MEMORANDUM REPORT
May 30, 1991

TO: PYRAMID ENGINEERS AND LAND SURVEYORS
FROM: WILLIAM E. NORK, INC.

RE: A SUMMARY OF THE HYDROGEOLOGY OF THE GEOTHERMAL RESERVOIR AT SUSANVILLE, CALIFORNIA WITH EMPHASIS ON POTENTIAL IMPACTS AS A CONSEQUENCE OF RE-INJECTION OF HEAT-SPENT GEOTHERMAL EFFLUENT.

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INTRODUCTION

Current conceptual models of the hydrogeology of the geothermal aquifer in the vicinity of Susanville, California are based on a number of investigative efforts. The most comprehensive and insightful work to date is that of Benson, _et. al._ [1980]; Sanyal _et. al._ [1984]; and the U.S Bureau of Reclamation [1982]. More recent work completed for the California Energy Commission (WEN, INC.; 1989) supports the conclusions reached in the previous studies and yielded new information regarding a vertical hydraulic connection between the geothermal aquifer and overlying non-thermal aquifers. All of the information tendered in these works is not reprised in the ensuing discussion. Instead, salient aspects of the hydrogeology are addressed in order that re-injection of the heat-spent thermal effluent from the City of Susanville's district space-heating system can be discussed in the context of the hydrogeologic conditions known or believed to exist in this area.

SUMMARY OF THE HYDROGEOLOGY

The areal extent of the Susanville geothermal reservoir is very limited, perhaps as small as one square mile, depending on perception of the boundaries. The principal aquifer materials are fractured basalt flows, permeable beds in the alluvial deposits, and scoriaceous horizons along the tops and bottoms of individual basalt flows.

The geothermal aquifer is dominated by faults. That is, geothermal fluids upwell along conduits related to fractures resulting from faulting and move laterally in a southeasterly direction through permeable horizons within the aquifer beneath a relatively impermeable "cap rock". Numerous steeply dipping faults subdivide the area into multiple "structural blocks" (Figure 1). The hydrogeologic properties of the reservoir vary from block to block. Recent alluvial deposits overlie the geothermal aquifer. These deposits obscure the precise locations of the faults. Consequently the boundaries between the individual blocks must be inferred from borehole geologic and geophysical logs, temperature data, etc.

The top of the reservoir, as inferred from bore-hole temperature logs, ranges from an elevation of approximately 4,100 feet above sea level to 3,800 feet, or approximately 60 to 100 feet below land surface. The elevation of the top of the reservoir decreases from west to east.

The concept of compartmentalization of the resource into these structural blocks which are bounded by faults is significant from both regulatory and technical perspectives. Underground Injection

Control (UIC) regulations are predicated on: (1) re-injection to an extensive hydrostratigraphic unit with more or less uniform hydrochemistry; (2) a widespread confining layer (aquiclude) serves to isolate the injection horizons from overlying underground sources of drinking water (USDW); and (3) faults or other conduits for vertical leakage of injectate are undesirable within the area of influence of the injection well.

All of the geothermal investigations completed in the Susanville area to date indicate that the geothermal aquifer there does not fit the UIC conceptual model. The geothermal flow system is clearly not isolated from USDWs nor are its lateral boundaries clearly defined. Rather, there is a gradual transition from geothermal to non-thermal water as the natural thermal plume is attenuated by leakage to shallower aquifers, mixing with non-thermal waters, and conductive heat loss.

Geothermal water derived from the two City geothermal production wells (Susan-1 and Naef) contains approximately 900 milligrams per liter (mg/l) total dissolved solids. The ambient ground water derived from Richardson-1 (the City's re-injection well located approximately 1,200 feet from Susan-1) is similar to the water originating from the production wells, albeit slightly diluted with water of meteoric origin. Farther downgradient, the divergence from the parent fluids becomes more pronounced. One mile southeast (downgradient) of the eastern-most thermal well, one of the City's quasi-municipal wells discharges ground water which is a mixture of 45 percent geothermal fluid and 55 percent non-thermal water.

Stratification of waters exists in the formation. For example, the ground water sampled from Allen-1 at a depth of 90 feet (within the cap rock) is typical of the shallow meteoric water (TDS of 184 mg/l). At a depth of 120 feet (bottom of the cap rock), the water becomes similar in overall character to that of dilute fluids derived from Susan-1 (sodium-potassium-sulfate water with a TDS of 614 mg/l).

Given these facts, the boundary between the thermal and nonthermal aquifers is very nebulous on the basis of chemistry alone.

The areal extent of the geothermal aquifer is ill defined in terms of temperature as well. The wells showing the highest temperature fluid are found along the western margin of the resource. Ground water with a temperature of 180°F is derived from Susan-1, the City's principal production well. Approximately one-half mile downgradient (southeast), the temperature of the Naef well is 151°F. One-half mile farther downgradient (one mile southeast of Susan-1) the temperature declines further to 143.7°F in SGI-1. A short distance farther downgradient, the temperature declines to less than 90°F. Even within the shallow alluvial aquifer which is exploited as a source of water to supply to individual domestic wells, there is vertical variation in temperature caused either by conductive heating or natural upward leakage of geothermal fluids from below.

Analyses of aquifer stress tests (both pumping and injecting) yield generally consistent values for the hydraulic properties of the aquifer. The geothermal aquifer is considered to be moderately to highly transmissive, in the range of approximately 24,000 gallons per day per foot width of aquifer (at 70°F). The presence of recharge and discharge boundaries is open to interpretation. These boundaries almost certainly exist, but are not clearly evident in the testing results either because they are too far from the wells which were tested (or so close that their effects are virtually instantaneous, thereby imperceptible). Also their presence is masked by "noise" in the data, limitations in the instrumentation, or they are otherwise hydraulically transparent.

An early interpretation of test data suggested an impermeable boundary exists somewhere in the study area, but further analysis dismissed its presence. However, the moderately low transmissivity of the aquifer in the vicinity of Davis-1 and the very low transmissivity in the vicinity of the unsuccessful injection well, SGI-1, implies that a negative boundary may exist approximately one mile southeast of Susan-1. This boundary presumably represents a block of relatively impermeable geologic materials in this area. It probably is discontinuous, however, because testing of other wells elicited a measurable response across this hypothetical boundary, a phenomenon which may result from vertical offset of permeable zones consequent to faulting.

