7 March 1975, Volume 187, Number 4179 SCIENCE

Environmental Impact of a Geothermal Power Plant

Chemical and thermal effluents from a New Zealand plant rival those from fossil or nuclear fuel technologies.

Robert C. Axtmann

To supply urgent energy needs, many nations are initiating or expanding ventures in geothermal technology. Although geothermal power enjoys a reputation for "cleanness," relevant environmental data are sparse; as far as I know, no detailed impact analysis of a mature installation has heretofore appeared.

Since the geophysics and geochemistry of hydrothermal reservoirs vary widely, each plant has a unique set of effluents. Moreover, unlike conventional technologies, geothermal power provides no siting options—the plant must be adjacent to its hydrothermal reservoir whether or not, say, an adequate source of cooling water is near. Despite its singularity, a *first* environmental impact analysis of a geothermal plant may have paradigmatic and heuristic values, may indicate fruitful directions for research, and may help focus national discussions on the course of development for a potentially major, energy source.

For these reasons the subject matter of this article is less circumscribed than its title. There is a special emphasis on facets of the plant's impact which, if extended on a regional scale, might overburden the environment's ability to assimilate wastes. Certain effects, for example, carbon dioxide (CO_2) emissions to the atmosphere and thermal pollution, are considered from a world perspective since they could have dramatic implications for global climate if many nations were to derive the same proportion of their electrical energy from geothermal sources and with the same thermal efficiency as does New Zealand.

I chose New Zealand's Wairakei plant for investigation because (i) its operations and the characterization of its hydrothermal reservoir are better documented than those of other installations, (ii) Bowen's pioneering but general analysis (*1*) emphasizes vapor-dominated (steam) fields whereas most geothermal reservoirs—like Wairakei's—are liquid-dominated, and (iii) New Zealand's distinguished cadre of geothermal scientists and engineers expressed a gratifying willingness to share their knowledge and data.

The major focus of the study is on the plant's effluents and their chemical, physical, and biological consequences. Phenomena which evolve more gradually—changes in the natural geothermal activity in surrounding areas, ground subsidence, and the depletion of the hydrothermal reservoir—are also considered. Because of limitations in the time available for the study, it was necessary to ignore a number of important subjects: impacts during the development of the borefield and construction of the plant, the effects of well blowouts, changes in the natural habitat, land use considerations, and socioeconomic factors. Many of these topics have been discussed before, albeit briefly (*2*).

Certain other aspects, most notably the complex interactions between the plant and the Waikato hydroelectric system, seemed so unique as to lack general interest. Accordingly, I sketch them lightly here but have treated them in detail elsewhere (*3*).

A Physical Description

The Wairakei plant is 10 kilometers north of Lake Taupo in the volcanic belt of the North Island (see Fig. 1). The lake's outlet river, the Waikato, provides cooling water for the plant and then feeds eight serial hydroelectric plants before discharging to the Tasman Sea, 320 km downriver. The closest hydroelectric station is at Aratiatia Dam, about 4 km north of the plant. On the outskirts of Taupo, a lakeshore resort town (permanent population, 12,000), the Taupo Gates control the river's flow to match the needs of the hydroelectric system.

The plant's power station lies on the river's west bank about 7 km from the epicenter of the 60-odd wells in the borefield, which is on the opposite side of Highway 1 (see Fig. 2). At the wellheads, the geothermal fluid is a 1 : 4 (by weight) mixture of steam and water. After processing by cyclone separators and multistage flash units, at which steam at atmospheric pressure exhausts through twin silencers, dry steam proceeds to the main steam lines and thence to the turbines in the power station.

The plant reached full power in 1964; it currently operates at about 145 megawatts (electrical) and supplies ~ 7 percent of New Zealand's power needs. The plant is base-loaded; that is, it produces continuously at full power. The annual load factor (the number of kilowatt-hours produced divided by the product of the maximum number of kilowatts and the number of hours per year) is typically 0.9. The "Permanent Village" (Fig. 2) houses about 150 families, mostly of workers at the plant. More complete descriptions of the pow-

The author is a professor in the Department of Chemical Engineering and a member of the Center for Environmental Studies at Princeton University, Princeton, New Jersey 08540. During the first 5 months of 1974 he was a visiting scientist at the Physics and Engineering Laboratory of the New Zealand Department of Scientific and Industrial Research, Lower Hutt, New Zealand.

Table 1. Chemical discharges to the Waikato River, based on a total mass discharge rate of 6.5×10^6 kg $hour^{-1}$ and a river flow of 127 m^3 sec^{-1}. To obtain the total annual discharge (in tons per year), multiply the incremental concentration by 4000.

Constituent	Increment in river concentration (ppm)	Constituent	Increment in river concentration (ppm)
B	0.27	Cl	20.8
Li	0.13	Br	0.055
Na	12	I	0.0047
K	1.9	NH_4^+	0.0014
Rb	0.029	SO_4^{2-}	0.24
Cs	0.026	As	0.039
Mg	4.7×10^{-5}	Hg	1.5×10^{-6}
Ca	0.17	Silica	6.3
F	0.077		

er station (*4*) and borefield (*5*) are available.

The Broadlands field, approximately 20 km downriver from the plant, has been bored and partially characterized but not yet exploited. As this is written, the New Zealand government is considering the optimal use for the field.

Characteristics of Geothermal Effluents

Because the Wairakei borefield discharges continuously, the total effluent rate is virtually constant (*6*). It is independent of electrical output and independent of whether there *is* an output, a situation which contrasts with other central station power technologies and has not, to my knowledge, been remarked upon in the geothermal literature. Comparisons between geothermal effluents and those from conventional plants can be misleading, therefore, if limited to effluent mass or energy rates per unit capacity (*1*). For the comparison to be valid, the geothermal rate must be divided by the load factor (please see the previous section).

Likewise, pollutant emissions during preoperational testing and from wild bores (uncapped and uncappable wells) should be assessed against a geothermal plant. At Broadlands, 16 or more boreholes with a combined power potential

