In this issue of Yellowstone Science, Alethea Steingisser and Andrew Marcus in Human Impacts on Geyser Basins document the global distribution of geysers, the destruction of geysers at the hands of humans, and the tremendous importance of Yellowstone National Park in preserving these rare and ephemeral features. We hope this article will promote further documentation, research, and protection efforts for geyser basins around the world. Documentation of their existence is essential to their protection in the future.

In her article, Sarah McMenamin describes some unusual salamanders living in the park. The discovery of their translucent color sparked excitement about physiological—rather than genetic—differences caused by environmental factors. Their manifestation is made possible by the environmental diversity Yellowstone provides.

We also report on the status and distribution of white-tailed jackrabbits in Yellowstone in response to a study that claimed they had been extirpated from the park. As they have since the park’s establishment, jackrabbits continue to persist in the park in a small range characterized by arid, lower elevation sagebrush-grassland habitats. With so many species in the world on the edge of survival, the confirmation of the jackrabbit’s persistence is welcome.

The Nature Note continues to consider Yellowstone with a broader perspective. Shannon Barber-Meyer, who did her PhD work in Yellowstone on elk calf mortality (see issue 13:3), describes her new experiences as the Tiger Conservation Program Officer for the World Wildlife Fund. She considers the similarities and differences between Yellowstone and India’s Corbett National Park as well as wolves and tigers.

We hope you enjoy the issue.
Human Impacts on Geyser Basins

Alethea Steingisser and W. Andrew Marcus

Geysers and hot springs are relatively rare geologic features that are vulnerable to impacts from human activities. Geysers in particular are susceptible to human impacts, with many of the world’s geysers having already been altered or completely extinguished by geothermal energy development and tourism. Yellowstone National Park was set aside as the world’s first national park due primarily to its multiple geyser basins, an act that set the stage for protecting lands deemed unique in the world. The park has lost a relatively small number of geysers to tourism-related activities, but there is potential for greater damage if geothermal development occurs outside the park.

This article places the remarkable geyser activity of Yellowstone within a global context, examines human impacts to geyser basins worldwide, and examines historical and potential future impacts to thermal features in Yellowstone resulting from tourism and possible geothermal development outside the park. This article is based on a master’s thesis in geography completed at the University of Oregon in 2006.

Data

There are few global, systematic accounts of human impacts to geysers and other geothermal features; most research is site specific. T. Scott Bryan provided a synthesis of global geyser basin distribution and human impacts as an appendix in his guidebooks, The Geysers of Yellowstone (1991, 1995). Donald White, known for his research on geothermal resources and geyser basins in particular, also documented global impacts of geothermal development on geyser basins (1967, 1968, 1979, 1988, 1992). This article expands on the contributions made by Bryan, White, and others to provide a historical summary of geyser basins as a global resource that has been altered by various types of human activities.

In addition to a literature review, research in this article comes from many wonderful hours absorbed in the archives at the Yellowstone National Park Heritage and Research Center in Gardiner, Montana, and the National Park Service (NPS) library and photo archives at Harpers Ferry, West Virginia. Additional geyser information and historical photos were found through the Geyser Observation and Study Association, a nonprofit organization dedicated to the collection and dissemination of information about geysers.

Geysers and Their Controls

Geothermal regions occur where heat from Earth’s interior rises and creates phenomena such as volcanoes, geysers, and hot springs. While volcanic features are generally spread over relatively large areas associated with plate boundaries and hot spots, hydrothermal areas (where heated water rises to the surface to create springs and geysers) are more limited in extent due to local-scale controls on subsurface heat flow, water availability, and pressure. Fournier (1989) describes these controls in Yellowstone in detail.

The difference between geysers and hot springs is the presence or absence of pressure. Pressure is controlled by a variety of factors including rock type and configuration of the
underground passage through which the heated water passes on its way toward the surface. If the water can flow freely toward the surface, it bubbles out as a hot spring. Alternatively, if there is enough pressure to prevent the water from rising easily to the surface, it may eventually burst to the surface in an eruption.

Because the geologic and hydraulic components responsible for geysers are so precisely balanced, there may be significant natural variability in the temperature, discharge, periodicity, or (non)eruptive characteristics of individual features within a single basin. In many cases, the behavior or characteristics of a feature will change with no identifiable cause. In other examples, natural events such as earthquakes, volcanic eruptions, and landslides have created changes in multiple features simultaneously. For example, the 7.1 magnitude Hebgen Lake earthquake outside of Yellowstone in 1959 caused major changes in geothermal features throughout the park. The discharge of many hot springs greatly increased while others were nearly drained. Geysers erupted that had never before been recorded. In many thermal features throughout the park, the temperature increased and their waters became murky with sediment (Marler 1964).