THERMAL EFFLUENT DISPOSAL

It is clear that utilization of the geothermal resource at Susanville, or anywhere else for that matter, requires disposal of the heat-spent thermal effluent. Intuitively, at least, the most desirable method of disposal is re-injection because this alternative imparts the added benefit of maintaining reservoir pressure. It is imperative that injection well sites be carefully selected to minimize the potential for temperature breakthrough, the deleterious consequences of which include unacceptable cooling of the fluids discharged from production wells. In an aerially limited aquifer such as the one which exists beneath Susanville, adequate separation between production and re-injection wells may provoke an entirely new series of problems, particularly if the chemical quality of the injection horizon is "degraded" by the thermal effluent. Unfortunately, a great deal of effort and funds can be expended selecting and completing an injection well, only to have authorization to use the well for disposal purposes denied on the basis of an overly restrictive definition of degradation.

The City of Susanville has been unsuccessful in its efforts at fluid disposal via re-injection to date. Two wells have been drilled for the express purpose of disposal of the effluent. The first, Richardson-1, is located approximately 1,200 feet northeast of Susan-1. The well and/or the formation apparently sustained major damage during the drilling process and consequently accepts only a fraction of the water currently discharged from the City system, which equates to an insignificant amount of the effluent which would be generated if the system is expanded. At present, approximately 150 gpm is re-injected into this well. If the well was rehabilitated, and the workover effort was totally successful, Richardson-1 could be expected to accept 500 gpm at approximately 73 psi. Under this scenario, at least one more well would be required in order to dispose of the current quantity of effluent and several more wells would be necessary for the City to expand the system in order to fully exploit and utilize the resource.

The second injection well drilled by the City is SGI-1. It is located approximately 4,200 feet southeast (downgradient) of Susan-1. It was completed in a structural block which appears to be much less permeable than the one(s) in which the principal production wells completed within the Susanville geothermal anomaly are located. The amount of water which could be injected in this well is insignificant.

Successful geothermal wells at Susanville are completed in fracture zones associated with the faults or permeable horizons identified within a particular block, but which are discontinuous on a larger scale. For reasons alluded to above, these producing zones are not clearly delimited at the surface. As a result, siting a successful well conveys substantial risk, as illustrated by the results of SGI-1. This injection well was drilled at a location which the available information suggested a good potential for success, and yet, proved to be a total failure.

The SGI-1 experience indicates that investigative techniques which are routinely used to characterize subsurface hydrogeologic conditions in simple environments, do not yield a sufficiently high level of confidence for the conditions which exist in the study area. These traditional methods simply do not have the necessary resolution to clearly identify drilling targets which are limited in vertical or horizontal extent. Exploratory tools such as surface geophysical surveys, are hampered by cultural interference, such as buried pipes, overhead power lines, traffic, and rail lines, all of which preclude their use in this urban setting. Higher resolution might be achieved, but at a cost which is not warranted by the size and scope of the City's district space-heating system. Drilling strategies degrade to that of "poke and hope". Under this approach, a well is completed at the chosen location to test the accuracy of the selection process. One then hopes that the injectivity of the well will be sufficiently high to enable re-injection and that the chemistry of ambient ground water will be such that injection will be allowed by agency regulations.

To date, there has been no rigorous analysis of the influence of re-injection of thermal effluent on the Susanville geothermal reservoir in terms of thermal breakthrough or maintaining reservoir pressure. This is in large part due to the complexity of the geothermal flow system itself and its interrelationship with the overlying potable water aquifers. Such an analysis demands development and calibration of a three-dimensional numerical ground-water flow and contaminant transport model. While a great deal of data exist, more data are necessary to yield a model which will have predictive value. The cost to generate these data and that of the modelling effort itself can be expected to be very high and could easily offset the energy savings currently realized by the district space heating system or otherwise dramatically affect the long-term economic benefits. Such a model still does not guarantee that a specific well site will be successful because, by their very nature, models must average the physical conditions which exist in the aquifer and may not accurately depict variations over small distances.

A degree of insight into the current conditions resulting from present-day withdrawal and injection rates can be gained through simplified modelling of the system, however. Furthermore, possible repercussions of discharging and re-injecting at rates different from those currently in effect can also be examined. Such a model may even provide guidance regarding the "safe" distances between pumping and injecting wells to minimize the potential for thermal breakthrough.

A simple model which superimposes withdrawals and re-injection on a uniform ground-water flow field was examined and is proffered below. The model constitutes a 10,000 foot by 7,000 foot area of the geothermal aquifer. Ground-water flow in a southeasterly direction was simulated by fixing constant-head boundaries along the northwest and the southeast model borders and a uniform transmissivity equal to the average for the geothermal aquifer over the model area.

The specific model which was employed is FLOWPATH, ver. 3.02 [Franz & Guiguer, 1990]. This steady-state finite difference model was selected for two reasons. First, it allows the model to be set up and modified within a computer aided design (CAD) environment. This feature greatly simplifies and expedites model creation and changes in input. Second, it includes a subroutine which tracks the movement of imaginary particles in the ground water as they migrate toward pumping wells and away from injection wells. This feature enables the user to readily follow the path of the injectate in a pumping/injection well couple and to visually judge the potential for breakthrough of the injectate.

A series of model runs were performed. Initial runs assumed pumping Susan-1 or the Naef well at an average rate of 500 gpm and injecting 150 gpm of the effluent at Richardson-1 (Figures 2 and 3). These simulations showed no potential for breakthrough at either production well. Since neither well appears to be suffering from breakthrough at present, this model run appeared to duplicate current conditions to a limited degree. The next set of model runs increased the injection rate at Richardson-1 to 500 gpm, the hypothetical maximum injection rate assuming that the well can be successfully rehabilitated. The result was a small potential for breakthrough at both production wells (greater at Naef than Susan-1) (Figures 4 and 5).

The third set of model runs assumed that both production wells were pumped at a combined rate of 1,100 gpm (Susan-1 at 700 gpm and Naef at 400 gpm) and injection into Richardson-1 at rates of 150 and 500 gpm (Figures 6 and 7). The result suggested a large proportion of effluent would breakthrough to the Naef well regardless of the injection rate. Breakthrough to Susan-1 appeared to be a potential problem only at the higher injection rate.

A fourth series of model runs simulated pumping Susan-1 and the Naef well at a combined rate of 1,100 gpm, injecting 150 gpm in Richardson-1, and injecting the balance (950 gpm) in a hypothetical injection well located near Tsuji-2 (approximately 1,400 feet southeast of the Naef well) (Figure 8). This scenario resulted in breakthrough of approximately 20 percent of the effluent to the Naef well. The injection rate in the hypothetical injection well was reduced to 350 (total injection rate of 500 gpm for the two injection wells). The remainder of the effluent was otherwise disposed. The outcome was a decrease in the potential for breakthrough to the Naef well, but breakthrough still appears to be a potential problem (Figure 9).

