Early explorers, park personnel, and visitors have observed changes on the terraces of Mammoth Hot Springs for the past 130 years. Mammoth Hot Springs is a dynamic hydrothermal system where the presence of flowing thermal water at specific vents is seldom constant. Springs can form or dry up in a matter of days, switch between periods of activity and inactivity multiple times in a given year, or remain active for years in the same general location, dry up, and then reignite.

Since the first explorations of Yellowstone National Park, scientists have asked the same question about the fluctuations in water flow at Mammoth Hot Springs that many visitors ask today: “Are the springs drying up?” From 1928 to 1932, researchers Eugene Thomas Allen and Arthur Lewis Day studied outflow of thermal water and documented a decline. Like park visitors, they wondered whether a prevailing drought had any effect upon the thermal water flowing on the Mammoth terraces. A summary of their investigations is the following statement: “It has been concluded by observers of the US Geological Survey, that spring water when it ceases to flow at any point in this area, as it not infrequently does, reappears in equal amount at some other point, so that the aggregate discharge remains constant.” Studies by Bargar (1978) and Sorey (1991) argue for “continual change in the location and flow rate of individual vents.”

Previous studies of Mammoth Hot Springs show that thermal water discharge can vary seasonally (Sorey 1991; Freidman and Norton 2007; Allen and Day 1935). The
studies attribute the variability to the hydraulic pressure exerted on the hydrothermal systems by the volume of water entering the system at the surface. When the volume is high during the spring and early summer, greater pressure is exerted and more thermal water is discharged at the outlet of the system. The thermal water flowing on the terraces accounts for approximately 10% of the total discharge of the Mammoth hydrothermal system (Sorey 1991). Most of the remaining hydrothermal water discharges at Boiling River. Therefore, the thermal water discharge at Boiling River is one indicator of the total discharge of thermal water in the Mammoth hydrothermal system.

Despite the wealth of observations since 1871, when the Hayden survey described Mammoth Hot Springs, there are few maps showing the locations of flowing thermal water over time. Our goal was to create a series of maps or “snapshots in time” that show flowing hydrothermal water and the dynamic nature of the Mammoth hydrothermal system.

**Study area**

Located outside the 640,000-year-old Yellowstone caldera, Mammoth Hot Springs formed in the northern part of Yellowstone National Park, five miles south of Gardiner, Montana (fig. 1). The Mammoth hydrothermal system forms terraces composed of travertine (a sedimentary rock made of calcium carbonate) from the Upper Terrace Drive (Pinyon Terrace) to the Gardner River. The historic Fort Yellowstone, park headquarters, Mammoth Hotel, Mammoth campground, and other buildings in Mammoth Hot Springs were built on the travertine terraces.

**Geology**

Examination of Yellowstone’s bedrock map helps place the Mammoth hydrothermal system in a park-wide, geologic context (U.S.G.S., 1972). The Mammoth hydrothermal system is one of the few hydrothermal areas in Yellowstone National Park that has carbonate-rich hot spring deposits. Glacial sediments overlie travertine and the travertine overlies sedimentary and volcanic rocks. During the last 2.1 million years, the Yellowstone volcano has covered parts of the region with tuffs (a volcanic rock made of glass, pumice, and small rocks) and basaltic lava flows (Christiansen, 2001). Fifty million years ago, the Absaroka volcanism affected the Mammoth area; today Sepulcher Mountain and Bunsen Peak are reminders of that volcanic past. Outcrops of sedimentary rocks, 550-million- to 100-million-year-old limestones, sandstones, siltstones, and shales, are reminders of a geologic past dominated by shallow seas. The limestones are crucial to the formation of the Mammoth terraces as the rock supplies the carbonate necessary for building them.

The Norris–Mammoth corridor, a zone of faults trending generally north–south, stretches from the edge of the 640,000-year-old Yellowstone caldera to Mammoth Hot Springs (Pierce 1991). The faults in this region may allow groundwater near Norris to reach a depth where it is heated and provide a potential path for the heated water to reach Mammoth (Sorey 1991). The other potential source of the Mammoth hydrothermal water is localized deep circulation of water from the Gallatin Mountains interacting with a possible local heat source beneath Mammoth (Kharaka 1991).