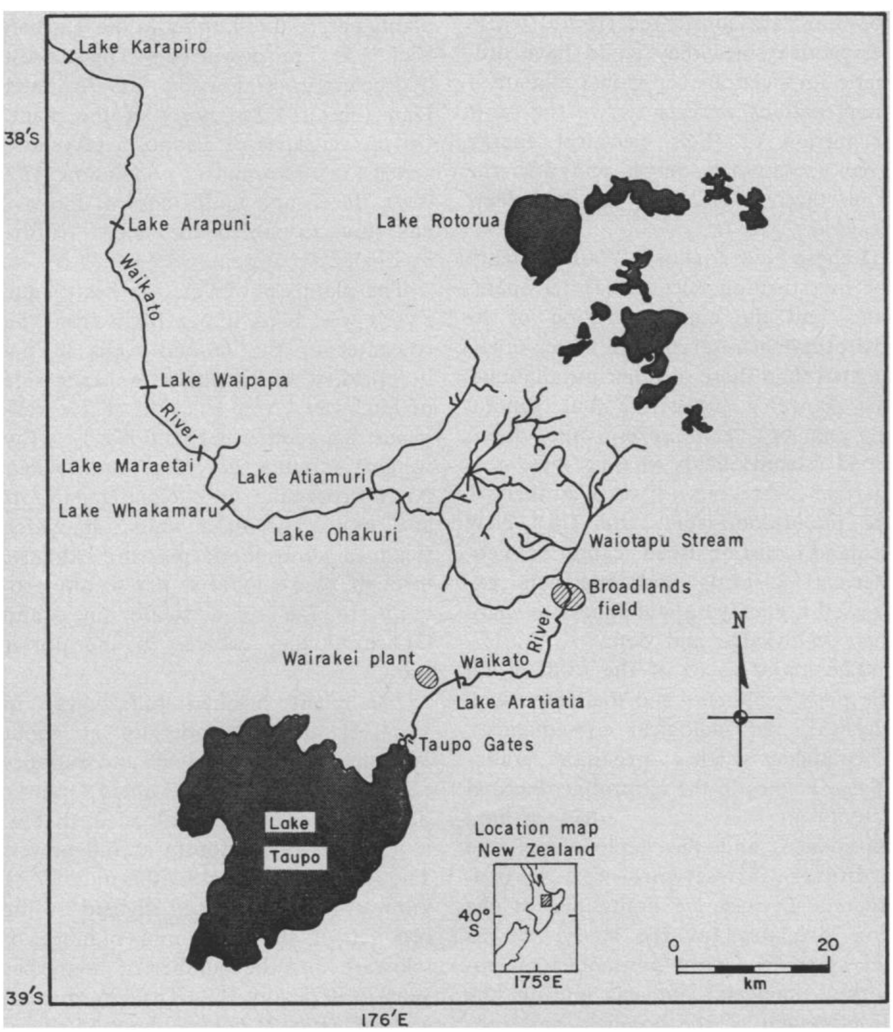


Fig. 1. The Wairakei plant, the Broadlands geothermal field, and the New Zealand Electricity Department's hydroelectric network on the Waikato River.

Table 2. Gas composition of steam from the Wairakei boreholes, based on data from (*42*, p. 36).

Gas	Percent (by volume)
CO_2	0.060
H_2S	0.004
H_2	0.001
CH_4	0.0005
C_2H_6	0.0001
N_2	0.0003
NH_3	0.0008
H_3BO_3	0.00001
HF	0.000016

of 120 Mw (electrical) discharged for periods of up to 3 years without the production of a single electrical unit; at The Geysers, California, a wild bore has been discharging since 1957.

Although the geothermal mass and thermal discharge rates may remain relatively constant, the *pathways* of the several discharges may change gradually as the field matures, or abruptly as the electrical plant's output is shut off or reduced. Here again, there is a contrast with other technologies; the *quality*, although not the pathway, of the emissions of a fossil-fueled plant may undergo a step-function change when, for example, it switches from fuel oil to natural gas.

Geothermal effluent rates, however, are not constant in the long term. Emissions at the Wairakei installation underwent changes, mostly increasing ones, from the early 1950's until January 1964. Since then, most trends have been downward: the mass discharge rate, enthalpy, salinity, gas content, the ratio of CO_2 to hydrogen sulfide (H_2S), and power output are now below the 1964 values. Some of the trends were caused by physical and chemical alterations in the hydrothermal reservoir—the result of exploitation—but the falloffs in the mass discharge rate and power output came about as a result of decisions concerning the management of the field.

Chemical Effluents

Except for noncondensable gases in the steam, substantially all the chemical effluents are dissolved in the waste water which discharges to the river. Table 1 gives the incremental concentrations of each chemical species at average river flow (127 cubic meters per second), assuming complete mixing without precipitation or adsorption.

In the power station's direct-contact, turbine condensers, the noncondensable gases partition between the cooling water stream, which returns to the river, and the gas ejector effluent, which exhausts to the atmosphere on the station roof. In the case of CO_2, roughly half of the total (1450 kilograms per hour) departs by each path. Of the total H_2S emission rate (nearly 68 kg hour^{-1}), approximately 80 percent goes to the cooling water and the remainder to the atmosphere. The minor concentrations of other noncondensable gases are given in Table 2.

Of the 26 chemical species listed in Tables 1 and 2, only arsenic, mercury, H_2S, CO_2, and silica appear to produce significant environmental effects. The total concentration of dissolved solids in the waste water is approximately 4400 parts per million (ppm). After the waste water mixes with the river, even at the lowest river flow rate (14 m^3 sec^{-1}), the resulting concentration is still well below the 500 ppm maximum recommended for potable water.

Arsenic. In 1971–1972 Reay (*7*) investigated arsenic concentrations in the Waikato River and concluded that: (i) the Wairakei plant supplies nearly 75 percent of the total arsenic input; (ii) sediments from Lake Aratiatia contain from 20 to 30 milligrams of arsenic per kilogram (the average for soils in nonthermal areas is 5 mg kg^{-1}); (iii) *Largarosiphon major*, a weed which dominates the aquatic plant population in Lake Aratiatia, has a concentration factor (*8*) for arsenic of 5300; (iv) despite (ii) and (iii), "most of the arsenic" is discharged ultimately to the sea; and (v) the importance of the accumulation of arsenic by aquatic plants in transferring to the food chain is unknown.

According to Table 1, the arsenic effluent could result in a concentration of about 0.04 ppm under average river flow conditions with complete mixing. Samples taken at the intake to the water supply of the Permanent Village (Fig. 2) have given concentrations as high as 0.070 ppm. The intake is approximately 1000 m downstream from the mouth of the Wairakei Stream where the waste water enters the Waikato.

During periods of drought, the average daily flows past the plant fall to extremely low levels and could result in arsenic concentrations downriver from the plant as high as 0.250 ppm or more. Accepted U.S. standards for drinking water limit arsenic concentrations to 0.050 ppm (*9*).

Mercury. Close genetic and geographical relationships frequently exist between the occurrence of mercury ores and hot springs (*10*). Although apparently not associated with ore deposits, the waters of several geothermal areas —Wairakei, Broadlands, Waiotapu, and Orakeikorako, all of which discharge to the Waikato—do contain measurable concentrations of mercury. Weissberg and Zobel in their 1973 survey (*11*) of mercury pollution in the Waikato River system (Fig. 1) reported that (i) Lake Taupo trout contain "normal" concentrations of mercury (about 0.12 mg per kilogram of axial muscle tissue on a wet weight basis); (ii) 33 trout samples taken upriver from the Whakamaru Dam averaged 1.29 kg and contained an average mercury content of 0.53 mg kg^{-1}; (ii) a rough 1 : 1 correspondence exists between concentrations of mercury in lake sediments and in coexisting trout; (iv) mercury concentrations in trout increase with increasing fish weight; and (v) essentially all the mercury in trout was in the form of methylmercury.

Other data suggest a downward trend in both fish and sediment concentrations as the river progresses seaward from Lake Ohakuri to Lake Whakamaru, although the situation is somewhat clouded by differences in the ages and characteristics of this series of artificial lakes. Nonetheless, the evidence suggests that the Wairakei plant makes a contribution to mercury contamination in the river, but the relative roles of Broadlands and the natural areas are still not clear.

