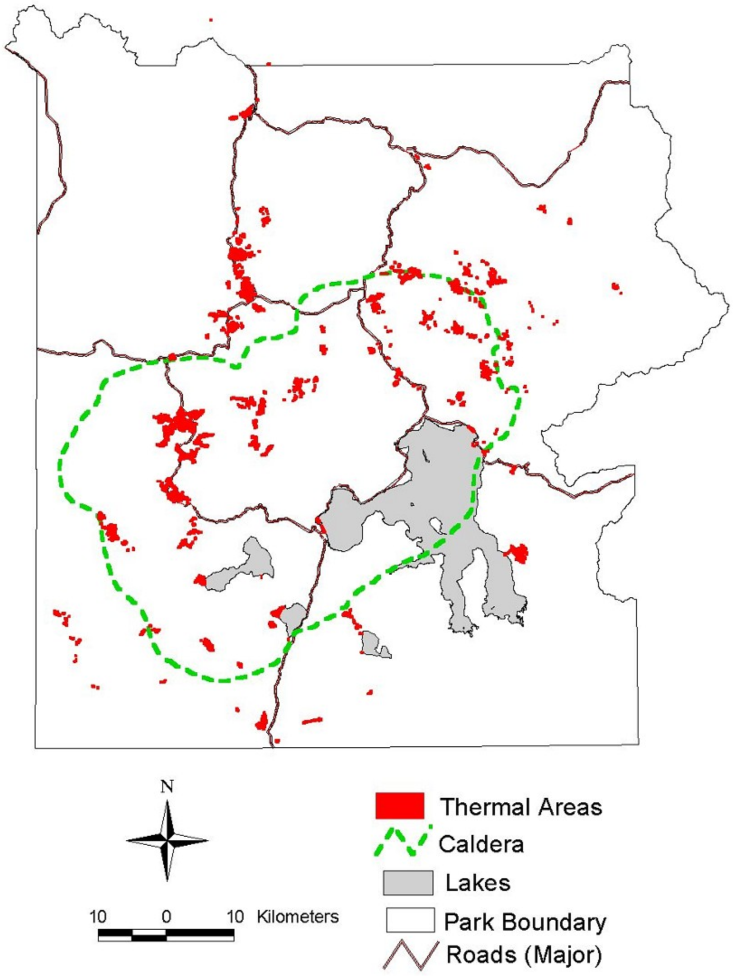
A Geothermal Monitoring Plan for Yellowstone National Park



January 6, 2004

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EXECUTIVE SUMMARY

Protection of Yellowstone's unique geothermal features is a critical mission of Yellowstone National Park (YNP). Yellowstone is required to protect its geothermal features from external threats such as those posed by geothermal development both in Idaho (Island Park Known Geothermal Resource Area) and Montana (Corwin Springs Known Geothermal Resource Area). Other threats include oil, gas, and groundwater development in Wyoming, Montana, and Idaho. The proposed geothermal monitoring plan presents a program designed to systematically gather hydrologic, geochemical, remote sensing, and geologic information to meet YNP's legally mandated geothermal monitoring and protection requirements.

This proposal will complement monitoring of the Controlled Groundwater Area in Montana adjacent to the park by the Montana Bureau of Mines and Geology through monitoring the water resources within the park, including both cold groundwater and thermal water.

Funding is requested for five components of YNP's Geothermal Monitoring Plan:

1. Groundwater inventory, monitoring and assessment

This component assesses Yellowstone's hot and cold groundwater resources and develops a long-term data set to detect natural and anthropogenic changes to the groundwater system.

2. Chloride flux inventory, monitoring and assessment

The chloride flux program monitors overall changes in the amount of chloride exiting various sections of the park. Because chloride in Yellowstone is predominately from a magmatic source and is conserved in water, chloride can be used as a proxy for heat flux and geothermal activity and can be used to monitor natural and anthropogenic changes to the geothermal system.

3. Individual thermal feature inventory, monitoring and assessment

Monitoring of specific thermal features and thermal areas provide information on natural and anthropogenic changes in the pathways of thermal waters between areas both inside and outside the park.

4. Remote sensing of hydrothermal features

The large number, complexity and rapid change of thermal features in the Park make inventory and change assessment difficult. Remote sensing provides an effective method to inventory, monitor, and assess historic and ongoing changes in Yellowstone's thermal features. Satellite and airborne imagery will be used to provide maps of thermal areas of the entire park that will quantify changes in thermal areas through time.

