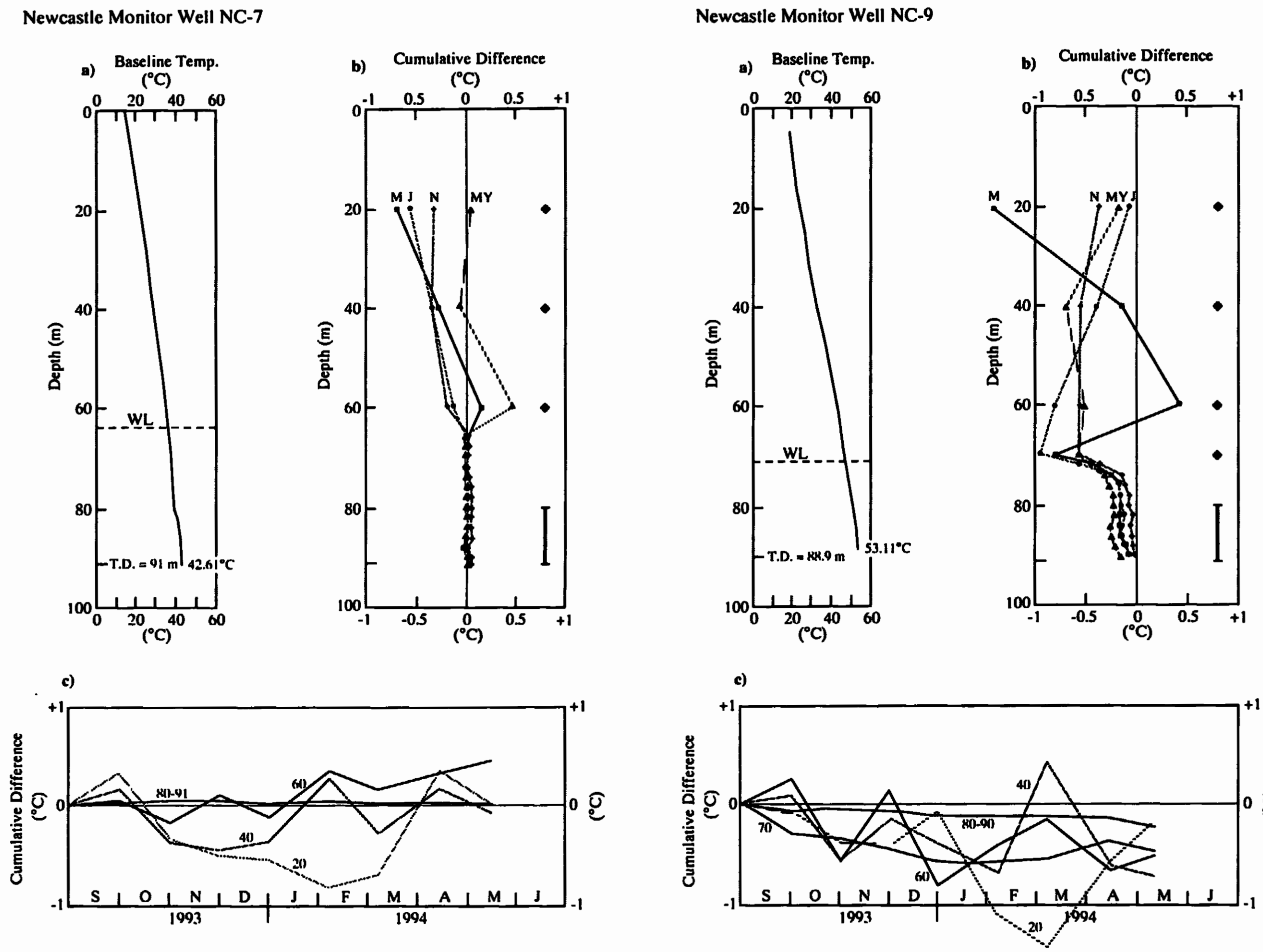

Figure 4. Newcastle monitor wells NC-7 and NC-9. (a) Baseline temperatures on August 31, 1993; (b)Cumulative temperature differences for November 1993(N), January (J), March (M) and May (MY), 1994; and (c) Cumulative temperature differences for selected depths (filled diamonds) or depth intervals (vertical bars) shown in (b), September 1993 through May 1994. WL = water level; T.D. = total depth.