The generally accepted, maximum concentration of mercury in fish for human consumption is 0.5 mg kg^{-1}, a concentration that might be expected from the average trout in the upper Waikato River that weighs more than about 1.25 kg (*11*).

Hydrogen sulfide (atmospheric). The most noticeable of the geothermal effluents is H_2S, a noxious, highly poisonous gas. Although individual responses vary,

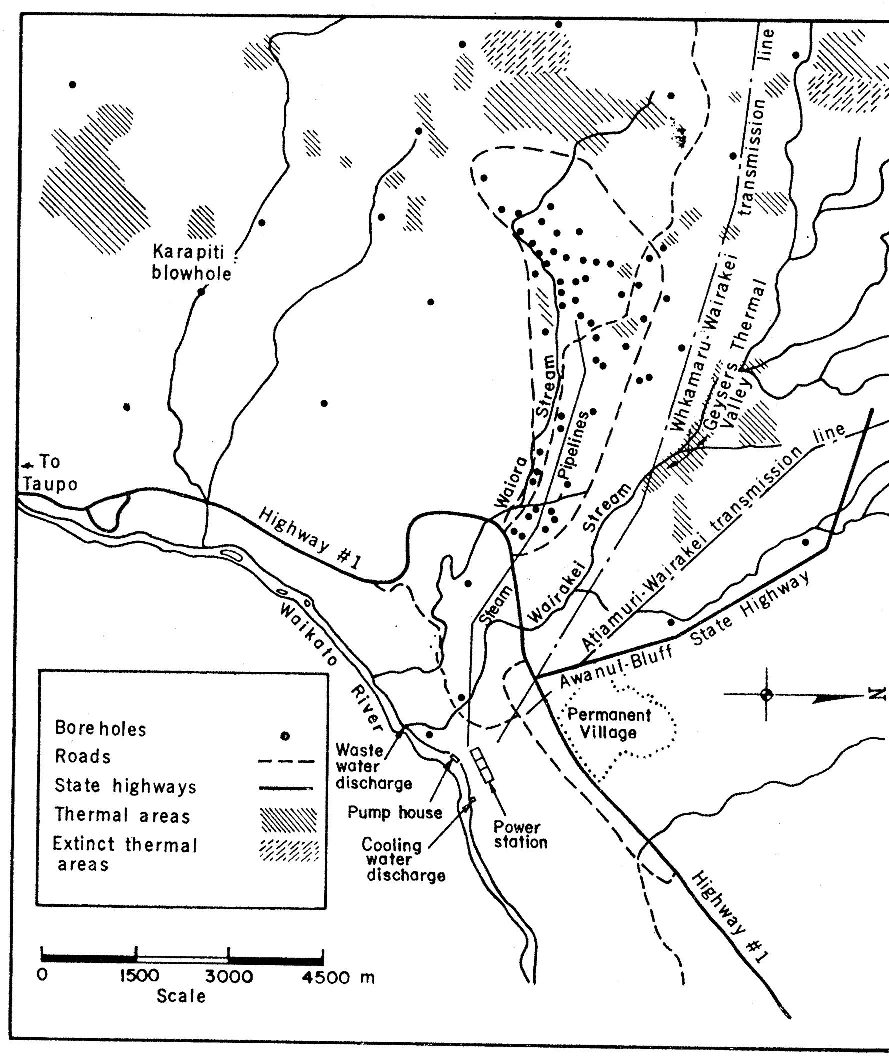
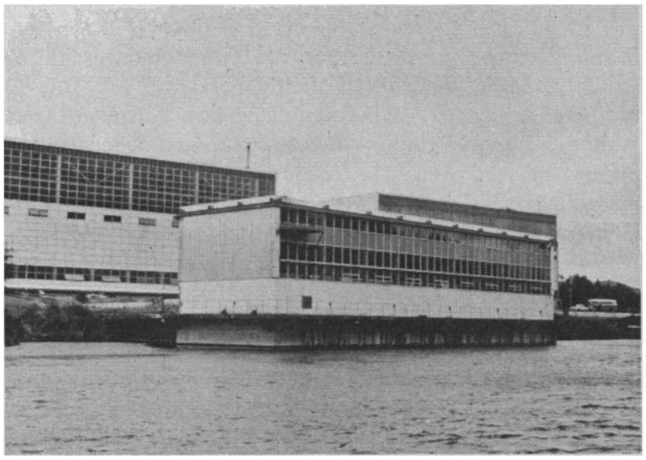


Fig. 2. The Wairakei power station and borefield.



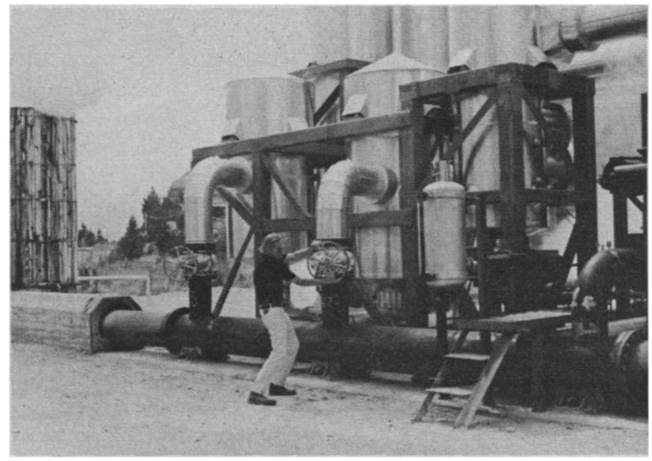


Fig. 3 (left). The Wairakei power station is located on the west bank of the Waikato River. The pump house in the foreground provides cooling water for the turbine condensers in the two buildings to the rear. Several stacks on the roofs of the latter exhaust CO_2 and H_2S to the atmosphere. Fig. 4 (right). A geothermal engineer turns a valve on a second-stage steam separator that was installed in late 1973 to increase the overall efficiency of the plant. Two wooden silencers, which exhaust atmospheric steam, are shown at the left.

the mean concentration for human detection is only 0.002 ppm; irritation to the human eye occurs at 10 ppm and to human lungs at 20 ppm. This gas is fatal to humans in 30 minutes at concentrations of 600 ppm (*12*).

In liquid-dominated systems, such as Wairakei, H_2S equilibrates between the steam and water fractions before separation, but substantially all of it passes to the steam during separation. Since 1964 the H_2S content in the geothermal mass discharged from the Wairakei boreholes has averaged close to 0.6 millimole per 100 moles and that in the steam has averaged approximately 30 ppm (*13*). The turbines' direct contact condensers transfer 80 percent of the H_2S to the cooling water of the river; the rest (approximately 14 kg $hour^{-1}$) emerges from the gas ejectors via four short stacks (elevation, 30 m above grade) on the roofs of the power station. Diluted by a 3 : 7 mixture of CO_2 and air, the concentration of H_2S in the stack gas is about 5000 ppm. Since both H_2S and CO_2 are heavier than air, they tend to settle toward the ground, particularly on foggy, windless days; the smell of H_2S in and around the power station is frequently strong (Fig. 3). When the power station is shut down for maintenance, all the steam from the borefield discharges to the atmosphere, whereupon all 60 wells discharge with an H_2S concentration of 30 ppm (by volume).