5. Information transfer using the Yellowstone Geothermal Database

Information gathered as part of this plan will be stored and disseminated using an Internet-based Geographic Information System with links to the Yellowstone Controlled Groundwater Area data on the Internet. Coordination between Yellowstone National Park and the Montana Technical Oversight Committee will be accomplished through continued annual meetings to review data and activities.

Budget

The proposed budget for the five components is $846,400 (first year), $841,600 (second year), and $839,000 (third year) with funding continuing in perpetuity.

INTRODUCTION

When the first exploring parties surveyed the Yellowstone region in the late 19th Century, it was the geologic wonders - geysers, hot springs, mudpots, fumaroles - that captured their imaginations. Because of these treasures, the U.S. Congress set aside and dedicated this land of “natural curiosities” as the world’s first “public pleasuring ground”.

Protection of Yellowstone’s unique geothermal features is a key mission of Yellowstone National Park (YNP). This mission is challenging due to a variety of threats posed by widely disparate mechanisms. Yellowstone is required by law (see Appendix A) to protect its geothermal features from external threats such as those posed by geothermal development both in Idaho (Island Park Known Geothermal Resource Area) and Montana (Corwin Springs Known Geothermal Resource Area). Other external threats include oil, gas, and groundwater development (in Wyoming, Montana, and Idaho).

In 1994, the State of Montana and the National Park Service established a water rights compact and controlled groundwater monitoring program within Montana adjacent to Yellowstone National Park. The purpose of the compact is to protect Yellowstone’s unique geothermal resources from groundwater or geothermal development that might occur within Montana adjacent to Yellowstone National Park. The inventory and monitoring of Yellowstone’s geothermal features is a necessity for the success of the Montana Compact and will complement monitoring activities undertaken separately by Montana State agencies under the direction of the Compact.

In order to protect Yellowstone from the adverse effects of development in adjacent communities, we must have knowledge of the undisturbed state of its thermal features. However these features change over time in response to various processes. For example, the conduits feeding these features can be filled with chemical deposits. These conduits can also be sealed or opened by earthquakes, so that the thermal fluid flow paths change in time naturally. In addition to these localized changes, large-scale changes in the supply of thermal water from the magma beneath the park can occur. Yellowstone’s geothermal system is very dynamic, and changes occur on time scale of days to years. Monitoring these changes will provide important context for assessment of human-induced threats from outside the park. Such monitoring data are essential both inside and outside the Park. In order to secure a database of the geothermal system, it is necessary to use various monitoring techniques and to observe the system over many years.

Coordination between Yellowstone National Park and the Montana Compact Technical Oversight Committee

In order to continue coordination of the geothermal monitoring activities of the State of Montana under the Controlled Groundwater Area of the Montana Compact with that of Yellowstone National Park, the annual meetings between representatives of the Technical Oversight Committee of the Controlled Groundwater Area, Montana Compact, and Park personnel will continue.

GEOTHERMAL MONITORING COMPONENTS

Groundwater Inventory, Monitoring and Assessment

Objectives

The objective of groundwater assessment in YNP is to collect basic data necessary to analyze short and long-term changes to Yellowstone's geothermal systems and to understand the interaction between cold groundwater and the geothermal systems. Analysis of the data will improve the understanding of Yellowstone geothermal and geothermal systems and will complement monitoring undertaken as part of the Montana Compact in lands adjacent to Yellowstone for the long-term protection of Yellowstone's geothermal systems.

Other components of this proposal will assess individual geothermal features and their extent and distribution as well as the measurement of the gross heat flux from the geothermal system with the chloride flux-monitoring program. In addition, water level records may be used to evaluate deformation and seismic events within the Yellowstone Caldera (Hamilton, 1987).

Without these data it is not possible to investigate the interaction between cold groundwater systems and geothermal systems and to separate seasonal or anthropogenic changes from long-term fundamental changes in the geothermal system.