Thermal features such as hot springs, geysers, fumaroles, and mud pots can assume characteristics of one another on a monthly, yearly, or decadal scale. Geysers are the most rare of these forms and occur in close proximity to other geothermal features, although the degree of inter-connectedness between geothermal features is still poorly understood.

Global Distribution of Geysers

Globally, there are at least 40 locations where geyser activity has been documented, but geysers are now extinct in many of those locations. Figure 1 shows these locations as reported by Bryan in 1995. Even in the few sites where geysers have been carefully documented, enumeration at any scale is problematic if not impossible because geysers are inherently unstable both temporally and spatially. Historical and contemporary accounts often disagree about the number of features. The definition of what constitutes a geyser rather than a boiling spring may change from one observer to the next, the length of field observations may vary, and access can be difficult. There is, however, general agreement in the contemporary literature regarding those areas that historically have contained significant numbers of geysers. Figure 2 shows geyser counts for the eight historically largest geyser basins, for which reasonably high quality data are available on geyser distributions and associated human impacts. Although precise counts are elusive because of the nature of geysers, all sources agree that Yellowstone has more geysers than any other thermal area in the world.

Human Impacts to Geysers

Historical Use of Geothermal Resources

It is believed that human use of geothermal resources may date as far back as the Paleolithic period, but concrete evidence only dates to 8,000 to 10,000 years ago, as exemplified by archeological finds near hot springs in North America. The first written evidence of human use of hydrothermal basins dates to the twelfth century BC, when the Etruscans established urban centers such as Bolsena, Populonia, and Saturnia near geothermal sites to extract hydrothermal minerals such as sulfur, kaolin, and travertine for export to foreign markets. Bathing in thermal springs was also highly valued for spiritual
and therapeutic reasons and is still popular today. Historical use of hydrothermal basins was mostly confined to hot springs, due in part to the great abundance of hot springs relative to the very few geyser basins worldwide. More importantly, historical use of thermal features was limited to those found at Earth’s surface. It was not until the Industrial Revolution in the nineteenth century that technological development and increasing demand for electricity inspired a new use for geothermal resources: energy production.

**Geothermal Energy Development**

Even though geothermal energy comprises less than 1% of total global energy production and only 4% of total renewable energy use (IEA 2007), geothermal energy prospecting and development has had a greater impact on geyser basins worldwide than any other human activity. Globally, at least eight geyser basins have lost all or most of their natural geyser activity due to geothermal energy development (Bryan 1995), while several others are threatened by potential development from geothermal leases on site or in adjacent areas. Because of the lack of long-term documentation of geysers in many locations, the exact number of individual features that have been altered or destroyed is uncertain.

Damage to geysers and springs from geothermal energy development results from drilling into the subsurface hydrothermal reservoir. Drill holes created to extract heated groundwater and steam create new channels that rob geysers and springs of water and heat needed to sustain pressure.

Geysers often stop erupting or erupt less frequently and with less volume, and springs dry up.

Although the first use of geothermal energy for electric generation occurred in 1904, geothermal energy production was initially concentrated in vapor dominated reservoirs that contain relatively large mounts of steam. Development where geysers were located did not occur until the 1950s, when there was a shift toward the use of geothermal systems that contain an abundant supply of heated groundwater relatively close to the surface. These systems were less expensive to develop, easier to find due to obvious geothermal activity at the surface, and more abundant worldwide (Duffield and Sass 2003, Rinehart 1980).

**Tourism**

Geysers and hot springs have also suffered impacts from human activities related to tourism, such as vandalism and infrastructure development. Throwing objects into geysers, whether to induce eruptive activity or simply for “good luck,” can change the delicate balance of water pressure and circulation (in essence, plugging the vent), resulting in alteration or cessation of the feature’s natural activity. Rocks, sticks, clothing, coins, and numerous other items have been pulled from geyser vents. The circulation change can also change the water temperature, harming microbial algae mats that require specific temperatures.

Development of tourist facilities such as roads, structures, walkways, and paths in thermal areas has undoubtedly dam-

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*Figure 2. Relative sizes of selected geyser basins (Steingisser 2006). Geyser counts include active, dormant, and extinct geysers, and do not imply that all were active simultaneously. Geyser counts at a location can vary from one researcher to the next. The counts shown here are based on the sources cited in the figure.*
aged some features, although these infrastructure impacts are poorly documented. While these impacts do not often alter entire geyser basins, they are responsible for impacting individual features.

Global Summary of Impacts

Half of the major areas containing geysers have been hydrologically altered by geothermal energy development, and individual springs and geysers at four or more locations have been altered as a result of tourism (Table 1). The Valley of the Geysers on the Kamchatkan peninsula and the geysers on Umnak Island in Alaska have sustained few, if any, impacts due to their relatively remote locations, while the geyser basins of New Zealand and Iceland were severely altered due to their location in areas where substantial populations needed energy resources. New Zealand, in particular, has suffered the loss of more geysers than anywhere else in the world. The exact number of features altered at most locations is uncertain, owing to the dynamic nature of geysers and lack of long-term documentation.