The New Zealand Clean Air Act of 1972 does not specify either emission or ambient air quality standards. The former are negotiated at the time a plant is licensed by the Health Department (*14*); current practice (for new plants) limits H_2S emission to 5 ppm. For greater concentrations to be at issue requires proof of a public nuisance. Residents with whom I spoke had not detected H_2S odors in the Permanent Village but did report a blackening of silverware and brass.

The plant's H_2S emissions clearly fall outside present licensing practices but, in the absence of public dismay, do not violate the law—a situation that might change should the local population density increase. In summary, atmospheric H_2S emissions appear less an environmental issue than one of industrial hygiene.

Hydrogen sulfide (aqueous). Approximately 54 kg $hour^{-1}$ dissolve in the turbine condenser sprays. A fraction may oxidize to sulfur dioxide (SO_2) [Kellogg *et al.* reported that the reaction may be "very fast" in fog or cloud droplets (*15*)], but most of the dissolved gas passes to the river via the condensate canals. Water near Aratiatia Dam has a strong H_2S odor, and botanists have reported filamentous sulfur bacteria of the genera *Thiothrix* and *Beggiatoa* growing on plankton collected in Lake Aratiatia and Lake Ohakuri. The bacteria are known to thrive only in the presence of sulfide (*16*).

If no oxidation occurred in the condensers, the completely mixed H_2S concentrations in the river would be 0.1 ppm at average flow and 0.9 ppm at lowest flow. Smith and Oseid investigated the effects of dissolved H_2S on the eggs and fry of rainbow trout and concluded that only concentrations less than 0.006 ppm are safe (*17*).

Carbon dioxide (atmospheric). Fossil-fueled power plants emit copious quantities of CO_2 to the atmosphere, a circumstance that may have drastic consequences for the global climate (*18*). How do geothermal emissions compare? A comparison of the Wairakei plant with the Huntly plant, a 1000-Mw (electrical) fossil-fueled station on the lower Waikato River, is instructive.

The combustion of 1 kg of North Island coal yields 2.7 kg of CO_2. At an energy conversion efficiency of 35 percent, this number translates to 2.9×10^4 kg of CO_2 per megawatt-day. Even when the Wairakei plant discharges its entire CO_2 effluent to the atmosphere, the result is less by a factor of 60 than Huntly's emission rate.

If the CO_2 effluent from a plant at Broadlands were discharged totally to the atmosphere, the result could approach to within a factor of about 2 of the Huntly rate since gas concentrations in Broadlands steam run 20 to 30 times those at Wairakei. The situation is even more startling for "gassy" geothermal fields such as that at Monte Amiata, Italy, where the CO_2 discharge rates (on a per megawatt-day basis) could be ten times that of a fossil-fueled plant.

These comparisons illustrate that geothermal power need not be necessarily cleaner, in all respects, than the "dirty" fossil-fueled technologies. They also suggest an environmental opportunity: CO_2 can be a valuable resource, particularly when concentrated as it could be in the gas ejector exhausts at a Broadlands plant. It could provide a valuable feedstock for the production of carbonic acid, Dry Ice, or methyl alcohol. In the case of H_2S emissions at Broadlands—also markedly higher than at Wairakei—the manufacture of elemental sulfur may present a similar opportunity (*19*).

Carbon dioxide and lake weed. In May 1968, accumulations of *Largarosiphon major* (a bottom-growing weed commonly used to supply oxygen in aquariums) on the intake screens of Aratiatia Dam forced the shutdown of the generating station. Since then it has been the custom periodically to lower the water level in Lake Aratiatia by approximately 5 m for about a 2-week period each time, in order to harvest the weed—a costly procedure in terms of labor, reduced operating efficiency of the hydroelectric station, and increased pumping costs for cooling the Wairakei plant (*20*).

The optimum temperature for *Largarosiphon* growth is 25°C (*21*); normal river temperatures are less than 20°C, and so thermal effluents (see below) undoubtedly accelerate the weed's growth. It seems possible that aqueous CO_2 in the turbine condensate might also enhance growth by providing additional carbon for photosynthesis. Recently Brown *et al.* demonstrated that in laboratory experiments the photosynthetic rate in *Largarosiphon* was directly proportional to CO_2 concentrations in the surrounding water (*22*).

Pure water in equilibrium with the atmosphere contains ~ 0.5 ppm (by weight) of CO_2. Approximately 1 metric ton per hour of CO_2 discharges to the river in the condenser effluent. At average river flows this would increase the CO_2 concentration to 3 ppm after complete mixing if no gas transport to the atmosphere occurred in the meantime.

The mixing of the condenser effluent with the river water is essentially complete at a point 1 km (about 10 minutes) downstream of the condenser outfall. Thereafter, gas transport to the surface should be slower since, from this point on, the river is 10 m deep. For gases of modest solubility, the rate of change in concentration, c, of a dissolved gas in a liquid volume is given by

$$\frac{dc}{dt} = K\frac{A}{V}(c^* - c)$$

where c^* is the equilibrium concentration, K is the overall mass-transfer coefficient, and A/V is the surface-to-volume ratio of the liquid (*23*). With a rough river model, a wind velocity of 13 km hour^{-1}, and a literature value for K of between 1.5 and 2.0 centimeters per hour (*24*), the integral form of the equation predicts that nearly 50 percent of the CO_2 excess would reach Lake Aratiatia.

Table 3. Approximate waste heat balance for the Wairakei plant.

Waste heat	Normal operation (Mw)	Shut-down period (Mw)
To the river		
Condenser effluent	580	0
Waste water stream	270	270
To the atmosphere		
Steam separators	460	1275
Pipeline losses	45	0
Power station losses (including pumping)	45	0
Evaporation from waste water stream	175	175
Total	1575	1720

The case is not conclusive since H_2S is also present and, conceivably, could exert a countereffect. Atmospheric concentrations of H_2S of 0.15 microgram per cubic meter of air affect the growth of common land plants (*25*), but the effects of H_2S on aquatic plants have received less attention.

Water (atmospheric). The silencers (Fig. 4) discharge 8×10^5 kg per hour of water vapor to the atmosphere, and evaporative losses from the waste water canals add another 5 percent. During a power station shutdown, all the steam from the borefield is discharged for a total H_2O production rate of 1.9×10^6 kg hour^{-1}, the same rate as that for the emanation from the cooling towers for a 750-Mw (electrical) conventional power plant (*26*). At Wairakei, however, the water vapor discharges close to the ground (< 5 m), whereas natural draft cooling towers, which may be $\geqq 130$ m high, normally have very little effect on ground-level visibility.