Hydrologic Regime

Groundwater in YNP is found in a diverse variety of aquifers. Shallow alluvial and glacial aquifers are found throughout the park usually associated with streams, river channels and valleys. Volcanic aquifers composed of fractured rhyolite and basalt flows are found in the central, western and southern parts of the park while andesitic volcanic units are found in the eastern and northeastern parts of the park. The Madison Aquifer system is present in and adjacent to the park and has been identified as an important part of the groundwater flow system associated with Mammoth Hot Springs. The Madison Aquifer system connects coldwater inside and outside the park to thermal features within the park. The Madison aquifer system forms one of the foundations for boundary delineations in the Yellowstone Controlled Ground Water Area (Custer et al, 1993). These aquifers are loosely grouped and referred to as "cold water" aquifers.

High temperature geothermal fluids associated with magma bodies beneath and near the Yellowstone Caldera are the other major component of the groundwater system in Yellowstone. Geothermal fluids are convected toward the surface in fracture systems that are self-sealing and tectonically sensitive, which results in frequent changes to the flow system. Waters from the "cold" aquifers are part of the hydrothermal flow system which is heated and discharged in geothermal features throughout Yellowstone Park. The heated water may also mix with cold water locally. Fournier hypothesizes that annual, generally widespread changes in thermal features in the Norris Geyser Basin are the result of changes in the potentiometric surface of cold water adjacent to or interconnected with the geothermal system (Fournier and others 2002). In order to understand short-term cyclical, catastrophic changes as well as long-term, natural or anthropogenic changes to the Yellowstone geothermal system, both cold groundwater and geothermal systems must be monitored and assessed.

Well Locations

There are three general categories of wells in YNP: 1) water supply, 2) groundwater monitoring usually associated with sewage treatment plants, lagoons and abandoned landfills, and 3) research wells. Most water supply wells and groundwater monitoring wells are completed in valley fill or alluvium, are shallow (<30 m) and generally located near park infrastructure - visitor centers, hotels and maintenance facilities. Groundwater monitoring wells are located around sewage treatment plants, underground storage tanks or landfills. A number of old landfills within YNP have monitoring wells around them. From the well records compiled to date there are no known wells completed in any of the volcanic aquifers. Additional well data need to be compiled for many of the wells in the data set including measuring ground elevations, water levels, perforated intervals, well logs, field parameters (water temperature, pH and specific conductance). Historic data for many of these wells are located in various offices within Yellowstone and need to be compiled into a single database. Monitoring of wells is important if pressures exerted by cold-water in thermal areas does control thermal water discharge.

There have been 15 high-temperature research wells drilled in Yellowstone starting with the Carnegie wells in the Norris Geyser Basin drilled in 1931 (Fenner, 1936; White and others, 1975). The U.S. Geological Survey drilled 13 research wells in the late 1960's (White and others, 1975). These wells were drilled in or near the Old Faithful, Norris Geyser Basin, the Mud Volcano and Mammoth thermal areas. Many of these wells have deteriorated because of high temperature/pressure/acidity of geothermal fluids. Most of the USGS research wells were plugged with the exception of Y-7 at Old Faithful and Y-10 at Mammoth. A well drilled as a water supply well at the South Entrance of YNP also has elevated water temperatures. Other research wells drilled in the park are generally not associated with the geothermal system and have been drilled to study and monitor wetlands. These wells are generally very shallow (<6 m).

Cox (1976) inventoried many of the wells in YNP. New supply and monitoring wells have been drilled since Cox's study. An updated inventory of wells drilled in YNP was completed in summer of 2002 by YNP's Spatial Analyses Center. Records of 170 wells and springs were compiled. This inventory of wells includes springs used in the park for water supply. Of these 170 wells, 50 could not be found when field checked or had been abandoned or plugged.

Establishment of a Monitoring Network

The groundwater monitoring well network proposed for Yellowstone will be a hierarchically nested network design (Klusman and Chappell, 1980). In this type of monitoring network, data are collected from sampling sites at different intensities, both spatially and temporally, with the objective of optimizing the amount of data collected while minimizing the cost. Areas where the most variance in the data is expected will be monitored more intensely.

There will be three types of sites with different levels of data collection intensity. Level 1 sites will have continuous water level and temperature recorders, and water-quality samples will be collected quarterly. Water levels and temperature will be collected at a minimum of 15-minute intervals. Level 2 sites will have continuous water level and temperature recorders sampling at hourly intervals and water-quality samples collected annually.