**Methods**

Bargar’s 1978 geologic map of Mammoth Hot Springs provided the basis for mapping areas covered by thermal water. In total, we created 11 maps showing flowing thermal water from 1954 to 2010 (table 1), including nine maps (1954–2006) generated from historical aerial photographs. For 2009 and 2010, we sketched visual observations of flowing thermal water on Bargar’s geologic map and used airmosaic photography from 2009 and 2010 to confirm and edit the sketched field maps. We converted the mapped areas showing thermal water into polygons using ArcGIS software.

The three types of aerial photographs, black and white (B&W), color infrared (CIR), and true color, generated different quality maps (table 1). On a CIR aerial photograph (fig. 2), vegetation shows up as a bright red color. Healthy vegetation emits near-infrared radiation, which is not visible to the human eye. A true-color image shows the landscape as a human would see it. Some aerial photographs (1969, 1994, 2001, and 2006) were georectified. The process of georectification, or tying airborne images to known places on the ground, makes it easier to work with multiple...
Table 1. Date, type, source, and method for obtaining the thermal water polygons and thermal water area for each of the nine aerial photographs and two field maps used in this study.

<table>
<thead>
<tr>
<th>Year</th>
<th>Day</th>
<th>Type</th>
<th>Source</th>
<th>Polygon Method</th>
<th>Area ($m^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1954</td>
<td>Sep 14</td>
<td>B&amp;W</td>
<td>HRC</td>
<td>Scan and draw</td>
<td>8,500</td>
</tr>
<tr>
<td>1964</td>
<td>Sep 12</td>
<td>B&amp;W</td>
<td>ETIC</td>
<td>Scan and draw</td>
<td>28,200</td>
</tr>
<tr>
<td>1969</td>
<td>Sep 7</td>
<td>Color</td>
<td>HRC</td>
<td>Feature extraction</td>
<td>30,300</td>
</tr>
<tr>
<td>1976</td>
<td>Sep 8</td>
<td>Color</td>
<td>ETIC</td>
<td>Feature extraction</td>
<td>21,800</td>
</tr>
<tr>
<td>1988</td>
<td>Oct 6</td>
<td>CIR</td>
<td>HRC</td>
<td>Scan and draw</td>
<td>31,500</td>
</tr>
<tr>
<td>1994</td>
<td>Sep 3</td>
<td>B&amp;W</td>
<td>USDA</td>
<td>Feature extraction</td>
<td>15,800</td>
</tr>
<tr>
<td>1998</td>
<td>Aug 5</td>
<td>CIR</td>
<td>HRC</td>
<td>Scan and draw</td>
<td>17,900</td>
</tr>
<tr>
<td>2001</td>
<td>Aug 25</td>
<td>CIR</td>
<td>Sanborn</td>
<td>Feature extraction</td>
<td>14,300</td>
</tr>
<tr>
<td>2006</td>
<td>Aug 14</td>
<td>Color</td>
<td>NAIP</td>
<td>Feature extraction</td>
<td>20,000</td>
</tr>
<tr>
<td>2009</td>
<td>Aug 26</td>
<td>Field map</td>
<td>Authors</td>
<td>Map and draw</td>
<td>32,900</td>
</tr>
<tr>
<td>2010</td>
<td>Jun 21</td>
<td>Field map</td>
<td>Authors</td>
<td>Map and draw</td>
<td>21,400</td>
</tr>
</tbody>
</table>

Overexposure of the bright, white travertine presents a challenge during image processing (fig. 2). The first step in making hydrothermal water areas more visible was to improve the image contrast and easily distinguish vegetation from the highly reflective travertine. Once the image contrast was improved, we applied ENVI’s automated feature extraction wizard (ITT Visual Information Services, 2008) on each of the aerial photographs. Feature extraction uses spatial, spectral, and textural characteristics of an image to define areas sharing similar characteristics. We were able to optimize parameters and consistently identify the areas of flowing thermal water on the terraces. These areas were imported into ArcGIS and visually grouped into a set of larger areas, thus representing the thermal water from different vents or sets of vents on the terraces. Finally, we calculated the total area with flowing thermal water for each photograph.