Several potential developers have expressed interest in the Newcastle geothermal system since 1990, and additional development of the thermal aquifer, and perhaps the source-zone of the geothermal system, can be expected. Milgro Nurseries has announced plans for a systematic expansion to as many as five units (8 ha) if reservoir and market conditions permit. The upflow area, with temperatures above 130°C (Blackett and Shubat, 1992), may be suitable for power generation using binary technology if market and other economic conditions become favorable. Local power demands include pumping for irrigation to support a considerable agricultural industry (spring through early fall) and pumping of thermal fluids to support the greenhouse industry (fall through spring). The Dixie Escalante Power Cooperative, located in nearby Beryl Junction, is the local power distributor.

MONITORING STUDIES

Reservoir testing of the thermal aquifer has been very limited, and the long-term production potential is not known. Anticipating a possible large demand upon the thermal aquifer, the Utah Geological Survey (UGS) and the University of Utah Research Institute (UURI) began a program of temperature monitoring in August 1993. Temperatures observed in August 1993 are regarded as the baseline case because a minimum of thermal fluids were being pumped for greenhouse heating, and initial testing of the Milgro well had been discontinued. No funds were available for drilling new observation holes so monitoring has been limited to preexisting observation holes which could be accessed. Temperature logs were completed in NC-7, -9, -11, and -15 on August 31, and a fifth hole, NC-13, was added on October 5 after obtaining landowner permission (Figures 2,3).

The data obtained from monthly temperature profiles in the monitor holes have been reported in a series of UGS Technical reports by Blackett (1993, 1994). The reports document baseline temperatures, previous and current month temperatures, and incremental (one month) and cumulative (since baseline observations) temperature changes at standardized