Fogs frequently enshroud the area near the Wairakei plant, and signs on Highway 1 warn motorists of drifting steam (sic). (What drifts across the highway is fog, not steam.) However, there have been no traffic accidents near the plant attributable to poor visibility during the past 8 years.

Water (liquid). The plant's waste water discharge (1.3 m^3 sec^{-1}) bolsters the electrical output of the eight stations in the Waikato hydroelectric system. The plant also discharges approximately 850 Mw (thermal) in the river (see Table 3) which produces an enhanced evaporative rate which may be estimated from nomographs (*26*) and is about 0.3 m^3 sec^{-1}. The net addition to the river is thus 1 m^3 sec^{-1}. If no further evaporation occurs as the river flows to the sea, then the Waikato River hydroelectric system would produce about 2.4 Mw (electrical) from the plant's waste water for a total of 2×10^7 kwh year^{-1}. At 1972 rates, this is equivalent to a revenue of approximately $140,000.

Silica. Hydrothermal waters at depth are saturated with respect to quartz, but, as the fluid rises in the borehole, its temperature decreases and it becomes supersaturated with quartz. When steam is extracted at the wellhead, the volume of the water fraction decreases, and its temperature falls further. At this point the silica concentration (550 ppm) in the water exceeds the solubility of amorphous silica (Fig. 5). As the supernatant stream flows toward the river, the silica first polymerizes and then begins to precipitate in the amorphous form. The discharge canals must be cleaned periodically with a pneumatic shovel, a dangerous and expensive operation.

Silica precipitation is one of the serious impediments to utilizing the heat in the waste water and to reinjecting the fluid. In the former case, the problem is fouling of heat-exchanger surfaces; in the second case, the problems are clogging of the reinjection pipes and reduction of the aquifer's permeability. Work under way in the New Zealand Department of Scientific and Industrial Research is aimed at treating the hot waste water with slaked lime to precipitate calcium silicate. An alternative process, also under study, involves acidification of the waste to a *p*H of 3 which retards the polymerization reaction.

Thermal Effluents

Thermodynamic constraints and the low temperature of the hydrothermal reservoir dictate waste heat discharge rates that are startlingly higher than those from conventional technologies. To produce 143 Mw of electrical output in August 1973, the Wairakei plant utilized a thermal input of approximately 1720 Mw. The thermal efficiency of the cycle, when corrected for the load factor (0.9), is 7.5 percent (*27*). Table 3 gives a rough, waste heat balance both for full power and for station maintenance conditions.

Table 4 compares the Wairakei plant with two 1000-Mw (electrical) fossil-fueled plants—the Huntly plant in New Zealand and a typical state-of-the-art, oil-fired one in the United States.

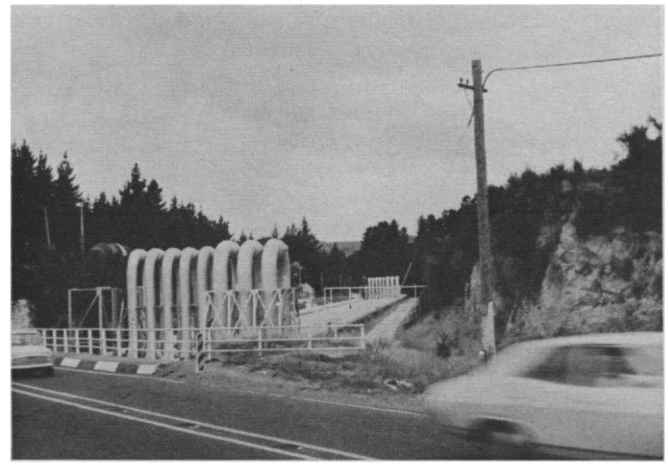


Fig. 5 (left). Steaming waste water, laden with dissolved silica and other minerals, flows through open concrete trenches to the Wairakei Stream and thence to the Waikato River. Fig. 6 (right). Steam mains from the Wairakei borefield pass under New Zealand Highway 1 to reach the power station. Large loops allow for thermal expansion and may ameliorate the effects of ground subsidence.

An obvious conclusion from Table 4 is that, if cold water sinks are in short supply, it may be shortsighted to use them to cool geothermal plants.

The Carnot efficiency

$$\epsilon_c = (T_2 - T_1)/T_2$$

where T_1 is the absolute temperature at which waste heat is rejected to the environment and T_2 is the maximum temperature of the working fluid, is the theoretical limit on any heat engine (such as a steam-driven turbine). The efficiency of the Wairakei plant, barely 0.25 ϵ_c, contrasts with those of modern fossil-fueled plants with efficiencies of about 0.7 ϵ_c. Raising the efficiency at Wairakei could increase the power output, prolong the life of the reservoir, reduce the thermal burden, or all three. James (*28*) has offered a number of proposals to increase efficiency, but all would require substantial capital outlays.

The 445 Mw (thermal), which emerge at 100°C from the wellhead separators at Wairakei, present a tantalizing challenge—unlike the thermal effluents from conventional plants, which are only a few degrees above the ambient temperature. Water heating by heat exchange is not Carnot-limited. Since nearly a quarter of New Zealand's electrical power is used to heat water, and its new electrical plants are increasingly fossil-fueled and therefore Carnot-limited, Wairakei's 445-Mw waste water stream represents a potential equivalent to the electrical output of a new 1300-Mw (electrical) coal plant.

A final impetus for improving the efficiency of geothermal power plants derives from the results of a 1971 study, which projects that within 80 years man's energy-releasing activities could trigger melting of the polar ice caps (*18*). Although it is difficult to judge the prophecy, which was based on extrapolations of present power technologies at efficiencies of 30 to 40 percent, should geothermal power contribute significantly to world energy needs without drastic improvements in efficiency, the time scale of the prophecy would be foreshortened alarmingly.

River temperatures. Waste water from the borefield enters the river at about 60°C and 1.3 m^3 sec^{-1}; turbine condensate enters at about 33°C and nearly 10 m^3 sec^{-1}. At the river's mean flow rate (127 m^3 sec^{-1}) the increase in temperature would be 1.3°C, assuming no heat loss to the atmosphere and complete mixing. Such an increment is far less than the "natural" changes in the river's temperature, which normally ranges from 10° to 20°C over the year at the exit of the Taupo Gates (see Fig. 1). Temperature measurements under high flow conditions (> 200 m^3 sec^{-1}) indicate that complete mixing of the effluents occurs at a point 1 km downriver from the plant, that is, well before the water reaches Lake Aratiatia (*29*).

Bulk water temperatures recorded at five fixed points from immediately above the plant to 20 km downstream disclosed that in summertime (i) daily variations as great as 4°C occur in the water from Lake Taupo (as a result of solar heating of the upper layers of the lake), (ii) water at the Aratiatia Dam's tailrace occasionally rises to 28°C, and (iii) changes in river temperature induced by the plant's effluents persist as far as the Broadlands field —presumably because of reduced evaporative losses to the humid atmosphere and solar heating of the river.

A prolonged drought in the Lake Taupo catchment basin caused a severe drop in the lake's level during April 1974. Waikato River flows fell to 28 m^3 sec^{-1}, and the (computed) temperature rise in the river from the plant's effluents rose to 6°C—twice that permitted by New Zealand's water standards (*30*).