New Zealand. The geyser basins of New Zealand once contained the second largest concentration of geysers in the world outside of Yellowstone. More than 20 geothermal areas are located in the Taupo Volcanic Zone on the North Island, five of which (Wairakei, Orakeikorako, Rotorua, Waimangu, and Waiotapu) have contained geyser activity. It is estimated that more than 220 geysers existed in these basins as recently as the 1950s. By the 1990s only 55 geysers remained, with many losses due to geothermal resource development (Scott and Cody 2000).

The withdrawal of geothermal fluids for electricity production in the Wairakei basin resulted in the extinction of all geysers (about 70), loss of approximately 240 hot springs (Scott and Cody 2000), and ground subsidence of 14 meters, the largest ever recorded for any type of fluid withdrawal including gas and oil (Allis 2000). At Orakeikorako, nearly 70 geysers and 200 hot springs were flooded by the creation of Lake Ohakuri in 1961 when the Waikato River was dammed for hydroelectric power production (Environment Waikato Regional Council 2006).

The exploitation of geothermal resources at Rotorua began in the 1920s, primarily to pipe geothermal water through homes and businesses for heating. By 1980 more than 500 geothermal wells were producing electricity. The increased fluid withdrawals, combined with a long-term decrease in precipitation, caused many geysers to stop erupting, while others showed the largest decreases in activity seen in 140 years. Government regulations later forced the closure of many wells to protect the remaining geysers. Some geysers have reverted back to their former state while others show sporadic recovery and many remain dormant (Allis and Lumb 1992, Scott and Cody 2000). Several geysers in Rotorua were soaped to induce

<table>
<thead>
<tr>
<th>Location</th>
<th>Altered by geothermal energy development</th>
<th>Documented negative effects of tourism</th>
<th>Geyser historically documented</th>
<th>Geyser lost due to human activities</th>
<th>Percent of geysers lost</th>
</tr>
</thead>
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<td>Yes</td>
<td>61</td>
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</tr>
<tr>
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<td>80</td>
<td>*</td>
<td>*</td>
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<tr>
<td>Valley of Geysers (Russia)</td>
<td>*</td>
<td>*</td>
<td>200</td>
<td>*</td>
<td>*</td>
</tr>
</tbody>
</table>
* No data available

Table 1. Range of geyser counts and summary of human impacts to geysers.

Waimangu Geyser, the largest geyser ever documented in terms of height and volume, formed in 1900 near Mt. Tarawera in New Zealand, and became extinct in 1904 as a result of landslide materials blocking its vent. (A. Shepherd, 1903. Printed with permission of the Museum of New Zealand Te Papa Tongarewa, #C.016361).
eruptions for tourist displays, and channels and dams were also built around thermal features to manipulate geyser activity (Cody and Lumb 1992, Rinehart 1980). Other geysers were lost as a result of natural activity. Waimangu Geyser, the largest geyser ever documented in terms of height and volume, formed in 1900 and became extinct in 1904 as a result of landslides blocking its vent (Hunt et al. 1994).

**El Tatio, Chile.** El Tatio has so far been spared large-scale geothermal development, in part because of its remote location in the Chilean Andes. The Chilean government drilled six exploratory wells and seven production wells between 1969 and 1974, but the project was soon abandoned and no studies on impacts to thermal features were undertaken. El Tatio has since become a tourist destination, albeit not a developed one. There are no designated roads or walkways, nor is there a management system in place. Human impacts observed by Glennon and Pfaff (2003) were relatively minor and included objects thrown into springs and geysers and tire marks on thermal features.

**Iceland.** Being a volcanic island, Iceland lacks fossil fuel energy reserves and depends almost entirely on geothermal energy and hydropower. The primary use of geothermal resources is for space heating; 87% of Iceland’s 280,000 residents live in homes with geothermal heat (Ragnarsson 2003). Prior to exploitation, approximately 60 geysers existed in scattered basins, mostly on the western side of the island (Barth 1950). There are no specific studies, at least in the English language, that document the disappearance of geysers in Iceland. There is evidence that geysers were soaped and fitted with pipes to induce eruptions (Barth 1950, Nielsen 1937), but it is uncertain if these actions had any long-term effects on geyser activity. Bryan (1995) indicates that most of the thermal features in the Reykir geyser basin have been destroyed by geothermal drilling, and that many of the individual features scattered across the island are gone as well. Iceland now has fewer than 30 active geysers.