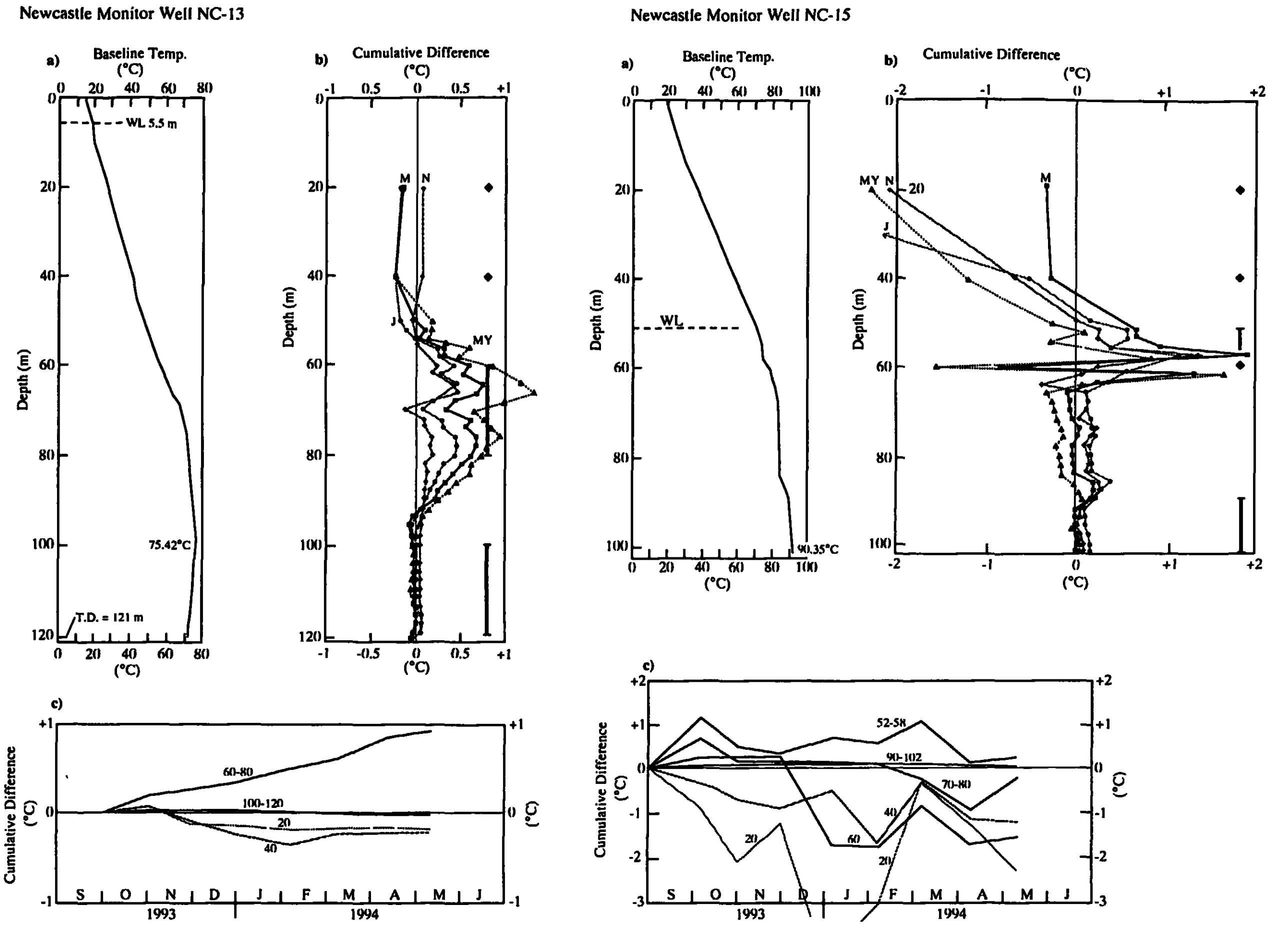

Figure 5. Newcastle monitor wells NC-13 and NC-15. (a) Baseline temperatures of August 31, 1993; (b)Cumulative temperature differences for November 1993(N), January (J), March (M) and May (MY), 1994; and (c) Cumulative temperature differences for selected depths (filled diamonds) or depth intervals (vertical bars) shown in (b), September 1993 through May 1994. WL = water level; T.D. = total depth.

depths. The data will be reported in more detail in a future UGS technical report. Temperatures are measured at 20-m intervals above the water level (readings made in air) and at 2-m intervals below the water level. Casing strings in three wells (NC-7,-9,-11) are apparently ruptured within the saturated zone. Water levels in these holes appear to fluctuate in response to changes in the water table. Figures 4, 5, and 6 summarize baseline temperatures and cumulative temperature differences for several months, and temperature variations at selected depths with time. Climatological data from the Cedar City Airport weather observatory are shown in Figure 7 for reference to heating demands.

Although the distribution and depth of the monitor wells (Figure 3) are not ideal, monthly temperature measurements could provide some early indications of aquifer response. Hole NC-7 is located near the Antelope Range fault about 1100 m north of the upflow zone, and NC-9 is near the church supply well. Observation holes NC-13 and NC-15 are within 610 m of the Hildebrand Greenhouse wells, and NC-11 is only 19 m east of the MN-1 well.

Temperature measurements were made with UURI's N. P. Instruments high-precision thermistor probe and temperature logging equipment. Instrument characteristics and monthly calibrations result in a temperature measurement precision of 0.01°C, but observation hole conditions, and convection within the hole may sometimes reduce the measurement accuracy to +/- 0.05°C. Beginning in October 1993, fluid level measurements were made in all observation holes using a Soiltest Water Level Indicator. All observation holes were initially completed with a cap at the bottom of the pipestring and filled with water to facilitate temperature measurement, but most pipes have ruptured and reflect the local water table depth.