The final model run examined, by trial and error, the distance between pumping and injection wells which would be required (under the constraints of the model analysis) to eliminate breakthrough at a pumping and injection rate of 700 gpm, each. The results suggested injection wells should be placed approximately 3,000 feet downgradient from production wells at this rate. This outcome is significant because water chemistry data show the chemical quality of the ground water a distance of 3,000 feet downgradient of the city's production wells is substantially better than the produced geothermal fluids. Re-injection would almost certainly be perceived as causing degradation of the receiving waters.

CONCLUSIONS

The conclusion inferred from this extremely oversimplified analysis of the geothermal system is that it is highly improbable that a well can be completed that will satisfy all of the criteria which must be met to ensure a successful re-injection well. These criteria are:

1. The aquifer at the injection well site is sufficiently transmissive to enable re-injection of the total effluent from the City space heating system at acceptable pressures.

2. The ambient chemistry is sufficiently similar to the injectate so that there is no perceived degradation of the receiving waters.

3. The injection well is hydraulically isolated from the production wells to ensure that temperature breakthrough of the heat-spent thermal effluent does not adversely impact temperature of water derived from the production wells.

The analytical results suggest that as much as 500 gpm of the thermal effluent might be disposed of via re-injection within the reservoir area without adversely affecting the production well discharge temperature. This assumes continued disposal of 150 gpm via Richardson-1 and an additional 350 gpm via an injection well located approximately 1,400 feet southeast of the Naef well and 950 feet west-northwest of SGI-1. The site re-injection at higher rates may result in the breakthrough of heat-spent thermal effluent to the City's geothermal production wells.

Sources of Information

Benson, S.C., C. Goranson, J. Noble, D. Corrigan, and H. Wallenberg, 1980. Evaluation of the Susanville California geothermal resource: in Appendix to the concluding report on the evaluation of the Susanville and Litchfield geothermal resources.

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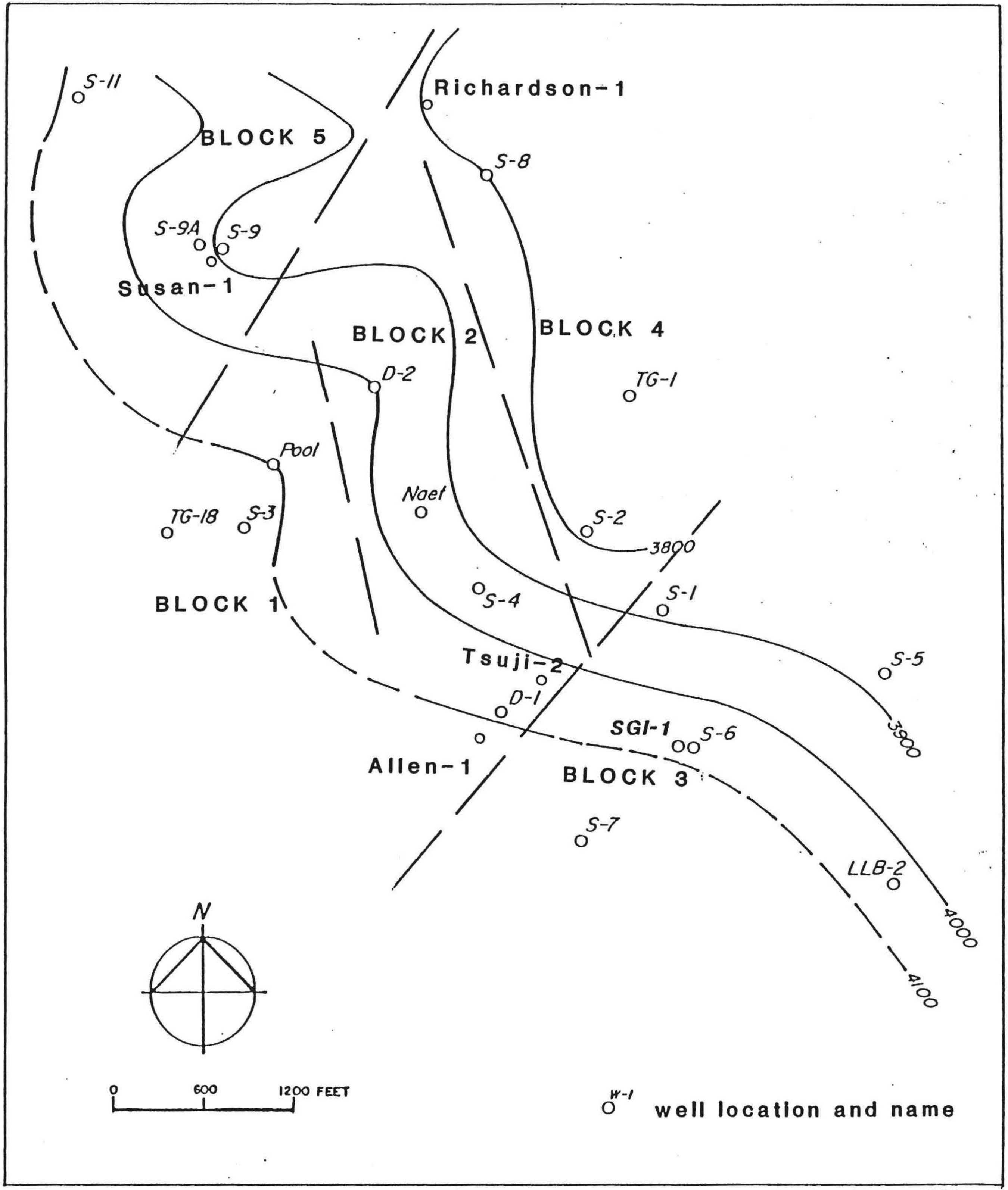
Sanyal, S.K., C. Klein, A. Campbell, S. Oloumi, T. Wright, and M. Peterson, 1984. An assessment of the geothermal resource underlying the City of Susanville and the disposal system for geothermal waste disposal: private consulting report prepared for the City of Susanville, CA.

U.S. Bureau of Reclamation, 1982. Appendix to the concluding report on the evaluation of the Susanville and Litchfield geothermal resources.