Five photographs used in this study were not georectified: two digital photos downloaded from the National Park Service (NPS) Technical Information Center (ETIC) in Denver and three hard copies from the Yellowstone Spatial Analysis Center and Heritage Research Center in Gardiner (HRC), Montana. To create digital files, we scanned the hard-copy photographs at 1200 dots per inch. We used Adobe Photoshop to increase the contrast between areas of flowing thermal water and other areas, and the georeferencing tools in ArcGIS to roughly align each photograph to a 2006 orthorectified, National Agriculture Imagery program (NAIP) true-color image. Then we used the ArcGIS editor tools to manually draw polygons around the areas on the terraces covered by thermal water. Finally, we calculated the total area of the polygons for each photograph (table 1).

We also used historical observations by NPS North District interpretive rangers from 1871 to the present. The historical observations confirm where thermal water was present in the aerial photographs. No thermal water polygons were drawn without supporting visual evidence from the aerial photographs. Historical observations were not used for years in which feature extraction could be used to create the polygons on the aerial photographs (1969, 1994, 2001, and 2006).

![Figure 2. Color infrared aerial photograph of the Mammoth terraces, August 25, 2001. Around the buildings, the grass appears bright red (top right). Overexposure makes accurate identification of flowing hydrothermal water on the terraces difficult.](image-url)
Results

We created 11 maps showing flowing thermal water at the Mammoth Hot Springs terraces from 1954 to 2010 (figs. 3A–I). Only the regions covered by flowing thermal water on aerial photographs or visually observed are shown on the maps. Historical observations by NPS interpretive rangers (Suderman 2009) may record activity, flowing thermal water, or inactivity where steam may be present.

Several general observations can be made (figs. 3A–I). The area near Palette Spring shows flowing thermal water on 9 of the maps and Canary Spring shows flowing thermal water on 10 of the maps. Considering the entire span of 56 years, most of Mound, Jupiter, and Palette terraces were active at some point between 1954 and 2010. Flowing thermal water from active springs is also present in the vicinity of the Upper Terrace Drive between 1954 and 2010, but difficult to map using aerial photographs.

Decadal variability

According to observations by NPS North District interpretive rangers, thermal water flowed somewhere on Mound Terrace from 1904 through 1963 and has been inactive since 1989. Mound Terrace shows eastward flowing thermal water on the 1964, 1969, 1976, and 1988 aerial photographs (figs. 3B, C, and D) whereas the 1994, 1998, 2001, and 2006 aerial photographs (figs. 3E, F, and G) show no colorful, thermal water flowing east. Colorful hydrothermal water began flowing from the north side of Mound Terrace in November 2007 and continues at present. The 2009 and 2010 maps (figs. 3H and I), generated by visual mapping along the boardwalks, show this north-flowing hydrothermal water.

New Palette Spring shows flowing thermal water on the 1964, 1969 (fig. 3B), and 1976 (fig. 3C) aerial photographs, no flowing thermal water on the 1988 (fig. 3D) and 1994 (fig. 3E) aerial photographs, and flowing thermal water again on the 1998 aerial photographs. Visual mapping showed flowing thermal water during the summers of 2009 and 2010 (figs. 3H and I).

From 1954 until 1998, visitors and NPS North District interpretive rangers observed flowing thermal water at Minerva Spring. The maps show Minerva Spring flowing in 1954 (fig. 3A), 1960 (fig. 3B), 1976 (fig. 3C), and 2001 (fig. 3F) and not flowing in 1964, 1988 (fig. 3D), and 1994 (fig. 3E). It is interesting to note that clear, hydrothermal water flowing on white and highly reflective travertine would not be visible or mapped on aerial photographs.