Water levels determined for the observation holes are summarized in Table 2. NC-7 shows a systematic rise in water

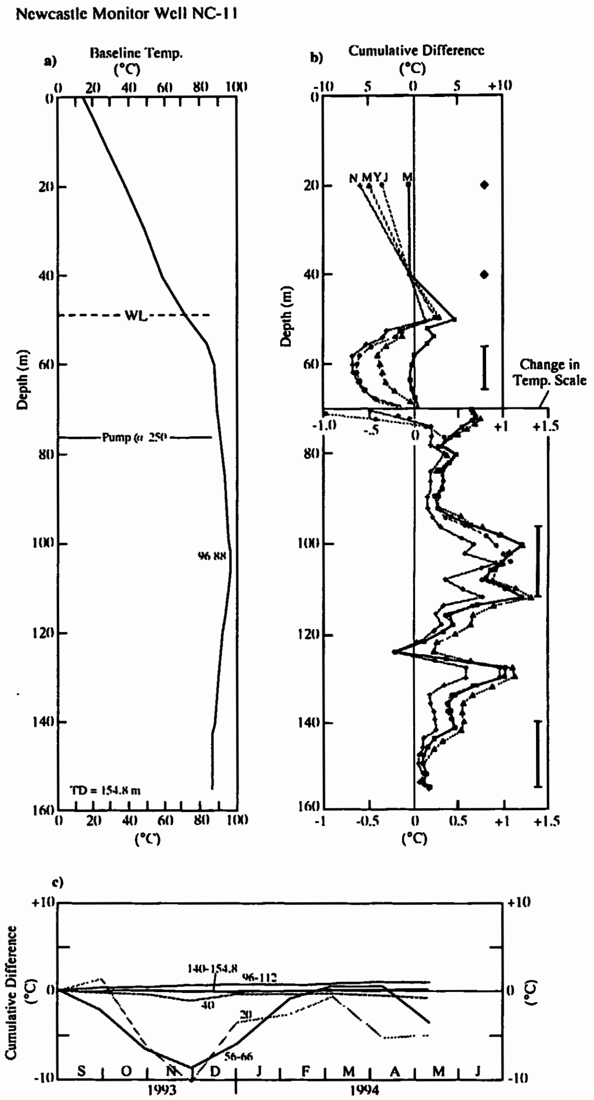

Figure 6. Newcastle monitor well NC-11. (a) Baseline temperatures of August 31, 1993; (b)Cumulative temperature differences for November 1993(N), January (J), March (M) and May (MY), 1994; and (c) Cumulative temperature differences for selected depths (filled diamonds) or depth intervals (vertical bars) shown in (b), September 1993 through May 1994. WL = water level; T.D. = total depth.

level from November to April amounting to 0.8 m. NC-9 rose 2.4 m over this period. Water levels in these observation holes probably indicate the depth of the true water table. The change in water level is the likely response to reduced pumping for irrigation rather than to increased recharge. Water levels in NC-11 declined 0.2 m during the heating season, then recovered to the November level by April. Water levels in all three holes declined between the April and May observations, probably in response to renewed pumping for irrigation. NC-13 and NC-15 are closed-loop systems which do not provide insight into the groundwater levels in the adjacent formations.

Date/ Hole	NC-7	NC-9	NC-11
11/02/93	64.7	71.5	48.2
12/02/93	64.5	70.9	48.33
01/05/94	64.3	70.3	48.33
02/07/94	64.25	69.82	48.43
03/07/94	64.12	69.40	48.34
04/11/94	63.92	69.07	48.22
05/10/94	64.00	70.04	48.31

Table 2. Water Levels in Observation Holes (depths in m).