GeothermEx, Inc., 1984

Figure 1. Locations of geothermal wells and structural blocks and the elevation of the the top of the geothermal reservoir at Susanville, California.

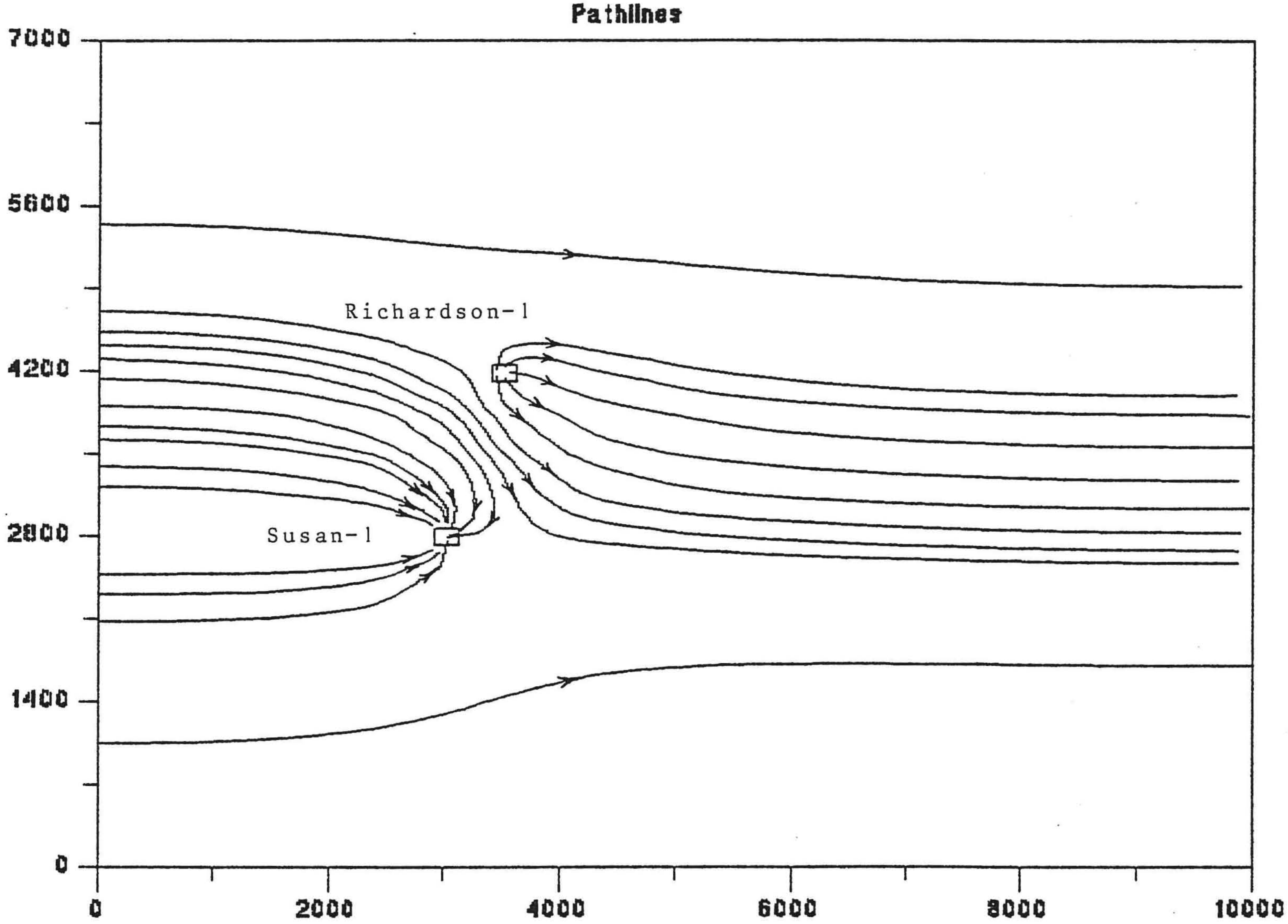


Figure 2. Pathlines resulting from pumping Susa-1 at 500 gpm and injecting 150 gpm in Ricahrdson-1.