Level 3 sites will have annual water-level and field water measurements. The objective of Level 3 sites is to develop a long-term record of annual changes in water levels and water quality and to do this over the widest area possible. Level 3 sites will be measured at the same time each year so that the annual values will be comparable. In additional, all Level 3 sites will be sampled once to analyze for complete water chemistry to establish a large baseline data set. Twenty wells will be selected for level 1 and level 2 monitoring. Up to 50 wells will be selected for level 3 monitoring.

Site Selection

Sites will be selected that are representative of the various aquifers and throughout the Park. There are two distinct climates within YNP (Despain, 1987) and YNP is located near the boundary between regional atmospheric flow patterns. Depending upon the location of this boundary, the annual climate and precipitation may be above or below normal. Water levels will respond to annual climate variations and the monitoring network will provide information regarding the amount and timing of response.

Wells will be selected near Old Faithful geyser basin, Norris geyser basin, and Mammoth terraces that are completed in alluvial aquifers. These cold water aquifers may mix or interact with the geothermal waters and thus are important to monitor. Additional cold-water wells will be selected in outlying areas of the Park to fill in the spatial distribution. These wells will be monitored as level 2 or level 3 wells

The two high temperature wells (Y-7 at Biscuit Basin and Y-10 at Mammoth Terraces) that remain will be monitored with continuous recorders for water level and temperature as Level 1 sites. Multiple temperature probes may be deployed to measure temperature gradients. Water quality samples will be collected quarterly at a minimum and possibly monthly in conjunction with other park monitoring efforts projects. The well at the South Entrance with elevated temperatures will be monitored as a level 2 well.

Existing water-quality monitoring programs will augment the groundwater-monitoring network proposed here for public water supply wells and springs and for groundwater monitoring wells associated with sewage treatment facilities and landfills. There are about 50 groundwater monitoring wells and many are sampled annually. Current and historic data from wells that are regularly sampled will be compiled. Data collected under these programs will be included in the Yellowstone Geothermal Database.

Groundwater Data Collection

All data collection will be done under the same standard operating procedures (SOP). A SOP will be prepared that will cover the use and calibration of field instrumentation, well pumping, sample collection and handling, sample login and shipment. The SOP will receive outside agency review prior to the start of monitoring. Each of the site types will have a different sampling protocol, which will be listed in the SOP. Field parameters (temperature, field pH and specific conductance, and water levels) will be collected at all sites. Water samples collected from Level 1 sites will be analyzed for stable isotopes (deuterium, 18-oxygen, and tritium) and common ions and trace metals. Samples collected from Level 2 sites will be analyzed for stable isotopes and common ions and Level 3 site samples will be analyzed for field parameters. All the Level 3 sites may be sampled once for stable isotopes, common ions and trace metals to establish baseline conditions. A quality assurance plan will be written for the groundwater-monitoring program to insure the long-term quality and integrity of the data. The plan will describe the types of quality assurance, quality control samples (spike, blanks, equipment blanks, duplicates) and the frequency of submission. The plan will also document the procedures and statistical methods for analysis of the control samples and establish data flags for noting data that fall outside of control criteria.

Groundwater Data Analysis

Data will be compiled and analyzed in an annual report. The report will be available electronically on the Internet. All data will be visually inspected and plotted. Maps of water level elevations, water temperature, pH and specific conductance will be prepared along with graphs for each parameter for each well. These graphs will be annually updated and trends analyzed. If on visual inspection of the data any large or unexpected changes occur, further analysis of additional constituents will be required including analysis of surface water, groundwater and thermal features at nearby sites.

Chloride Flux Inventory, Monitoring and Assessment

Introduction

Chloride (Cl) is a widely distributed element in the earth's crust and is conserved in water. Approximately 94% of the chloride in surface waters originates from the magma beneath Yellowstone (Norton and Friedman, 1985). Because chloride in Yellowstone is predominantly from a magmatic source and is conservative in water, chloride can be used as a proxy measure of heat flux and geothermal activity (Fournier and others, 1976; Norton and Friedman, 1985). Long-term changes in Cl flux are indicative of long term changes in the heat flux from the Yellowstone geothermal system and can be used to assess the impacts of proposed geothermal energy, oil , gas, and groundwater development adjacent to the park. Variations in chloride flux are also used to estimate groundwater recharge, to assess the effects of earthquakes, and other tectonic events on the geothermal system. The use of chloride flux for estimating heat flux and geothermal activity in YNP has been extensively published (Ellis and Wilson, 1955; Fournier and others, 1976; Norton and Friedman, 1985; Friedman and Norton, 1990; Norton and Friedman, 1991; and Friedman and others, 1993; Friedman and Norton, in press).