**Valley of Geysers, Russia.** Reports by Russian scientists indicated that there were more than 20 geysers present in the Valley of the Geysers on the Kamchatkan Peninsula when they first explored it in 1941. Bryan observed at least 200 geysers during field research in 1991. The area has not been commercially developed for tourism or energy development and is protected as part of the Kronotsky Nature Preserve, which encompasses an area approximately equal in size to Yellowstone. Access in the past was difficult, expensive, and usually undertaken only by ecotourism-related travel companies. As such, the Valley of Geysers thermal features are not believed to have been altered by human activity (Bryan 1995). However, in June 2007, a massive landslide buried some of the features under as much as 60 meters of debris and dammed the nearby Geysernaya River. The flooding from the river has turned much of the valley into a lake, silencing many of the remaining geysers. The ramifications of this natural disruption have not yet been fully evaluated.

**United States.** In the U.S., the shift from dry steam to hydrothermal reservoirs for geothermal energy production in the 1950s resulted in increased exploration of hydrothermal systems. By 1965, the drilling of exploratory wells had caused the loss of all natural geyser activity at Beowawe and Steamboat Springs in Nevada, the two largest geyser basins in the U.S. outside of Yellowstone (White 1967, 1992). The Geyser Bight Geothermal Area on Umnak Island in the Aleutian Islands is part of one of the hottest and most extensive areas of thermal springs in Alaska (Motyka, et al. 1993) and is the only geyser location in the United States other than Yellowstone that has not been altered by geothermal resource development. Geyser Bight has been spared mainstream tourism and geothermal development due to its remote location. However, research funded by the U.S. Department of Energy concluded that the region would make an excellent site for geothermal energy development for industries wishing to site themselves in the Aleutians (Motyka et al. 1993, Nye et al. 1990). In Yellowstone a small number of geysers have stopped functioning as a result of tourism-related activities, as described below, but there is potential for greater damage if geothermal development occurs outside the park boundaries.

**Yellowstone’s Geothermal Landscape**

Although Native Americans were aware of Yellowstone’s geyser basins, the first Euro-American reports of the region surfaced in the late 1820s when American trappers moved into the Yellowstone region. Few Americans believed trapper and mountain man Jim Bridger’s tales of hot water and steam shooting up out of the ground, but his stories inspired the Folsom-Cook expedition to investigate and finally confirm his stories by 1869. The following year, a party led by Henry
Washburn became the first white men to “discover” the Upper Geyser Basin and Old Faithful. In 1871, Congress funded the first official government expedition, which was led by Ferdinand Hayden, head of the U.S. Geological and Geographical Survey of the Territories. Hayden had the foresight to invite artist Thomas Moran and photographer William Henry Jackson, who provided the first visual representations of the Yellowstone region. Hayden’s scientific observations and catalogues, combined with Jackson and Moran’s artwork, inspired Congress to set aside Yellowstone as the world’s first national park in 1872. The creation of the park to protect the unique thermal features within its boundaries also protected it from the direct large-scale geothermal energy development that later altered or destroyed the natural activity of many of the world’s large geyser basins. It is now known that Yellowstone contains more than 11,000 thermal features (Rodman, pers. comm., 2008) and perhaps as many as 500 historically documented geysers, more than any other geothermal region in the world. There are at least 100 thermal areas in the park, with geysers documented in 9 of them.

Figure 3. Yellowstone contains more than 11,000 thermal features and perhaps as many as 500 historically documented geysers, more than any other geothermal region in the world. There are at least 100 thermal areas in the park, with geysers documented in 9 of them.

Steamboat Geyser, currently the tallest geyser in the world, and Black Growler fumarole, which holds the record for the highest surface temperature recorded in the park (138°C) (White et al. 1988). The Upper Geyser Basin is home to Old Faithful, which may be the most well-known geyser in the world and certainly in the U.S. It is also thought to contain up to 200 other geysers, more than any other single geyser basin in Yellowstone and perhaps the world (Bryan 1995).

Six of Yellowstone’s geyser basins (Norris, Gibbon, West Thumb, Lower, Upper, and Midway geyser basins) are developed for mainstream tourism with easy access by roads and trails. The Lone Star, Shoshone, and Heart Lake basins are only accessible via backcountry travel. The congressional act of drawing a line around a piece of land unknowingly protected Yellowstone’s thermal features from large-scale geothermal resource development, but exposed them to tourism-related impacts. With up to three million visitors per year, the struggle between protecting Yellowstone’s thermal features while allowing access for public enjoyment is constant.

Human Impacts to Yellowstone’s Geyser Basins

Human impacts in Yellowstone’s geyser basins are those that have resulted from tourism in the park. The following examples, which include historical accounts of alteration to individual geothermal features, are intended to provide a basis for understanding potential impacts in other geothermal locations, not a complete listing of all features that have been damaged in Yellowstone. Future geothermal development just outside the park poses a potential threat to Yellowstone’s thermal features and is also discussed.