Such conditions may have contributed to the deterioration of a trout fishery between the plant and Lake Aratiatia Dam (*31*). Other possible factors include: the diurnal variations in the river flow and river level ($\sim$ 2.1 m), which result from management of the hydroelectric system via the Taupo Gates; the periodic lowering of Lake Aratiatia by 5 m for purposes of weed harvesting; the chemical effluents, particularly H_2S, which are injected into the river; and the relative paucity of spawning areas on this stretch of river.

Physical Effects

It would be surprising if exploitation of the Wairakei field had not modified the natural thermal activity of adjacent regions in view of the near cessation of such activity near older fields at Lardarello, Italy, and Iceland (*32*). Indeed, changes at Wairakei were anticipated in the early 1950's, and a careful watch was begun (*33*).

Many changes have occurred. Among the more significant are the following: (i) marked increases from 1958 to 1964 and lesser decreases from 1964 to 1968 in both the surface discharge area (*34*) and the total discharge rate of the

Karapiti geothermal area south of Wairakei (*35*), and (ii) the demise of the Great Geyser in Geysers Thermal Valley (west of Wairakei) in 1954 and of the Karapiti blowhole in 1973. Geysers Thermal Valley was closed as a tourist attraction in 1972.

Plausible arguments relate these events either to the lowering of the fluid level, of temperatures, and of pressures in the Wairakei reservoir or to changes in precipitation patterns and subsurface hydrology. Even if it could be established positively that the plant were responsible, on balance I would take the view that the plant's contribution to the national well-being outweighs the loss of a few thermal springs, mud pools, and geysers in a land that has more than its share of such attractions.

Subsidence. The only ground movement so far reported for a geothermal field has been that at Wairakei (*36*). Vertical movement first became apparent in 1956, horizontal movement in 1965. The affected area is now greater than 65 km^2. The region of maximum displacement is well away from the borefield and power station, but its center lies only 500 m north of the steam mains. The movement is about 40 cm $year^{-1}$ at the point of maximum deflection; the total movement since 1956 is nearly 4 m (*37*).

An early correlation between aquifer pressure and subsidence no longer holds: although the pressure has tended to level off, the subsidence has accelerated slightly. Hatton reports a relationship between subsidence and surface strain that led him to conclude that surface strain results from a bending of the cap rock (approximately 150 m thick) (*37*). Bolton reports a linear relationship between the vertical surface movement and the thickness of the underlying breccia (*38*). A recent analysis by Glover of subsidence data between 1967 and 1971 indicates that the average ratio of the subsidence volume to the fluid drawoff volume was 0.0076 (*39*).

Bowen has written that "much has been learned about subsidence from the exploitation of petroleum reservoirs, and, with proper understanding and practice, any geothermal area where this could be a problem can be stabilized" (*1*). Bowen's theorem may meet a severe test at the Broadlands field, which is bisected by the Waikato River. Should Broadlands, under exploitation, repeat Wairakei's subsidence performance, there may well be a new lake since the river banks at that point are about 4 m high.

Table 4. Comparison of thermal effluents from three power plants; ϵ is the observed net electrical efficiency, equal to the net electrical output divided by the total thermal input. All plants are cooled by the "run of the river" method.

Plant	Output	Total waste heat	Waste heat ratios	
			Atmosphere	River
	Mw (electrical)	Mw (thermal)	Mw (thermal)/Mw (electrical)	
Wairakei ($\epsilon = 8.3\%$)*	143	1575	5.1	5.9
Huntly ($\epsilon = 35\%$)	1000	1860	0.6	1.3
U.S. plant ($\epsilon = 42\%$)	1000	1380	0.3	1.1

* Uncorrected for the load factor.

Resource depletion. The optimal utilization of a geothermal resource has two distinct aspects: (i) the extraction of the maximum integrated energy from the reservoir and (ii) the most efficient use of the energy that is extracted. Ideally, the two aspects would be ordered as written here but in practice they are ordered in reverse. Only after some years of operation does the correct strategy for management and further exploitation of the field emerge. To minimize the chance of error and overcommitment of capital, energy conversion facilities are added stepwise.

The Wairakei power station has a capacity of 192 Mw (electrical), yet today the plant operates at about 145 Mw (electrical) on the basis of judgments made on the optimum rate for exploitation of the reservoir. Beginning several years before the borefield reached its maximum drawoff rate, the aquifer pressures and deep-water temperatures began to decrease. At present they are, respectively, approximately 20 atmospheres and 15°C lower than in 1957. The rates of decline, however, have moderated; there are indications that the aquifer is recharging at 70 percent of the current drawoff rates. At least one observer believes that the field could produce indefinitely at 100 Mw (electrical) (*36*).

To predict reservoir performance before exploitation requires hard data on the total mass of the fluid, the permeability of and inhomogeneities in the permeability of the aquifer, the deep-water flow patterns, and the rate of water recharge (which will almost certainly be a complicated function of, among other things, the rate of drawoff). To obtain full knowledge of the underground structure would require a drilling program, the expense of which might well exceed its benefits; seismic surveys that have been made at reservoirs in New Zealand give no indications of the depth of the field (*38*).

A more economical approach to optimal exploitation strategies is through computer simulation of the reservoir (*40*). Unmeasured physical properties of the underground structure are adjusted until the model reproduces the past history of the field, whereupon some confidence may be placed on the predictive properties of the model.

Although optimal extraction and optimal utilization are separate issues, there is a potential, technological linkage between the two: reinjection of the *hot* waste water would decrease the net energy drawoff and thereby increase the thermal efficiency and, possibly, prolong the life of the reservoir. Moreover, many of the most serious environmental shortcomings of the plant would disappear, for example, arsenic, mercury, and some thermal contamination.

It is not yet clear whether reinjection is feasible or unharmful to the ultimate performance of the reservoir. The manifold benefits that might result from reinjection, however, make it a subject that deserves further rigorous examination. Reinjection has worked well at The Geysers, California, field and is under test at Lardarello but it has not yet been essayed in a liquid-dominated field.

Ecological Considerations

The comprehensive, ecological surveys which now routinely precede power plant construction were never made at Wairakei, and so it is impossible to assess the net impact of the plant. Moreover, the effects of the plant are so inextricably intertwined with those of the hydroelectric system that a proper sorting out would be extremely difficult.

One may, however, observe that the Waikato River between the Wairakei Stream and Aratiatia Dam is severely stressed: (i) the level of the river changes by about 2 m each day; (ii) Lake Aratiatia is periodically lowered by 5 m for a 2-week period; (iii) a 1.3 m^3 sec^{-1} effluent at approximately 60°C pours continuously into the river; (iv) there have been two recent, large kills of carp in the lake—in each case the kill occurred after weed harvesting; and (v) there are few trout in the area, although they are more abundant immediately upstream and downstream.