Hydrothermal springs along the Upper Terrace Drive are more dispersed and smaller than the thermal springs on the lower Mammoth terraces. Narrow Gage Spring, Orange Spring Mound, Highland Spring, and Angel Terrace show the most consistent hydrothermal activity over time.
Annual variability

The 2009 and 2010 maps (figs. 3H and I) show the changes in flowing thermal water from year to year. The thermal activity at Canary, Palette, New Palette, and Jupiter springs seems relatively constant, but the thermal water flowing out of the vents varies in both direction and extent. Cleopatra Spring is the most similar between the two years, and Angel Terrace (not shown) was the most variable, with two new vents initiating in the past year.

Weekly and daily variability

Canary Spring provides an example of weekly variability in vents and the effect upon mapping flowing hydrothermal water. On the morning of September 11, 2006, Canary Spring stopped flowing thermal water. The following day, some thermal water began flowing from Canary’s vent. During the next four days, flowing thermal water began to cover the colorful red-brown- and green-colored microbial mats. Aerial photographs and derived maps would show very different hydrothermal activity depending upon the day of the flight.
Discussion

The various sources of aerial photographs (table 1) make consistency in the mapping of thermal water areas difficult. Areas with thermal water flow look very different on CIR, B&W, and true color aerial photographs. NPS North District interpretive rangers observed flowing thermal water at Minerva Spring in 1964, 1988, and 1994. In contrast, our maps based on aerial photographs, do not show flowing thermal water. On color aerial photographs, the presence of colorful microbial mats aids mapping of flowing thermal water or thermal pools. The area of flowing thermal water is easiest to pick out on the true-color, aerial photographs from 1969, 1976, and 2006, making them the most accurate maps. On the 2001 CIR aerial photograph, we identified an area appearing to be thermal water at Minerva Spring when the interpretive rangers reported no activity. However, when interpretive rangers use the term “no activity”, steam and microbial activity may be present at a vent. The shades of gray in a B&W aerial photograph (1954, 1964, and 1994) make it difficult to distinguish between areas of flowing thermal water, shadows, or grasses on the terraces. Areas with clear or microbe-poor, thermal water are almost indistinguishable from dry areas covered by young, white travertine. Further work is necessary to account for the discrepancies between human observations and the aerial photographs.

The ENVI feature extraction wizard provides a consistent application of parameters but does not eliminate bias in our maps. The extracted areas undergo subjective human analysis as contiguous areas of flowing thermal waters are mapped. Human interpretation affects these estimates of flowing thermal water as the computer-generated areas are grouped visually.

The white-colored and highly reflective travertine terraces also affect the quality of the images. Most of the aerial photographs cover a wide area and include travertine, buildings, asphalt roads, and vegetation. This diverse landscape results in overexposure of the travertine terraces. For example, while North District Interpretation records indicate a large active area near Canary Spring in 2001, our 2001 map shows only a small area of flowing thermal water associated with the Canary Spring vent (fig. 3F). The overexposure on the 2001 CIR aerial photograph may underestimate the area covered by flowing thermal water at Canary Spring. In general, travertine terraces are less overexposed on the true-color images than the CIR or B&W images.

We place the most confidence on the area of flowing thermal water estimated for the 1969 (fig. 3B) and 2006 (fig. 3G) maps because both are true-color aerial photographs (green circles, fig. 4). Figure 4 shows the range of values from approximately 8,500 square meters to 33,000 square meters (91,300 ft² to 354,380 ft²). It is interesting that our estimates of flowing thermal water for summer 2009 and 2010 (33,000 and 21,400 m²) show a similar range of thermal water area (33,000 to 20,000 m²) for 1969 and 2006. The 2009 and 2010 visual mapping from the boardwalks provides additional confidence in our area estimates derived from ENVI’s automated feature extraction routine. For a visitor who saw the terraces in 1969 (figs. 3B and 4) and again in 1976 (figs. 3C and 4), it may appear that the terraces are drying up. In actuality, the visitor more likely witnessed the natural variability of flowing thermal water on the Mammoth terraces.