Several factors may contribute to temperature changes observed in Newcastle observation holes. Both short-term and seasonal air temperature variations (Figure 7) may perturb shallow temperatures above the water table. Reduced pumping of the cold water aquifer for irrigation (fall and winter) may result in increased inflow of cool, shallow groundwater and water table rises. Short-term production of thermal fluids may increase temperatures in more permeable zones of the thermal aquifer, as hotter water moves toward the pumped wells. Less permeable zones may show little change on a seasonal or short-term basis.

NC-7. Temperatures were significantly cooler (0°-0.5°C) above the water table through the heating season, and slightly warmer (0.02°-0.06°C) near the bottom (80-91 m) of the hole (Figure 4). Bottom-hole temperatures approached baseline values (+0.01°C) in March. This hole penetrated only the upper part of the thermal aquifer.

NC-9. Temperatures were also cooler above the water table during colder months (Figure 4). At depth (70-90 m) fluids were cooler (0.04°-0.18°C) through the heating season, perhaps due to proximity of the nearby LDS church well. This hole also penetrated only the upper part of the thermal aquifer.

NC-13. This borehole contains two concentric pipes installed as a simple down-hole heat exchanger. Water level was maintained at about 5 to 6 m depth. A broad zone near the water table (60-80 m) became progressively warmer (0.2°-1.0°C) through the heating season (Figure 5), probably due to a greater mix of thermal fluid moving through a permeable aquifer in response to pumping for nearby (HG) greenhouses. Minor fluid warming at the bottom of the hole (100-120 m) reversed by March and remained slightly (0.04°C) cooler.

NC-15. Substantial cooling above the water table (1° to 4°C) changed abruptly to heating in the thermal aquifer at the water table. A thin, cool water zone may occur at 60 m, but the remainder of the borehole showed heating, often between 0.1° and 0.4°C during the heating season. Temperatures declined at depths of 65 to 85 m from March through May. This borehole may be responding to pumping of wells at the Hildebrand and Utah Natural Growers' greenhouses.

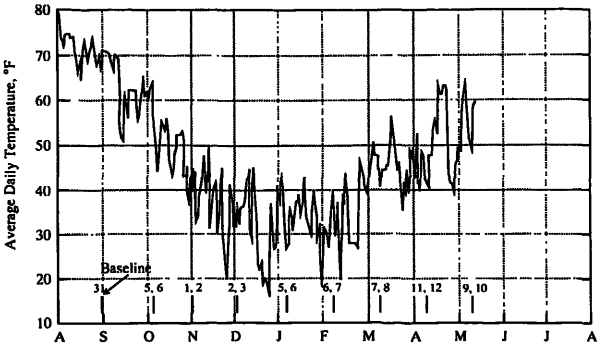

Figure 7. Daily average temperature at Cedar City airport, Utah, about 30 miles east of Newcastle. Baseline and monitoring dates are indicated on the time scale.

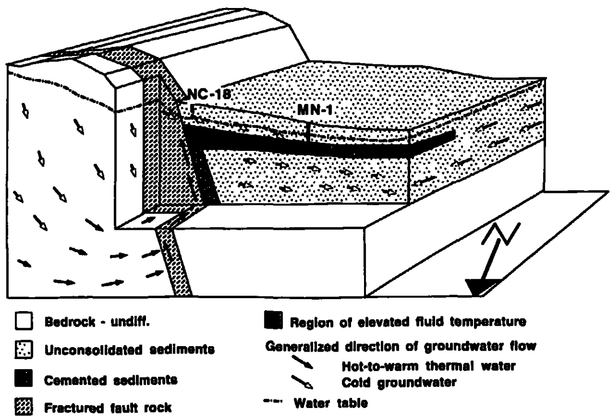

Figure 8. Conceptual model for groundwater flow in the Newcastle hydrothermal system (after Blackett et al., 1990.)