Impacts from Tourism

Vandalism, as we now consider it, has been a problem since the first park visitors, employees, and researchers arrived. Although the 1872 Yellowstone National Park Act reserved two million acres “as a public park or pleasing ground for the benefit and enjoyment of the people,’’ there were no institutional structures in place for managing the park. Park visitation was low at first (approximately 500 per year until 1896), but acts of vandalism were pronounced enough that Superintendent Nathaniel Langford’s assistant remarked in 1873 that “the parapets of sinter surrounding the ‘Castle’ and ‘Old Faithful’ and the ‘Bee Hive’ [geysers] have been much defaced by visitors to the park” (Bartlett 1985). Souvenir hunters broke up geyser formations and carved their names in thermal features, damage that still occurs today (Magoc 1999). The high demand for Yellowstone souvenirs inspired entrepreneurs to put horseshoes and bottles in hot spring formations so they would become encrusted with travertine.

Both visitors and park officials attempted to induce eruptions by throwing soap down geyser vents, a practice that is thought to have originated at Chinaman Spring in the Upper
Geyser Basin as early as 1885 (Whittlesey 1988). A concessionaire using the spring’s natural agitation to launder clothing apparently induced an eruption by adding soap to the mix, throwing clothing all over the landscape (Bryan 1995). Once tourists learned that soap could induce eruptions, sales of soap skyrocketed and toilet soap from the hotels was in constant short supply. When park Geologist Arnold Hague heard these rumors, he conducted his own experiments using both soap and lye, “which proved so satisfactory that I continued my investigations throughout the season on many of the hot springs and geysers in the principal basins.” In a letter dated September 6, 1888, Hague describes how this practice benefited park photographer F. Jay Haynes by producing eruptions at times with the best lighting, clouds, and wind rather than at the whim of the geysers’ schedule. However, Hague was unsuccessful in his attempt to induce Giant Geyser to erupt:

…In the “Giant” geyser, which, at the time of my experiments, had not played for several months, I was able to cause most violent agitation and the throwing out of water, but nothing that could be called a genuine eruption. People familiar with the behavior of the “Giant” before an eruption, but ignorant of what I had done, believed the geyser was ready to resume its former activity.

Throwing other objects into geysers and hot springs has been a problem since Yellowstone’s early days and has been a major cause of irreversible damage that continues to threaten the park’s thermal features today. Frank Carpenter, who visited the park from Radersburg, Montana, in 1877, described what happened after his party dropped their clothing into Old Faithful:

…the next instant, with a rush and a roar she “goes off” and the clothes, jackets, rags, etc., mixed in every conceivable shape, shoot up to a distance of a hundred feet or more and fall with a splash in the basins below. The water subsides and we fish out the clothing which we find nice and clean as a Chinaman could wash it with a week’s scrubbing.

The party then gathered up nearby items and continued their experiment:

…we collect an immense quantity of rubbish and drop it into the crater. We have filled it to the top with at least a thousand pounds of stones, trees, stumps, etc…. the earth begins to tremble…and away go rocks, trees and rubbish to a height of seventy-five or eighty feet in the air.

These types of activities are now known to cause tremendous and often irreversible damage to geyser systems. Objects introduced into thermal features disrupt circulation and pressure within the system and can result in permanent alteration or cessation of the feature’s natural activity.

After the Army was given responsibility for protecting park resources in 1886, thermal features continued to be vandalized. O’Brien (1999) comments that the focus was more on accommodating visitors than on protecting park resources during this time. The creation of the NPS in 1916 by the NPS Organic Act enunciated the primary goals of park management, whose mission was “to conserve the scenery and the natural and historic objects and the wildlife therein and to provide for the enjoyment of the same in such manner and by such means as will leave them unimpaired for the enjoyment of future generations.” This mission was to be accomplished by staffing the parks with personnel who would participate in all aspects of park management. However, correspondence by Yellowstone personnel during the 1940s and 1950s indicates the severity of the ongoing problem and the methods used to reduce vandalism and reverse its effects. Park Geologist George Marler (1946) stated:

…To name all the thermal features where vandalism is in evidence would be a cataloguing of most of the pools, springs and geysers in the Upper, Midway and Lower Basins. Just as a slowly advancing delta destroys the lake, just as certainly continually man-added debris will destroy the pools, springs and geysers of Yellowstone….

…granting he comprises but one percent or less of the traveling public, still this army of thousands is spreading a pestilence which if unchecked will produce a vastly different Yellowstone a few generations hence…. 

Geothermal features suffered heavily from vandalism during the summer of 1946, when the end of the war brought
increased visitation (Condon n.d.). Marler’s strong sentiments are due in part to his responsibility for cleaning debris out of thermal features in 1946, when he twice removed rocks weighing more than 40 lbs from the vent of Turban Geyser. In 1947, he reported hauling 55 wheelbarrows full of rocks and debris from springs and geysers in addition to a large tree from Emerald Pool, stating that “the culprits had resorted to considerable labor to drag this tree to the pool and shove it in.”