One assessment of the dynamic Mammoth hydrothermal system involves a comparison of the area covered by flowing thermal water (fig. 4) and the mean annual discharge of the nearby rivers. We know that the thermal water on the Mammoth terraces accounts for only 10% of the discharge from the Mammoth hydrothermal system (Sorey 1991) and that Boiling River is the primary source of thermal water discharge. Data collection began in 1989 for the Boiling River discharge (missing data from 1995 to 2002) and for...
the Gardner River in 1939 (missing from 1972 to 1984; see http:// water.usgs.gov). Although data gaps make detection of trends difficult, there is no consistent increasing or decreasing trend in the total area covered by flowing thermal water on the Mammoth terraces. Nor is there any correlation between areas of flowing thermal water and the discharge of the Boiling or the Gardner rivers. Thus, the relatively constant discharge of Boiling River since 1987 (within 10% of the average) implies that there has been a relatively constant outflow of thermal water from the Mammoth hydrothermal system (fig. 4).

Summary

The maps show the dynamic Mammoth hydrothermal system and the changes in flowing thermal water from year to year. Because thermal discharge can also change monthly, weekly or daily, these maps do not capture all the variability of the system. Additionally, we produced initial estimates of the area covered by flowing thermal water on the Mammoth terraces. Comparison of the thermal water area to Boiling River discharge indicates a generally constant outflow of thermal water from the entire hydrothermal system. Changes in flowing thermal water on the terraces and errors in estimating the flowing thermal water cause variations in the area estimates. We found no evidence to suggest that the volume of thermal water or level of activity changed significantly during the 56 years of visual record. The appearance of the terraces, with their changing patterns of flowing thermal water, varies much more than the actual flow of water.

We also applied a simple method for visually mapping the terraces that can be performed every year or multiple times a year. This mapping method can supplement aerial photography and easily document the changes at the Mammoth hydrothermal system.

Acknowledgements

This project began in the summer of 2009 as part of the Geological Society of America’s GeoCorps America Program. The geologists-in-the-park program is a collaborative partnership between the National Park Service Geologic Resources Division, the Yellowstone National Park Geology Program, and the Geological Society of America. During summer 2010, the Student Temporary Employment Program (STEP) made it possible to continue this work. Brian Suderman, Supervisory Park Ranger with the Division of Interpretation, provided access to the historical observations by his interpretive staff, and Colleen Curry, Supervisory Museum Curator at the Heritage Research Center, retrieved some aerial photographs. In addition, Brian Suderman and Jennifer Conrad, Supervisory Park Ranger with the Division of Interpretation, contributed information about ongoing changes at Mammoth Hot Springs. In 2009, Kevin Sattler, hydrologist at the USGS Montana Water Science Center kindly shared his hydrologic knowledge. My supervisors at Yellowstone Center For Resources, Hank Heasler and Cheryl Jaworowski, provided guidance and support. I also thank my fellow GeoCorps participants, Chelsea Feneey and Tim Moloney, and 2010 GeoCorps participant Lindsey Harriman for helpful suggestions and ArcGIS expertise.

Cheryl Jaworowski is a geologist at Yellowstone National Park. She received her doctorate in geology from the University of Wyoming and specializes in Quaternary geology and applying remote sensing to geologic mapping.

Hank Heasler is the park geologist at Yellowstone National Park, specializing in geothermal systems.

References


Brett B. Carr is a doctoral student at Arizona State University. He received a Bachelor of Arts degree in Earth Sciences from Dartmouth College in 2007 and a Master of Science degree in Geophysics from University of Wisconsin in 2008.

Carr is a doctoral student at Arizona State University. He received a Bachelor of Arts degree in Earth Sciences from Dartmouth College in 2007 and a Master of Science degree in Geophysics from University of Wisconsin in 2008.