NC-11. This hole, only 19 m from the MN-1 production well, showed the most pronounced changes. Temperatures above the water table declined by 1° to 10°C (Figure 6), then recovered as heating degree days (HDD) declined. Average temperatures for a 10 m zone below the water table declined by 5.9° to 8.7°C for November through January, a period of 20-50 HDD. We interpret this as drawdown of the top of the thermal aquifer in response to fluid production, with inflow of cooler waters from the margins of the system. With few exceptions, the rest of the thermal aquifer below the near-surface zone warmed significantly (0.5°-1.2°C, 90-130 m). A zone near 125 m cooled slightly and the bottom of the hole (140-154.8 m) warmed slightly (0.1° to 0.2°C), possibly indicating permeability contrasts.

In summary, all holes showed seasonal temperature declines above the water table which correlate with seasonal air temperature changes (Figure 7). Monitor hole NC-9 alone showed a temperature decline to depth, perhaps due to heat extraction for the LDS church. All other wells showed general temperature increases below the water table during most of the heating season, which later decreased near the end of the heating season. The most significant feature is the depression of the thermal aquifer at NC-11 by approximately 20 m, and its replacement by cooler, mixed waters. Wells NC-11, -13, and -15 all show increasing temperatures below the water table during the heating season.

Although significant temperature changes have been observed, neither temperature or water level changes impacted users during the relatively mild 1993-94 heating season. Increased production levels during a colder winter may impact closely spaced production wells. Water level declines near MN-1 were almost insignificant although shallow temperatures declined dramatically, suggesting relatively high permeability and connectivity with the cool water aquifer. Substantial water level increases at NC-7, NC-9 suggest a rapid aquifer response to reduced pumping for irrigation during the winter months. Additional monitor wells, suitable for both temperature and water level measurement, should be emplaced in areas anticipating substantial added development.

SUSTAINABLE DEVELOPMENT MODEL

Conceptual and numerical models of the Newcastle hydrothermal system are required to assist in planning for additional development with minimal adverse impact on existing users. Although a reasonable conceptual model has been formulated (Blackett et al., 1990), only preliminary modeling studies have been performed to date. Once the numerical simulator has been fully tested against the existing database, however, the model will provide a basis for assessing the impact of existing geothermal development and aid in siting additional production and injection wells.

Blackett et al. (1990) proposed the conceptual model for the Newcastle hydrothermal system shown in Figure 8. Inferred patterns of flow are indicated by the arrows shown within the various panels of Figure 8. Note that, in most cases, the arrows represent only the components of flow within the indicated panel. Topographic relief on the water table is assumed to provide the dominant driving force for fluid flow within the system. Therefore, meteoric water recharging in the highlands circulates deeply within the mountain massif before discharging into the valley-fill sediments. In the absence of the permeable fault zones shown in Figure 8, insufficient heat would be extracted to form a concentrated geothermal resource. The enhanced permeability associated with the intersection of two major faults provides for locally enhanced groundwater circulation to greater (hotter) depths and a well-defined conduit structure that focuses the upflowing thermal fluid. The location and size of upflow zones inferred from SP and resistivity surveys are shown in Figure 3. Clement (1981) and Rush (1983) estimate that a minimum volume discharge of 0.032 m^3s^{-1} from these upflow zones is required to produce the estimated heat loss of 13 MW (slightly less than the revised heat loss of 13.8 MW determined in this study).

Groundwater with elevated temperature and relatively high total dissolved solids (TDS) discharging from the fault zone intersection must mix with cool and relatively fresh groundwater circulating in the valley-fill deposits. This mixing process may contribute to the precipitation of siliceous and/or carbonate minerals within the porous sediments that, in turn, causes reduced permeability in the vicinity of the mixing zone. In early stages of system evolution, the region of mixing was likely located at the base of the valley-fill sediments. Through time, however, the mixing of fluids in the sediments may contribute to progressive construction of a low-permeability seal that extends upwards from the original point of discharge at the bedrock surface to a position relatively close to the ground surface (Figure 8). Concurrent downward movement of the hanging wall block of the mountain-bounding fault likely contributes to upward growth of the precipitate seal. Development of the seal may be enhanced wherever boiling occurs, due to mineral precipitation.