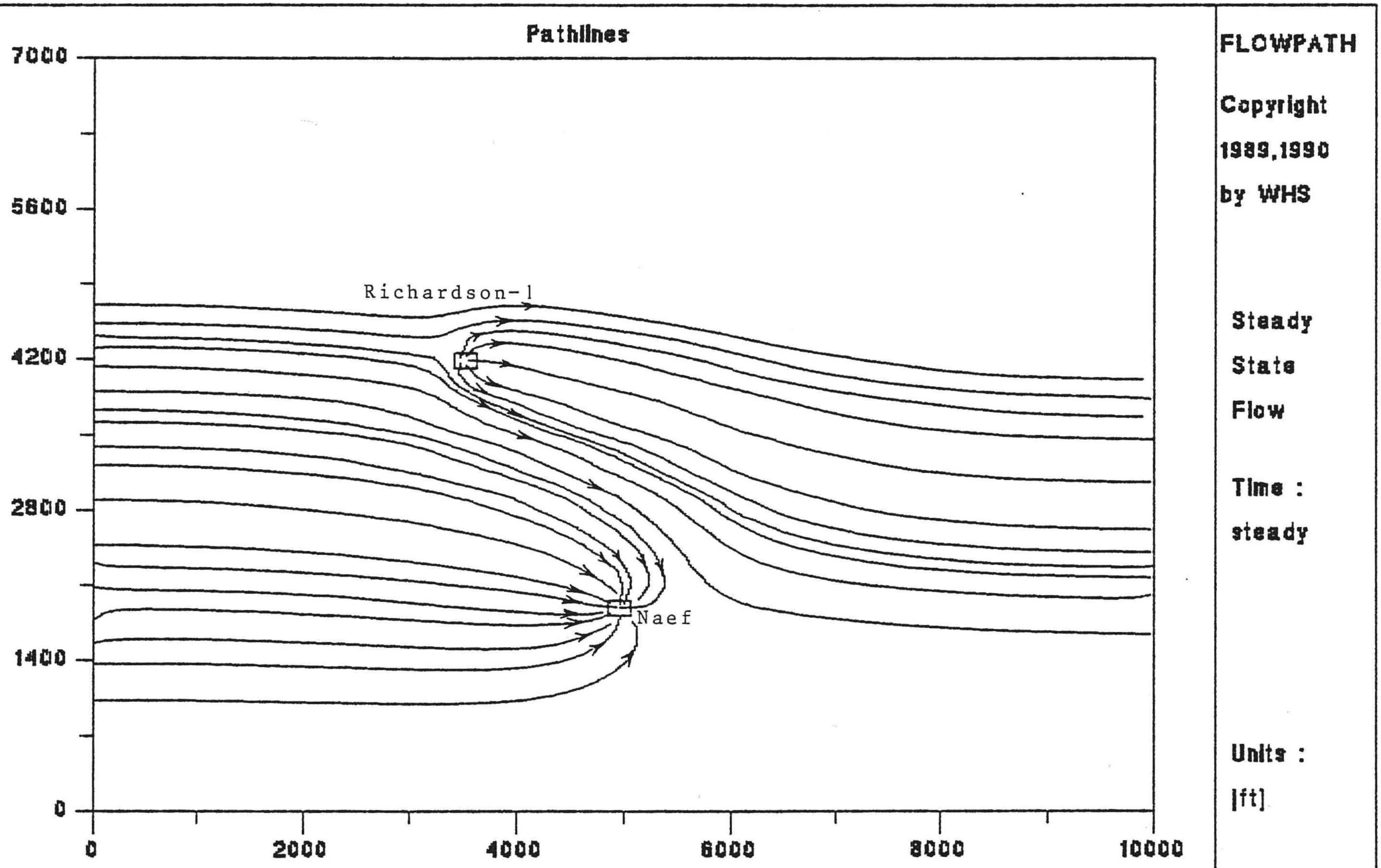


Figure 3. Pathlines resulting from pumping the Naef well at 500 gpm and injecting 150 gpm in Richardson-1.

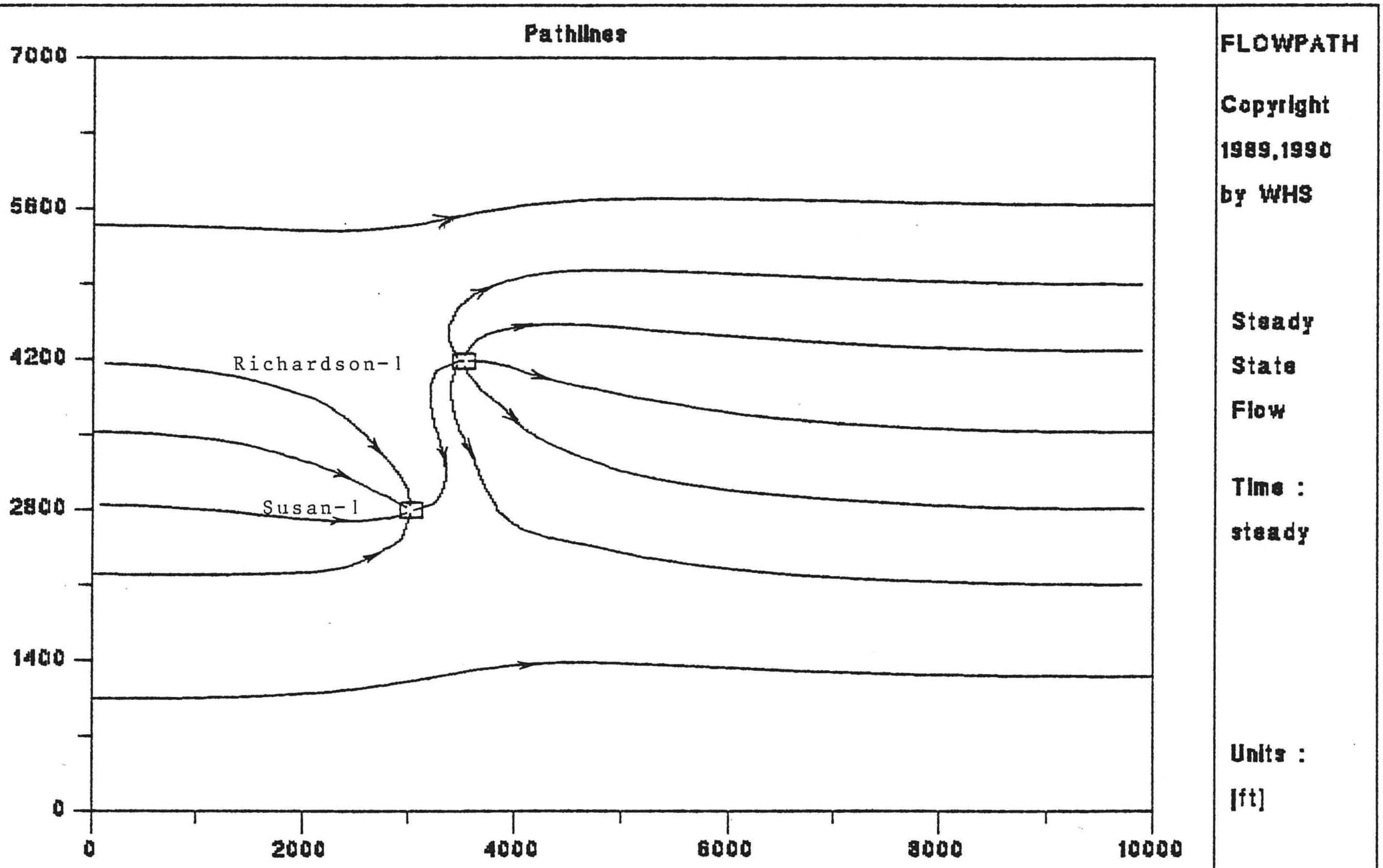


Figure 4. Pathlines resulting from pumping Susan-1 at 500 gpm and injecting 500 gpm in Richardson-1.