The chloride flux from Yellowstone has been measured for 19 years in Yellowstone's major rivers - the Fall, Madison, Snake, and Yellowstone Rivers. It is the only long-term data set available for monitoring changes in the Yellowstone geothermal system (Friedman and Norton, in press).

The sum of the annual chloride fluxes for the four rivers varies as much as 20% year-to-year. This sum, when corrected for climatic factors, shows a decline of 10% over the past 19 years. A decline in thermal flux from Mammoth Hot Springs has also been noted, as has a lengthening in the period between eruptions of Old Faithful Geyser. These changes may be related to deflation of the Yellowstone caldera documented by changes in ground levels surrounding Yellowstone Lake (Friedman and Norton, in press).

Objectives

This Geothermal Monitoring Plan seeks to continue and to improve the resolution of the existing chloride flux program in YNP by adding eight new streamflow gauging stations to the existing streamflow monitoring network. The locations of all gauging stations, both those already established and those proposed, are shown in Figure 1. The propsed new gauging stations are:: Tantalus Creek near the confluence with the Gibbon River, the Firehole River between the Upper and Middle Geyser Basins, the Firehole River between the Middle and Lower Geyser Basins, the Yellowstone River downstream from the Mud Volcano thermal area, the Yellowstone River near it entry to Yellowstone Lake, and at three locations in the Bechler region of southwestern YNP. The addition of these new gauging stations improves the descretization of the Cl flux monitoring, will allow the quantification of thermal activity (heat flux) in four significant thermal basins of YNP and helps assess long term changes in these basins whether natural or anthropogenic.

Streamflow Gauging Station Installation and Operation

New streamflow gauging stations will be installed and operated by the U.S Geological Survey (USGS) and as part of the USGS National Stream-Gauging Program (Wahl and others, 1995). Data will be collected in near real-time and will be available on the Internet. The location of the eight new river gauging stations (Figure 1) will be chosen in conjunction with the U. S. Geological Survey, Water Resources Division, Montana District Office. These automated stations will provide temperature, river flow, and gauge heights via telemetered data available real-time on the Internet.

Chloride Sample Collection, Analysis, and Flux Calculation

Water samples for chloride analysis are collected 28 times a year at river gauging stations: monthly during the winter at low flow, biweekly during the early spring and fall, and weekly during spring runoff (Friedman and Norton, 1990). Samples will be analyzed by the USGS Yellowstone Volcano Observatory laboratory in Menlo Park, California. Instantaneous chloride flux is calculated from the measured chloride concentrations and the discharge. The instantaneous chloride flux is integrated to provide annual chloride flux (Norton and Friedman, 1985; Friedman and Norton, 1991, Friedman and Norton, in press).

Chloride Flux Data Analysis

Data will be compiled and analyzed in an annual report. The report will be available electronically on the Internet. Chloride measurements and chloride flux calculations will be listed in tabular format along with graphs of chloride flux versus time for each gauging site. These graphs will be annually updated and trends analyzed. Chloride concentration and chloride-flux data will be incorporated into the Yellowstone Geothermal Database.