Heated groundwater discharging to the valley-fill deposits forms a thermal-chemical plume (Figure 2) with a size and shape controlled, in large part, by the character of the shallow groundwater flow system. Previous studies of the groundwater regime near Newcastle (Mower, 1982) indicate a predominant northward trend for groundwater flow. This pattern of groundwater flow would be expected to cause the increasing distance between heat flow contours when traversing the geothermal system from south to north (Figure 2). Further evidence for an elongate, northerly-trending thermal-chemical plume is shown by similarities in chemistry and isotopic signatures of groundwater samples collected from wells in the outflow plume (Blackett et al., 1990; Mower, 1982).

The conceptual models of Clement (1981) and Chapman et al. (1981) differ from the one discussed here because they assume that a localized, high-temperature fluid source is injecting hot water into a static groundwater regime. In our model, however, we assume uniform groundwater flow into the valley-fill from the adjacent bedrock along the mountain front. A zone of elevated temperature develops only because the fault intersection provides a conduit for localized upflow of hot water. Elsewhere along the mountain front, relatively cool water is likely discharging from the bedrock into the valley-fill sediments and contributing to the pattern of shallow groundwater flow in the sediments.

Use of geothermal heat at Newcastle involves producing hot water from a thermal plume using wells completed at locations relatively far from zones of upflowing thermal water (Figure 3). As a consequence there is a legitimate concern that excessive production could modify the geometry of the thermal plume. Several scenarios are possible. First, increasing production at one location might redirect northward flow of hot water away from other geothermal supply wells. Second, increased production by existing or new users might accelerate the movement of cold groundwater into the area and yield a smaller region of elevated temperature. Third, increased production might only have a small, unimportant impact on the geometry and character of the thermal plume that forms the geothermal production zone. The complex interaction between the upward flowing thermal water and the shallow

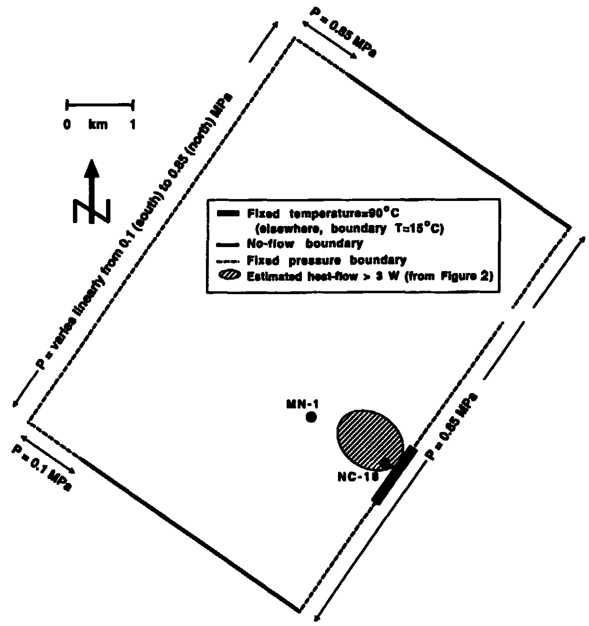

Figure 9. Numerical modeling domain and boundary conditions for two-dimensional simulations of coupled fluid-flow and heat transfer at the Newcastle hydrothermal system.

groundwater flow system dictates that a numerical model be used to distinguish among three scenarios.

Constructing and implementing a two-dimensional, horizontal model of fluid flow and heat transfer forms an important first step in attempting to model the Newcastle hydrothermal system. The well-defined thermal plume shown in Figure 2 provides an important set of field observations that can be used to constrain the numerical simulations. Although the Newcastle hydrothermal system must ultimately be simulated with a transient three-dimensional model, a series of steady-state, two-dimensional simulations provides a sound basis for developing a robust model of the system.