One tell-tale characteristic of a stressed ecosystem is the lack of diversity in the individual species at different levels in the system. The evidence in this river is suggestive: a 1970 survey of the plankton population in the eight hydroelectric lakes of the Waikato River system disclosed that Lake Aratiatia had the fewest different species of both phyto- and zooplankton, less than half in each case that of Lake Ohakuri which is immediately downriver (*41*).

Esthetics

While offering no detailed challenge to the proposition that beauty is in the eye of the beholder, I do insist that the Wairakei borefield ranks high in New Zealand's superb hierarchy of visual delights. If a tramper on Highway 1 were to pause at dusk 8 km north of Taupo on a moist day with a stiff breeze, he would see an eerie scene of haunting beauty. Scores of fleecy plumes arc skyward only to be seized and devoured by green demons that haunt the boughs of imperial conifers; bundles of silvery bullwhips, cracked by an invisible giant who lurks behind the western hill, are caught in stop-action as they rise and fall in unison (Fig. 6). It is an odd amalgam of technology and nature, of the Tin Woodsman of Oz and the Sorcerer's Apprentice, gently underscored by the whispering, slightly syncopated "whuff-whuff . . . whuff . . . whuff" of the wellhead silencers.

The Broadlands field, if it is developed, could look like an oil refinery and would be the worse for it. Recent improvements in geothermal technology promise greater efficiency but will probably be less visually appealing.

The power station at the Wairakei plant is not visible from Highway 1, although hikers in the scenic reserve across the river have an excellent view. Fossil-fueled stations are visual abominations; nuclear plants, those that are imaginatively conceived, can evoke planetariums; the Wairakei station lies somewhere in between. It is all right. The fierce noise levels (up to 90 decibels) that permeate its interior; the reek of H_2S that seeps off the roof and down into the offices of the station's supervisory force; and the ugly pile of insulators, conductors, and transformers that constitute a switchyard are all tucked away from public exposure. Even the transmission lines make a modest exit through a stand of stately *Pinus radiata*.

Adjacent to the borefield, on the west side of Highway 1, stands the Geothermal Information Centre. The tourist officer who mans the station estimates that 125,000 visitors (two-thirds of them from overseas) toured the field in 1973. Nearly all of the visitors are enthusiastic about geothermal power. The most frequent question he fields is, "Are there any environmental effects?" He tells them that there are not.

Summary

The Wairakei plant discharges approximately 6.5 times as much heat, 5.5 times as much water vapor, and 0.5 times as much sulfur, per unit of power produced, as would a modern coal plant in New Zealand. It also contaminates the Waikato River with H_2S, CO_2, arsenic, and mercury at concentrations that have adverse but not calamitous effects. Designed and built at a time when environmental sensibilities were less acute and geothermal technology was less developed, Wairakei produces an overall environmental impact that would be neither acceptable nor necessary in a new plant. Despite its imperfections, however, the Wairakei plant has been under development or in operation for more than 20 years without presenting any serious environmental problems for the local population. Reinjection of the hot waste water, an as yet unproven procedure for liquid-dominated fields, would reduce the plant's environmental impact sharply. Ground subsidence is not a severe problem at Wairakei but may prove to be one at the nearby Broadlands field.

There are several environmental characteristics that are unique to geothermal power: (i) pollutant formation may be independent of the power production rate; (ii) effluent pathways may change abruptly; (iii) preoperational testing and wild bores contribute significantly to the overall impact; and (iv) waste water may be discharged at temperatures high enough so that utilization of the waste heat becomes both practical and imperative.

References and Notes

1. R. G. Bowen, in *Geothermal Energy*, P. Kruger and C. Otte, Eds. (Stanford Univ. Press, Stanford, Calif., 1973), pp. 197–215.
2. R. S. Bolton, *N.Z. Minist. Works Doc. 92/14/1/1* (August 1972).
3. R. C. Axtmann, *N.Z. Dep. Sci. Ind. Res. Phys. Eng. Lab. Rep. No. 445* (December 1974).
4. T. G. N. Haldane and H. C. H. Armstead, *Proc. Inst. Mech. Eng. (U.K.)* **176** (No. 23), 603 (1962).
5. G. W. Grindley, *N.Z. Geol. Surv. Bull. 74* (1965).
6. Operators of liquid-dominated fields will not valve off a well, unless absolutely necessary, in order to prevent silication of the valves and blockage of holes in the well's liner. This is much less of a problem in vapor-dominated fields.
7. P. F. Reay, *J. Appl. Ecol.* **9**, 557 (1972); in *Proceedings of the Pollution Research Conference, Wairakei, 20–21 June 1973* [*N.Z. Dep. Sci. Ind. Res. Inf. Ser. No. 97* (1973), pp. 365–376].
8. The "concentration factor" is defined as the ratio of the metal's concentration in the dried plant to the concentration in water upstream of the plant.
9. *U.S. Public Health Ser. Publ. 956* (1962).
10. D. E. White, L. G. Hinkle, I. Barnes, *U.S. Geol. Surv. Prof. Pap. 713* (1970).

B. G. Weissberg and M. G. R. Zobel, *Bull. Environ. Contam. Toxicol.* **9** (No. 3), 148 (1973).

12. S. Miner, *Preliminary Air Pollution Survey of Hydrogen Sulfide: A Literature Review* (National Air Pollution Control Administration, Raleigh, N.C., October 1969).
13. R. B. Glover, in *Proceedings of the United Nations Conference on the Development and Utilization of Resources* (Pisa, 1970), *Geothermics*, in press.
14. R. T. Douglas, in *Proceedings of the Pollution Research Conference, Wairakei, 20–21 June 1973* [*N.Z. Dep. Sci. Ind. Res. Inf. Ser. No. 97* (1973), pp. 315–333].
15. W. W. Kellogg, R. D. Cadle, E. R. Allen, A. L. Lazrus, E. A. Martell, *Science* **175**, 587 (1972).
16. C. F. Hill, *N.Z. Elec. Dep. Rep. 21/22* (December 1970).
17. L. L. Smith, Jr., and D. A. Oseid, *Prog. Fish-Cult.* **33**, 81 (197 *Water Res.* **6** (No. 6), 711 (1972).
18. *Inadvertent Climate Modification (Report of the Study of Man's Impact on Climate)* (MIT Press, Cambridge, Mass., 1971).
19. R. C. Axtmann, *Environ. Lett.*, in press.
20. When the lake is lowered, the river level at the geothermal station's pump house also drops, thereby increasing the vertical distance over which the coolant must be pumped.
21. V. J. Chapman, *A History of Lake Weed Infestation of the Rotorua Lakes and the Lakes of the Waikato Hydroelectric System* [*N.Z. Dep. Sci. Ind. Res. Inf. Ser. No. 78* (1970), pp. 33–34].
22. J. M. A. Brown, F. I. Dromgoole, M. W. Towsey, J. Browse, in *Mechanism of Regulation of Plant Growth*, R. L. Bieleski, Ed. (New Zealand Royal Society, Wellington, in press).
23. L. G. Rich, *Environmental Systems Engineering* (McGraw-Hill, New York, 1973), pp. 7–8.
24. J. Kanwisher, *J. Geophys. Res.* **68**, 3921 (1963).
25. H. M. Benedict and W. H. Breen, *Proc. 3rd Natl. Air Pollut. Symp.*, Pasadena, Calif., 1955.
26. K. A. Oelson and R. R. Boyle, *Chem. Eng. Prog.* **67** (No. 7), 72 (1971).
27. The mass output rate from the borefield, the enthalpy of the geothermal fluid, and the electrical output have all declined in recent years. The numbers used in this section correspond to operating conditions in August 1973 as reported to me by a representative of the New Zealand Electricity Department, namely, 5.6×10^6 kg per hour of geothermal mass at an average enthalpy of 1110 joule/g and separated at an average pressure of 8.6 atm. The gross electrical output was 147 Mw (electrical), and the net output was 143 Mw (electrical). These values are inconsistent with a 1971 set which yield a thermal efficiency of 6.5 percent. The relative values of the quantities reported in Tables 3 and 4 are little affected by the discrepancy, however,
28. C. R. James, *N.Z. Eng.* **22** (No. 6), 221 (1967); *ibid.* **23** (No. 6), 230 (1968); *ibid.* **25** (No. 12), 325 (1970).