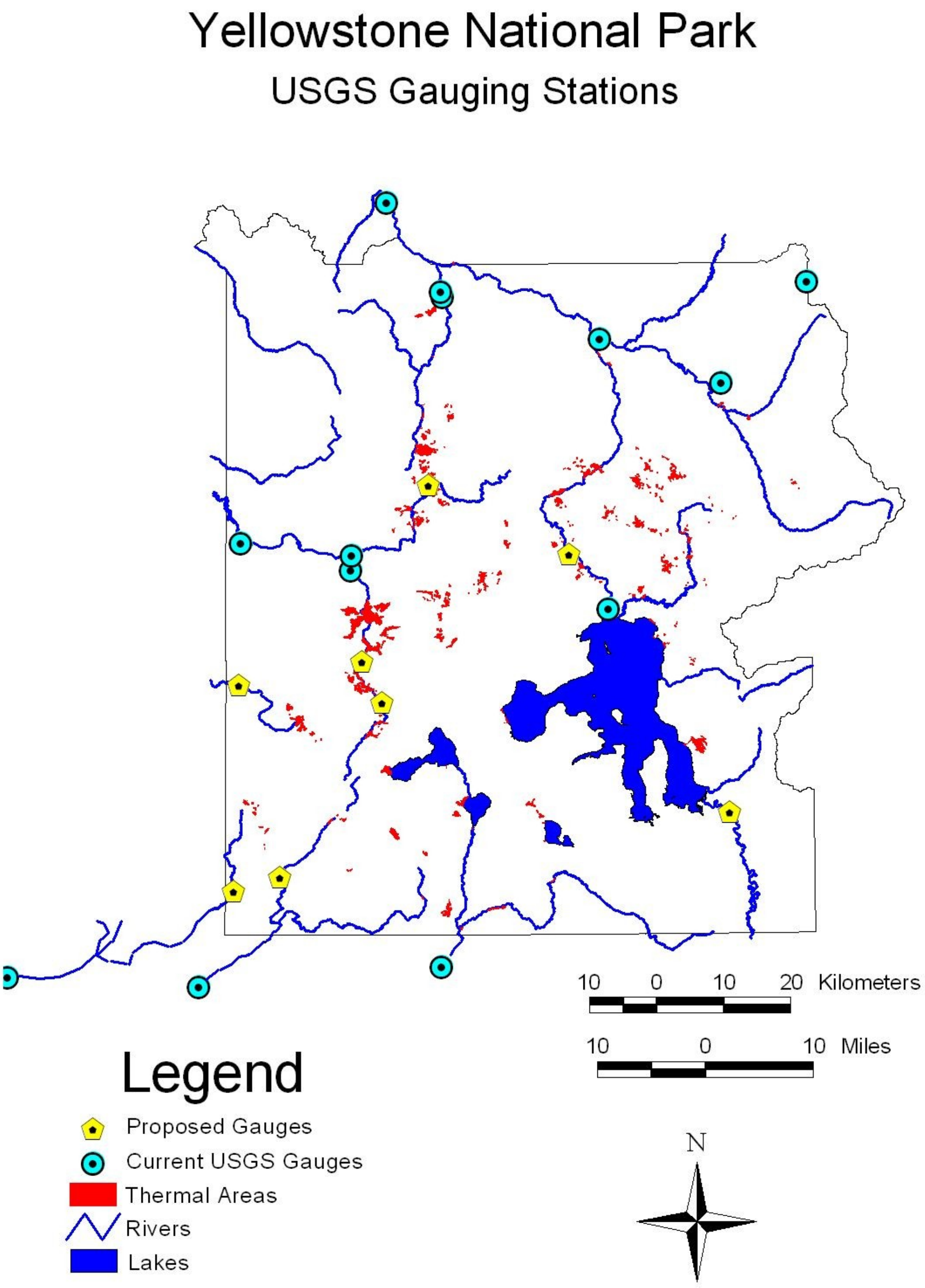

Figure 1. Current and proposed US Geological survey streamflow gauging stations.

Individual Thermal Feature Inventory, Monitoring, and Assessment

Introduction

Historically, the monitoring of individual thermal features has been the primary method for determining change in Yellowstone's geothermal systems. Individual thermal features, whether a geyser, hot spring or fumarole, are dynamic features, which regularly experience gradual and/or catastrophic changes. The quantification and assessment of changes to an individual thermal feature are difficult because a variety mechanisms maybe responsible for change. Changes in thermal feature activity, discharge, or heat flux may be the result of seismicity, self-sealing of fractures feeding the feature, changes in hydraulic head of groundwater system, or vent plugging from human activity. Overall, the objective of monitoring individual thermal features is to document the diversity of geothermal features, their baseline conditions, and activities and behavior throughout the park. Specific features will also be monitored with the focused objective of establishing baseline data to document natural variability and provide context for assessing human impacts within and adjacent to the park.

Another challenge facing the Thermal Feature Geochemistry and Extent program is the shear number of individual thermal features in YNP. Over 7,000 individual thermal features have been inventoried over the last four years by YNP's Spatial Analysis Center. Only 60% to 70% of the park has been inventoried. Thus, only a small subset of thermal features can be monitored due budget constraints.