Superintendent Fred Johnston tried to prevent vandalism by educating the public. He submitted Chief Naturalist David Condon’s essay, “Invaluable Natural Assets in Yellowstone National Park Suffer from Vandalistic Acts” to the park’s regional director, urging publication in the mass media. Condon described how even one pebble tossed into a spring or geyser, when multiplied by hundreds or thousands, can cause permanent damage or complete destruction of geysers and springs.

Despite the efforts of park management, numerous features have been damaged by vandalism. Morning Glory Pool, in the Upper Geyser Basin, is perhaps the most notorious damaged feature within the park. Before the highway was diverted away from Morning Glory in 1971, its easy access and high popularity caused the spring to be the receptacle for large quantities of objects, including coins, rocks, logs, bottles, and clothing. Many efforts were made to remove items from the spring, but the continual addition of material clogged the vent, perhaps enough to lower the spring’s temperature and allow the growth of algae. The color of the pool changed to a deeper blue because of bacterial growth, and its scalloped edges were destroyed (Bryan 1995, Whittlesey 1988). Yellowstone Park Geologist Henry Heasler (2008) notes that the temperature of Beauty and Chromatic Pools (located in the same general area as Morning Glory) also dropped, but as a result of natural causes. As such, it is unclear whether the temperature change in Morning Glory was natural, a result of vandalism, or a combination of both factors.

Minute Geyser in Norris Geyser Basin may be the most vandalized geyser within the park. During the late nineteenth century, it erupted once per minute, sometimes up to 40 ft high. A stagecoach stop located there sometime later encouraged passengers to throw coins and other items into the vent (Whittlesey 1988). When new roads were constructed, Minute Geyser remained relatively close to the main access road and was continually vandalized. In 1935, a park naturalist noted “I found about 10 boulders ranging up to the size of a man’s head, almost completely filling the smaller of the two openings.” By 1969 the vent was clogged with rocks that were cemented in place by the spring’s mineral waters (White et al. 1988), causing the geyser’s eruptive activity to shift to a side vent. Minute Geyser’s activity became irregular and it erupted only a few feet. Another Norris Basin feature, Ebony Geyser, also became...
highly irregular due to vandalism that clogged its vent (Bryan 1995).

Handkerchief Pool, in the Black Sand Basin, was well-known for its ability to suck down items of clothing and spit them back up in a few minutes, scrubbed and clean. Its activity ceased in 1926 as a result of a log shoved into its vent. Nonetheless, visitors continued to throw objects into the pool. When the pool was first cleaned in 1929, more than one and a half bushels of debris were removed, including handkerchiefs, coins, more than 100 hair pins, nails, bolts, a horseshoe and other various items. In 1950, George Marler cleaned the spring, removing the log and gravel that had washed into the spring. Although water flowed once again into the pool, it was forever changed by the long period of inactivity during which algae mats encroached on its rims (Whittlesey 1988, Bryan 1995).

There is little doubt that park development such as road building, subsurface utility emplacement, and the construction of boardwalks has affected thermal features. Many roads are located next to or directly on top of geothermal areas. There is, however, little information on the impacts of development on specific features except for the personal communications of George Marler and U.S. Geological Survey employee Robert Fournier. Beehive's Indicator, a small geyser located a few feet from Beehive Geyser, commonly erupted immediately before activity at Beehive Geyser began until its vent became plugged with sand and gravel in 1953. Marler, who attributed the plug to altered drainage patterns caused by boardwalk construction that diverted runoff from Giantess Geyser, attempted to clean out the debris. Bryan described Beehive's Indicator as active but irregular in the mid-1990s. Marler also noted that a road had been built over the base of the Great Fountain Geyser, much of which had been physically “hacked away” and removed during the construction process “despite extensive, suitable, adjacent terrain.”

Fournier worked closely with park maintenance staff, advising them on issues regarding hot spring activity. In a 1971 letter to Superintendent Jack Anderson, Fournier identified issues that presented maintenance problems and offered solutions that would minimize damage to thermal features. In particular, he noted the futility of building roads atop active springs. The chemical-rich water and release of carbon dioxide gas eventually breaks down the pavement above the spring, a fact made evident by the 1959 Hebgen Lake earthquake. In his correspondence, Fournier referred to road deterioration resulting from spring activity in the Chocolate Pot area. He suggested designing a drainage system made of coarse gravel that would preserve the spring’s natural activity but allow the water to drain to the edge of the roadbed. He also suggested covering the gravel with plastic sheeting to vent the gases away from the road.