29. J. P. F. Robinson, *N.Z. Elec. Dep. Rep. 32/4/3* (September 1968).
30. *New Zealand Water and Soil Conservation Act (No. 2)* (1971).
31. The situation has an ironic aspect: trout in the Waikato River are not "natural"; rather, they were introduced from stocks obtained in North America.
32. V. Armstrong, discussion following the paper of Haldane and Armstead (*4*), p. 636.
33. C. J. Banwell, in *N.Z. Dep. Sci. Ind. Res. Bull. 117* (1955), pp. 45–74.
34. The "surface discharge area" is defined as that area which displays temperatures above ambient at a depth of 1 m.
35. G. B. Dawson and D. J. Dickinson, *Geothermics* (special issue No. 2), **2** (No. 1), 466 (1970).
36. R. S. Bolton, in *Geothermal Energy* (Unesco, Earth Sciences No. 12, Unipub, New York, 1970), pp. 175–184.
37. J. W. Hatton, in *Proceedings of the United Nations Conference on the Development and Utilization of Geothermal Resources* (Pisa, 1970), *Geothermics*, in press.
38. R. S. Bolton, in *ibid.*
39. R. B. Glover, personal communication.
40. G. F. Pinder at Princeton University has recently initiated a computer simulation of the Wairakei reservoir [see J. W. Mercer and G. F. Pinder, in *Finite Element Methods in Flow Problems*, J. T. Oden, Ed. (Univ. of Alabama Press, University, 1974), pp. 401–414.
41. C. F. Hill, *Phyto- and Zooplankton Recovered from the Hydroelectric Lakes between Taupo and the Meremere Power Station* (New Zealand Electricity Department Report, Rutherford House, Wellington, undated).
42. S. H. Wilson, *N.Z. Dep. Sci. Ind. Res. Bull. 117* (1955), pp. 27–42.
43. This article is an adaptation of a report (*3*) to the New Zealand Department of Scientific and Industrial Research. The research was supported by that organization, the Engineering Foundation of New York, the National Science Foundation (grant GF-41575), and the Council on Environmental Studies of Princeton University. I thank the nearly 100 New Zealanders who contributed to the study but most particularly, Dr. I. G. Donaldson, who initiated me into the esoterica of geothermal power; Dr. M. C. Probine, whose sustaining interest was vital; Dr. W. A. J. Mahon, who provided helpful data and counsel; and Dr. A. J. Ellis, who first alerted me to the perils of eating New Zealand's meat pies in the summertime.

Shrubs—A Neglected Resource of Arid Lands

Cyrus M. McKell

Except under severely arid conditions, shrubs are the dominant vegetation of the world's extensive arid and semiarid regions, yet man's use of them falls short of their potential. Traditions, lack of suitable technology, ignorance, economic limitations, and a desire to preserve existing environments are among the reasons for underutilization or misutilization of arid shrublands. Observations, trial and error tests, and scientific investigations have gradually produced information about shrubs in terms of their nutritive value, palatability to livestock and big game, use for wildlife habitat, chemical and physical characteristics, and other biological functions in arid ecosystems. This accumulated knowledge was partially summarized in the proceedings of the International Symposium on the Biology and Utilization of Wildland Shrubs held at Logan, Utah, in 1971 (*1*). All too often, however, land management policies show insufficient awareness of the relevant data.

Shrub responses to disturbance or intensive use vary with location, competing vegetation, and type of use. Following settlement by the pioneers and the subsequent pressure of livestock grazing, great expanses of the sagebrush–perennial grass type in the Great Basin region of the western United States became a sagebrush–annual grass type. This accelerated succession or retrogression of vegetation prompted an eminent ecologist (*2*) to ask in 1947, "Is Utah Sahara bound?" He envisioned a loss of protective plant cover sufficient to turn large areas of the state into desert. His concern was valid, but improved management has reversed some of the trends he was observing. Other regions of the world have been less fortunate; Le Houerou (*3*) pointed out that shrubs and trees in Mediterranean North Africa are being seriously mismanaged and are therefore receding rapidly in the face of urban population pressures.

Many desert areas obviously are not suited to intensive utilization of their shrub cover, and climatic conditions may inhibit seedling establishment of the more usable shrubs. Shrub communities in such areas may be complex mixtures, as in the monte region of the Argentine Patagonia (Fig. 1), which is dominated by *Prosopis* species and *Larrea divaricata* but includes many other species (*4*); or they may be a simple mix of medium and low shrubs, such as bursage (*Franseria dumosa*) in stands of creosote bush (*Larrea tridentata*) in the Mojave Desert (Fig. 2); or the community may be dominated by a single species, as sagebrush (*Artemisia tridentata*) in parts of the Great Basin of Utah and Nevada (Fig. 3). When considering the potential for developing the shrub resources of arid lands, therefore, it must be emphasized that such efforts must incorporate specifically designed good land management practices. In this article I discuss some misconceptions about shrubs, adaptive features of shrubs that enhance their success in arid lands, and some ways in which shrubs can be used to the betterment of mankind.

Misconceptions That Hinder Objective Appraisals of Shrubs

Our inadequate knowledge of the biology and chemical nature of shrubs is complicated by the misconceptions many people have about the potential productivity of shrubs and shrublands. Some of these are discussed below.

"Shrubs are worthless invaders." This misconception is based on the observation that when some plant communities are disturbed, as by overgrazing, shrub numbers increase significantly. The routine conclusion, proposed even by many competent plant ecologists, is that the palatable grass and forb species have been replaced by less palatable, low-value shrubs (*5, 6*). However, Holmgren and Hutchings (*7*) found that, under protection from grazing, the salt desert shrub community moves toward dominance by blacksage (*Artemisia nova*), while intense winter grazing promoted an increase in shadscale (*Atriplex confertifolia*) and grass but a decrease in winterfat (*Ceratoides lanata*). Such a grazing-induced

The author is professor of range science and director of the Environment and Man Program, Utah State University, Logan 84322.