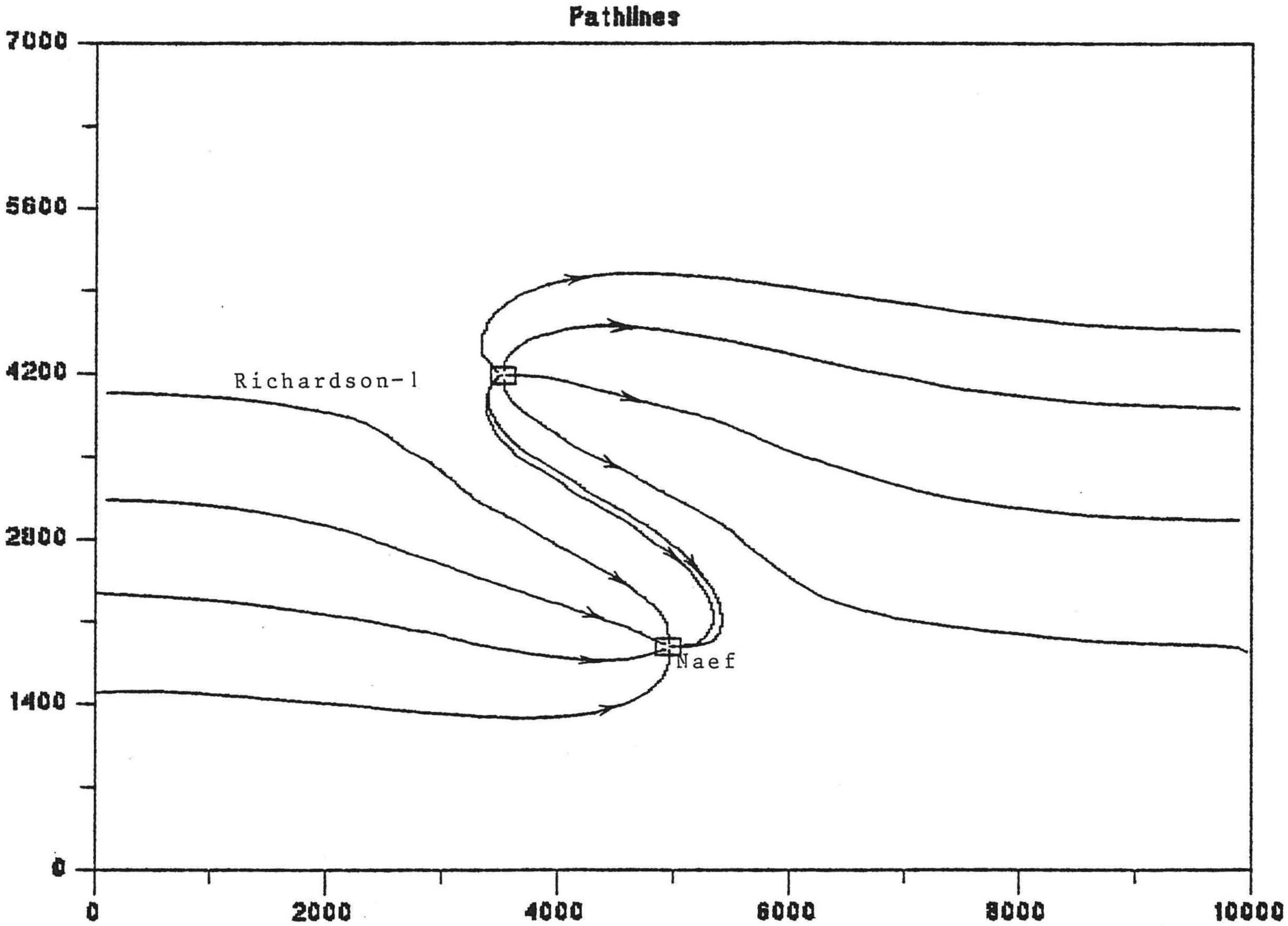


Figure 5. Pathlines resulting from pumping the Naef well at 500 gpm and injecting 500 gpm in Richardson-1.

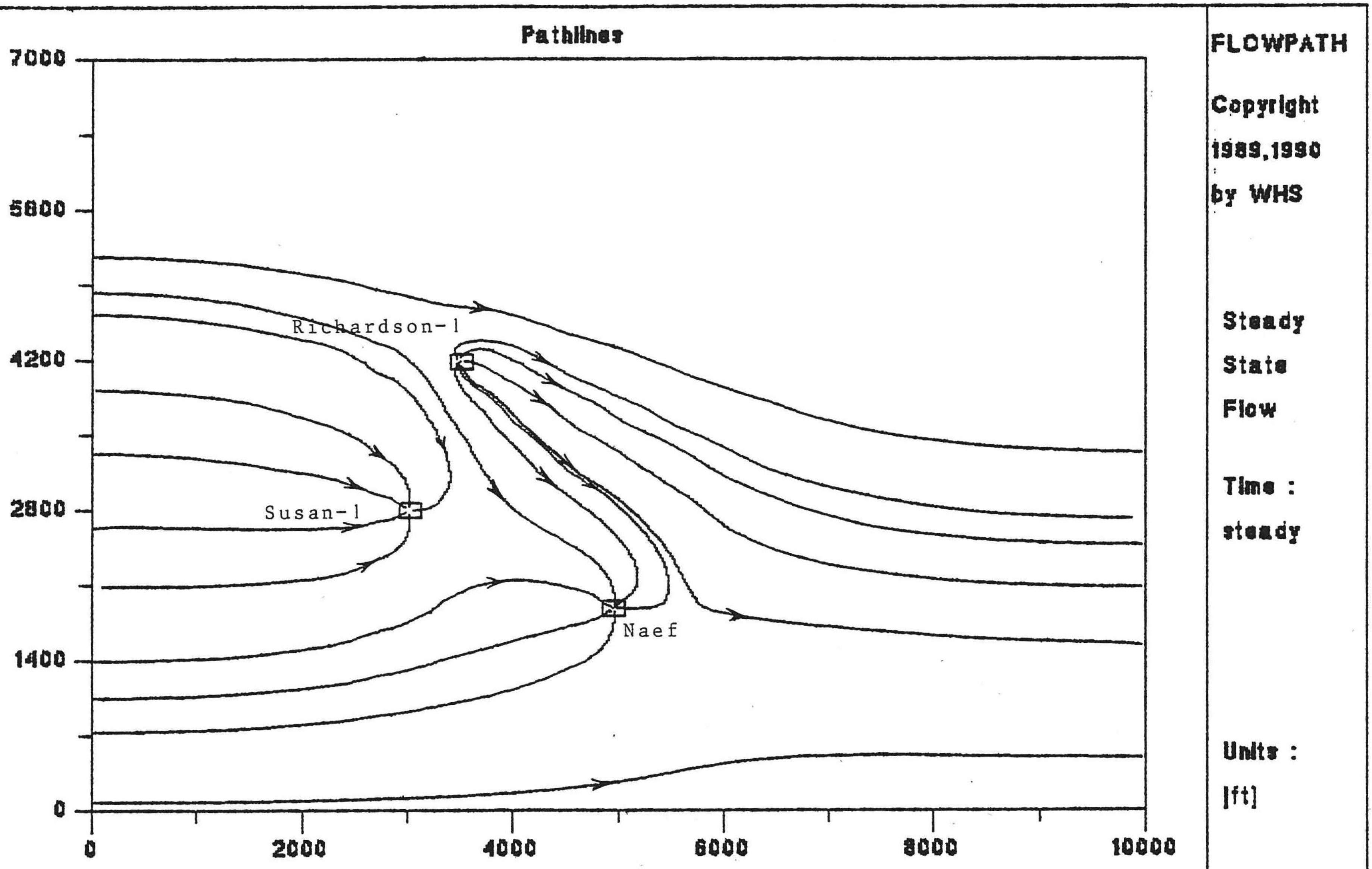


Figure6. Pathlines resulting from pumping Susan-1 at 700 gpm, the Naef well at 400 gpm, and injecting 150 gpm in Richardson-1.