Although the full extent of impacts resulting from tourism is poorly documented, these examples indicate that public access to thermal features, especially popular ones, can create significant problems. It is probable that intentional acts of vandalism by park visitors represent only a very small minority of Yellowstone’s visitors, and that the great majority of visi-
tors engage with the park in a manner that promotes preservation. However, damage to Yellowstone’s thermal features at any scale must be addressed and prevented because the damage is often irreversible. The effects of vandalism have been alleviated to some degree by aggressive public education campaigns that include roving interpretive rangers, signs, and information published in the park newspaper about how vandalism damages thermal features (Taylor 2005). Additionally, dedicated volunteers such as Ralph Taylor, president of the Geyser Observation and Study Association, perform surface cleaning of thermal features during the heavy summer tourist season as well as monitor geyser activity.

Potential Impacts from Geothermal Energy Development

While vandalism and in-park developments have altered individual features within Yellowstone, potential impacts from external threats may pose the greatest risk to the park’s hydrothermal systems. Two known geothermal resource areas (KGRAs), Island Park and Corwin Springs, are located adjacent to park boundaries (Figure 4). The potential for geothermal development in these areas poses a risk because the hydrologic connections between the KGRA and park features are poorly understood (U.S. Forest Service and Bureau of Land Management 1979, Sorey 1991). After the Geothermal Steam Act of 1970 opened federally-owned portions of the KGRAs to geothermal leasing, more than 200 applications were filed for locations in Island Park, but none were approved because of concerns about the effect on the park of extracting subsurface fluids there. Amendments to the Geothermal Steam Act in 1984 banned federal geothermal development in the Island Park KGRA. However, leases for 25,000 acres of state and private land were granted, and potential geothermal development from these leases still threatens park resources (Harting and Glick 1994).

In 1986 the Church Universal and Triumphant drilled a geothermal well near Corwin Springs, only 8 km from the park boundary and 14 km from Mammoth Hot Springs, sparking an outcry by the NPS and conservation groups. The well significantly reduced the flow of LaDuke Hot Springs, located adjacent to the well site. This drilling and other concerns regarding resource development adjacent to national parks resulted in the Geothermal Steam Act amendments of 1988 that gave the Secretary of the Interior the right to turn down a lease application if it was “reasonably likely to result in a significant adverse effect on a significant thermal feature within a unit of the National Park System.” The amendment also specified that there would be no further development or geothermal leasing at Corwin Springs until the U.S. Geological Survey and NPS conducted a study on the hydrologic connections and possible impacts of development on Yellowstone’s thermal features. The study later found that there was a possible hydrologic connection between Mammoth Hot Springs and the Corwin Springs KGRA, but determined that limited development could continue at LaDuke Hot Springs without adversely affecting Yellowstone’s thermal features (Sorey 1991). In 1992, the moratorium on geothermal development at Corwin Springs KGRA expired, so potential harm to Yellowstone’s thermal features could still result if large-scale development occurs. More legislation was introduced in 1994 to protect Yellowstone’s thermal features, particularly the Old Faithful Protection Act, which would ban geothermal development within 15 miles of the park boundary, but it failed to pass in the Senate (Harting and Glick 1994).

A major milestone in the protection of Yellowstone’s thermal features was the signing of the Montana–NPS Water Compact in 1994. The compact allows Yellowstone and Glacier national parks and Big Hole Battlefield National Monument to retain all federally reserved water rights based on the year of each park’s establishment. The compact also addresses the protection of Yellowstone’s unique hydrothermal systems. This was accomplished by designating a Controlled Groundwater Area located just north and west of the park that has potential hydrologic connections with Yellowstone’s thermal features (Amman et al. 1995, Custer et al. 1994). The compact allows restrictions on both hot and cold groundwater withdrawals and geothermal development within this area to prevent adverse effects to Yellowstone’s thermal features.

The NPS has only limited water rights agreements with Yellowstone’s other two bordering states of Idaho and Wyoming. Idaho has granted Yellowstone all reserved water rights, Figure 4. There is currently no geothermal development at Corwin Springs or Island Park. If development occurs in the future, it could potentially threaten Yellowstone’s unique geothermal features.
but the agreement does not specifically address waters with possible geothermal connections. Wyoming has only settled rights for a small portion of the park and has no agreements that address geothermal resources (Harting and Glick 1994).

Conclusions

This research illustrates how vulnerable geyser basins are to the effects of human activities. At least half of the major areas around the world that contain geysers have been impacted to varying degrees by human activities and countless minor thermal features have been lost. Those that remain are potentially threatened by growing populations, tourism, increasing development, the growing demand for energy, and the relative ease by which geothermal energy is developed. Even thermal features in Yellowstone are potentially endangered by geothermal energy development along park boundaries and by tourism in the park, despite the fact that the park has had protected status since 1872. As the analysis of Yellowstone has suggested, preservation-oriented management and public education can perhaps relieve some of these negative effects, but we need to be increasingly vigilant and aggressive in protecting these rare and special features.