We use a finite element model of transient fluid flow and heat transfer, FEHMN, developed by Zyvoloski et al. (1992) to simulate the geothermal system. The rectangular, two-dimensional model domain shown in Figure 9 represents only the upper 100 m of the saturated valley-fill deposits shown in Figure 8. Elements are square with length 100 m. Fluid pressure boundary conditions have been iteratively adjusted with the goal of creating a groundwater flow pattern that mimics the northerly trend of the thermal plume. The large modeling domain is used to isolate the critical interior region of elevated heat flow from uncertainties inherent in assigning boundary conditions. The uniform pressure condition applied along the southeastern boundary causes uniform inflow (representing recharge from bedrock) with a localized region of elevated temperature included to portray the inflow of thermal fluid.

Assigning plausible physical parameters (permeability = 10^{-11} m^2, specific storage = 0.002 m^{-1}, thermal conductivity = 2.7 W m^{-1} $°K^{-1}$) within the model domain (Figure 9) has produced a northerly trending thermal plume with a geometry that crudely resembles the heat-flow map shown in Figure 2. This positive result has led us to construct a two-layer, three-dimensional model domain similar to the two-dimensional domain shown in Figure 9. The three-dimensional modeling runs are currently under way.

The ultimate goal of the modeling study involves attempting to match, in steady-state mode, the heat-flow observations made at monitoring wells. Once this goal is accomplished we will attempt to match the changes in temperature observed in response to production-injection at selected sites. When a match of the transient system is achieved, the model will be ready to aid in predicting the response of the hydrothermal system to long-term geothermal development.

Additional data are needed to complete the modeling effort. Although the results of several short-term aquifer tests are available to provide insight into hydraulic properties of the hydrothermal system, insufficient information is available to fully evaluate the long-term thermal response of the geothermal system to pumping and reinjection of thermal fluid. Frequent temperature-depth measurements in temperature-gradient holes, coupled with observations of water level change and pumping-injection rates, must be continued to provide a baseline for interpreting future changes in the thermal regime and to monitor long-term response to ongoing pumping and injection. Because only one monitoring well (NC-11) is located close to a geothermal supply well (MN-1), it is difficult to assess the lateral impact of pumping and reinjection in the Newcastle geothermal system.

A better distribution of monitoring wells in free communication with the ground water table, is required for monitoring the thermal aquifer response at Newcastle. Lithologic information, to depths of at least 150 m, should be acquired for any holes drilled within the thermal aquifer, and aquifer testing should be completed to better determine reservoir properties. A minimum of three drill holes should be completed in the general locations suggested in Figure 3, to observe long -and short term changes in both water level and temperature that result from changes in the geothermal production schedules. A more complete numerical model could then be developed which could serve as a guide to well spacings, location of injection wells, and production levels for the thermal aquifer.

SUMMARY AND RECOMMENDATIONS

A hydrothermal system located along the Antelope Range fault discharges thermal fluids into a shallow alluvial aquifer, with an anomalous heat loss of about 13.8 MW. An expanding greenhouse industry utilizes the fluids for space heating, and may stress the thermal aquifer as development continues. Monitoring of five observation holes during the relatively mild 1993-1994 heating season revealed substantial temperature and water level changes, but no adverse effect on greenhouse fluid production or long-term changes to the thermal aquifer.

Full utilization of the hydrothermal resource would include binary power production which could produce electric power for irrigation and pumping of thermal fluids for greenhouse heating. Present economic conditions, however, seem to favor space heating to protect greenhouse investments and to sustain the anticipated increased employment levels.

The authors recommend the drilling of three new observation holes, lithologic studies, and aquifer tests to enhance a numerical model which could predict aquifer response under increased pumping levels. We also recommend a expanded effort in temperature and water level monitoring, but at a reduced frequency of two or three months during the heating season. These activities would require new funding and such funding has not yet been identified.

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