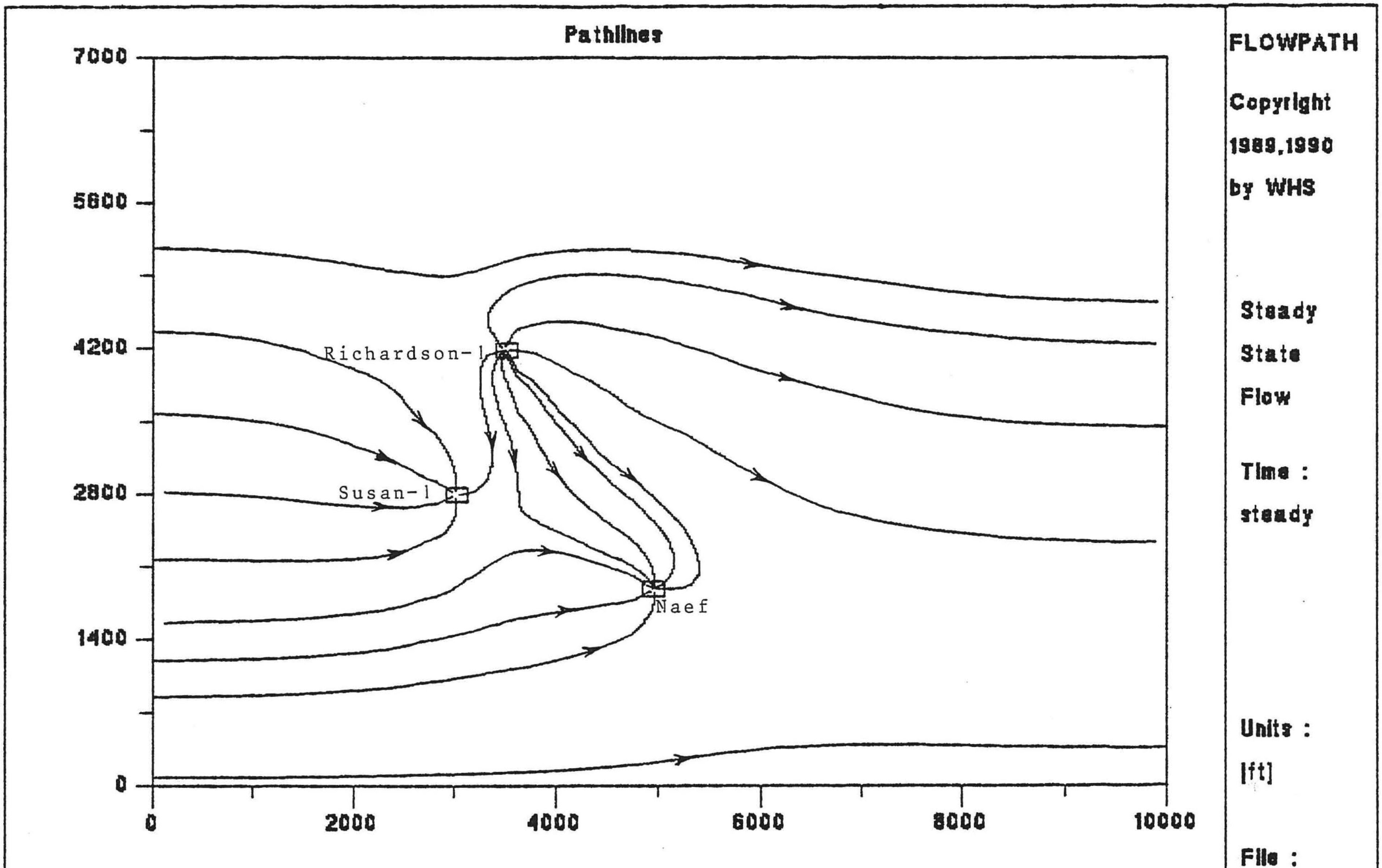


Figure 7. Pathlines resulting from Pumping Susan-1 at 700 gpm, the Naef well at 400 gpm, and injecting 500 gpm in Richardson-1.