This review indicates the tremendous need for widespread monitoring of geothermal resources in order to monitor existing resources and assess future human impacts. Unfortunately, many geyser basins of the world have not been carefully inventoried nor are they monitored to help protect them from potentially destructive future impacts.

Yellowstone has perhaps the most aggressive inventorizing and monitoring program for any large geothermal region in the world. Yellowstone’s Thermal Inventory Project contains more than 11,000 thermal features sampled by ground survey crews each summer since 1998. The project was designed to inventory Yellowstone’s thermal features spatially using Geographic Information Systems, and contains sampling data about acidity and temperature.

Congress funded geothermal monitoring projects for Yellowstone in 1996 and again in 2005, resulting in strategies that greatly improved monitoring efforts. Yellowstone scientists monitor and assess geothermal activity through indicators such as chloride flux measurements in streams draining thermal areas, groundwater inventories, and thermal remote sensing. Yellowstone is also engaged in cutting-edge geothermal monitoring studies including isotope and environmental tracers of thermal water to determine flowpaths, groundwater flow characteristics as determined from shallow wells, heat flow of hydrothermal areas from airborne thermal infrared imaging, and geochemical studies of hydrothermal basin-scale convective heat flow (Heasler pers. comm. 2008). These multiple methods of data collection, monitoring, and assessment provide the baseline data necessary to detect change due to natural and anthropogenic causes, but they can be labor intensive and are often costly.

In addition, Yellowstone is actively involved in protecting thermal features on a daily basis. Interpreters educate visitors and also warn visitors of improper actions. Law enforcement rangers aggressively protect thermal areas and park maintenance staff work to minimize impacts to thermal features from infrastructure development.

Much of the problem with protecting geysers around the world lies in the difficulty of measuring and quantifying a dynamic system whose origins lie beneath Earth’s surface. Insufficient documentation creates problems for protection because it is difficult to protect something that one does not know about. People in many areas have failed to recognize the fragility of these features, their rarity, and the need to protect them for future generations. This research documents and explains changes due to geothermal energy and tourist development, but it does not discuss the human values associated with the landscape that ultimately direct the path to protection or development. These aesthetic, cultural, spiritual, ecological, and economic values will ultimately determine how much effort is expended on geothermal protection, development, and monitoring. Yellowstone National Park is thus the most critical area in the world for protecting geothermal resources into the future because of the tremendous number of features within its boundaries and the park’s international prominence in helping the public develop a deeper appreciation for geothermal features, their scarcity, and their fragility.

Note: One of the problems we faced in compiling this research was the paucity of scientific literature on geysers outside of Yellowstone. Many of these areas are poorly documented in English language publications. T. Scott Bryan, in his popular book The Geysers of Yellowstone, relies on personal travels, records, and anecdotal accounts to generate a global map of locations where geyser activity has been reported historically. In many cases, Bryan was the only documentation we found.

Acknowledgements

We would like to thank many contributors to this work. The initial inspiration for this work came from a speech by then Yellowstone Center for Resources Director John Varley given to the Annual Meeting of the Greater Yellowstone Coalition outlining the rarity of geysers, the lack of data on non-Yellowstone geysers, and the tremendous need to protect Yellowstone’s geothermal features. James E. Meacham provided guidance on content and graphics in this article. Ann Rodman and Carrie Guiles from the Spatial Analysis Center at Yellowstone National Park as well as other National Park Service staff provided data and invaluable information about Yellowstone and also helped to fact check the data for the Yellowstone maps. Yellowstone National Park Geologist Henry Heasler reviewed the article and offered important insights. Communications with T. Scott Bryan and members of the Geyser Observation and Study Association and the Geyser email list-server offered information, advice, and references. The dedication of all these individuals to understanding and protecting geothermal features the world over and in Yellowstone in particular provided the inspiration for this work.
Alethea Steingisser completed her Master’s in Geography at the University of Oregon in Eugene in 2006. She is also a professional fine art photographer who focuses much of her work on the natural environment. Her photos have appeared in calendars and magazines and in several gallery showings. She currently works for the University of Oregon as the lead cartographic designer on the upcoming Atlas of Yellowstone. The atlas is a collaborative project among the University of Oregon, the National Park Service, and Greater Yellowstone Area researchers.

W. Andrew Marcus is a professor in the Department of Geography at the University of Oregon, where he has resided since 2001. Prior to that he was a faculty member in the Department of Earth Sciences at Montana State University. He began his research in Yellowstone National Park in 1991 with studies of how mining, fires, and floods have affected stream and riparian habitats along Soda Butte, Cache, and Pebble creeks. Later work examined ways in which remote sensing imagery can be used to map, monitor, and model these systems. More recently, Marcus has been one of the lead editors of the Atlas of Yellowstone.

Literature Cited