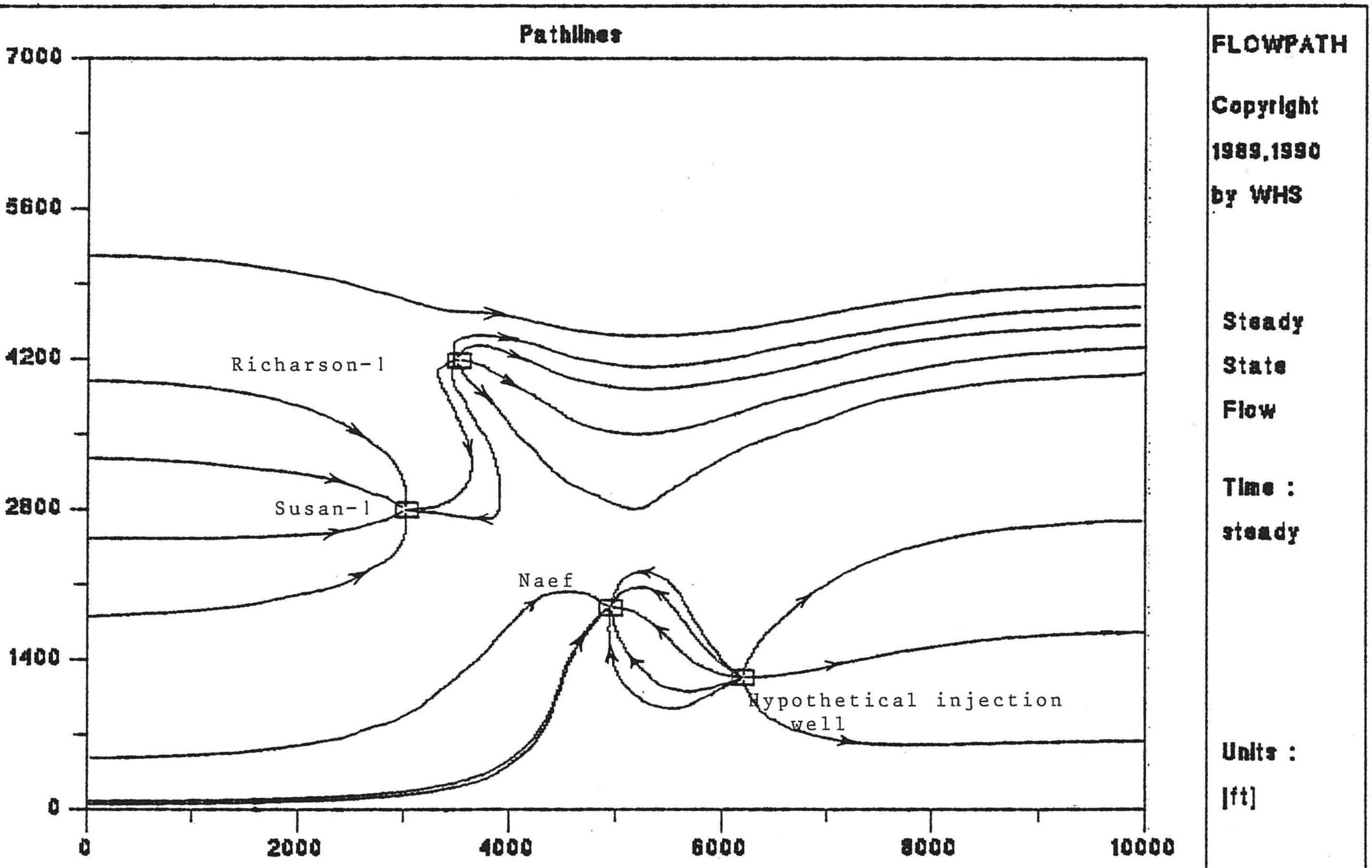


Figure 8. Pathlines resulting from pumping Susan-1 at 700 gpm, the Naef well at 400 gpm and injecting 150 gpm in Richardson-1 and 950 gpm in a hypothetical injection well located near Tsuji-2.

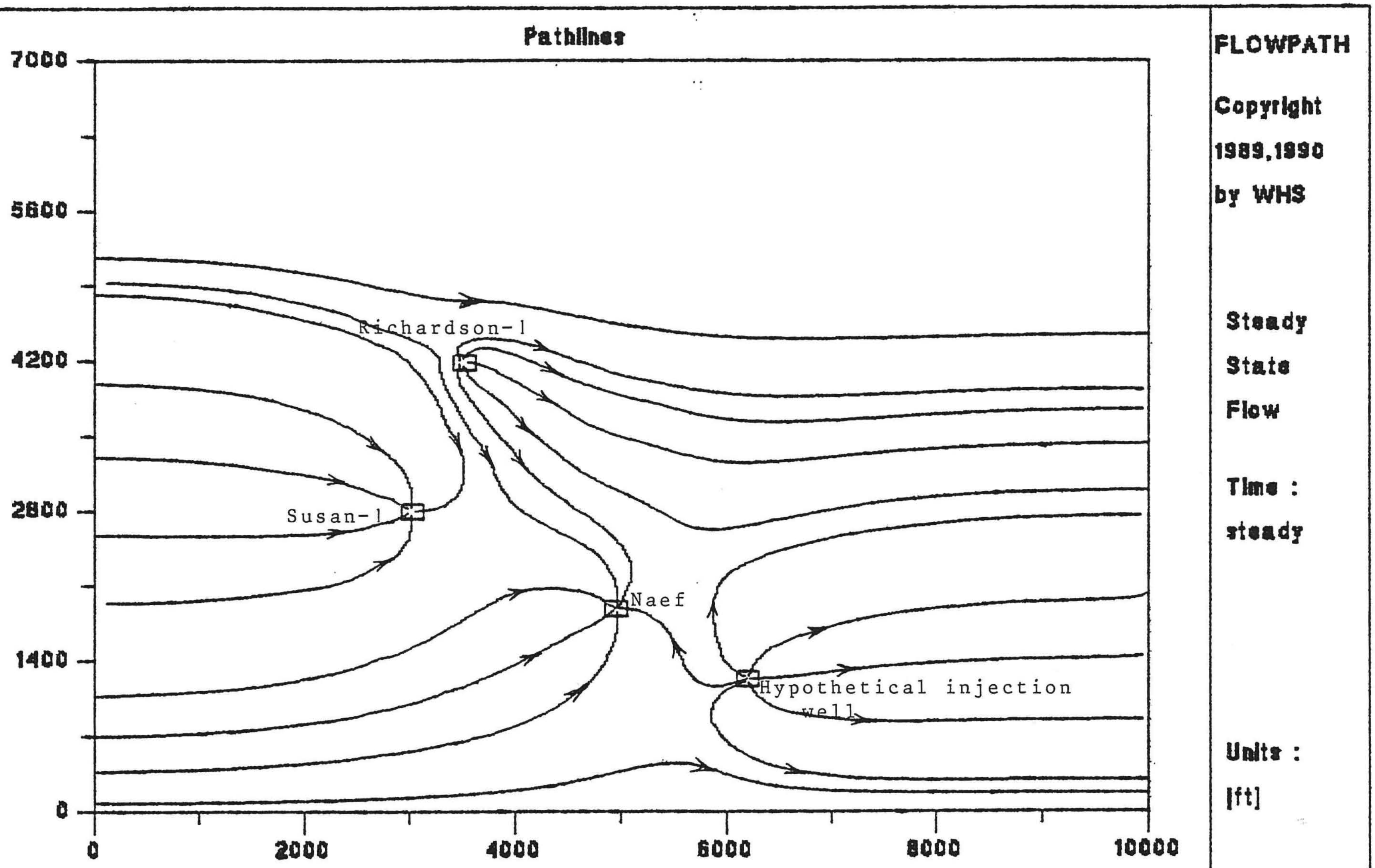


Figure 9. Pathlines resulting from pumping Susan-1 at 700 gpm, the Naef well at 400 gpm and injecting 150 gpm in Richardson-1 and 350 gpm in a hypothetical injection well located near Tsuji-2.

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