Previous inventories and monitoring of individual thermal features in Yellowstone has been done on an adhoc basis and qualitative manner. Thermal activity (eruptions of geysers, changes in hot spring pools size, color or discharge) in major geyser basins were noted by park personnel in internal reports and documents. Detailed qualitative surveys of backcountry thermal areas have been conducted as time and staffing allow. These surveys are important contributions for in many cases they are the only documented record of thermal activity over time in these areas. Data collected on these surveys largely are preserved in YNP archives in internal reports and notebooks.

Methodology

Monitoring individual thermal features will utilize a multifaceted phased approach. This monitoring program will be labor and data intensive. The sampling and data handling protocols will be written, pilot tested and reviewed before full implementation. A partial list of parameters that can be measured include temperature, flow, chemistry of water and gases (major anions, cations, metals, trace elements, isotopes, etc.), and spatial extent using techniques such as photographic surveying methods. Equipment used to take many of these measurements is expensive and requires expertise to operate, and will likely have a short life due to the aggressive water being analyzed. Sampling and analytical protocols as outlined by Hinman (2001) will be utilized. Not all aspects of the proposed thermal feature monitoring program can be accomplished with the proposed budget. Instead, components will be implemented through time. See appendix B for a discussion of the proposed methodology.

Remote Sensing of Hydrothermal Features

Introduction and Objectives

Remote sensing of thermal features with various satellite and airborne sensors is critical to monitoring Yellowstone's geothermal resources. Geyser basins contain numerous individual thermal features that are widely dispersed throughout YNP, including remote, rarely visited backcountry areas. It is extremely difficult for park personnel to visit and monitor all the thermal areas on an annual basis to assess change. Remotely sensed satellite and airborne imagery provides data to synoptically monitor and efficiently assess annual changes in geothermal activity for the entire park. The remote sensing component of the Geothermal Monitoring Plan will assess historic changes of the spatial extent of Yellowstone geothermal basins and monitor ongoing and future change. A future goal will be to quantify surface temperature and heat flux of geothermal basins and individual features.

Thousands of satellite images and airborne data covering Yellowstone National Park exist in various governmental archives, academic institutions, and private companies. Within Yellowstone National Park, a handful of satellite images and airborne data exist. In spite of the wealth of satellite images and numerous studies, no park-wide, historic maps of Yellowstone's geothermal features exist. Satellite images of Yellowstone collected over the past 30 years will allow a consistent and efficient way to generate maps of changing geothermal features. Maps derived from satellite and airborne imagery showing historic changes from the early 1970's to the present will allow geologic information to be placed on easily interpreted maps and provide a baseline for understanding future changes in thermal areas.

Mapping Historic Changes in Thermal Areas

Early Landsat multispectral scanner images (Landsat MSS 1, 2, 3) and thermal infrared satellite images showed promise for mapping Yellowstone's thermal features, warm rivers, linear features and land-use planning (Smedes, 1976; Levinson and Marrs, 1979). However, the low spatial resolution, (120-80 m) of Landsat MSS images made them most useful for geologic reconnaissance and synoptic views. Today, these satellite images provide the *only* park-wide coverage of Yellowstone's thermal areas in the 1970's.

During the 1980's and 1990's, the Thematic Mapper sensors on Landsat 4 and 5 satellites provided continuous coverage of Yellowstone with increased spectral (7 bands or channels) and spatial resolution (30 m in visible bands and near IR, 120 m in thermal band). In the late 1990's, the launch of the Landsat 7 satellite ensured that Landsat imagery would continue into the foreseeable future. The Landsat 7 satellite with enhanced thematic mapper sensors (ETM) plus one black-and-white band offers 8 channels (6 visible and near IR, 1 thermal and 1 panchromatic) and improved spatial resolution (15-60 m resolution). The 15-meter panchromatic band provides an intermediate scale map of thermal areas that can be linked to other satellite and airborne imagery. Landsat 7 images and other remote sensing data have been used for mapping thermal areas using snowfall calorimetry (Haze, 1971; Watson and others, 2002).

The 30-year history of Landsat satellite images allows a synoptic visualization of change in thermal areas over a few decades. No other satellite imagery or airborne imagery can claim a similar long-term historic archive. The advantages of using Landsat imagery are the following: (1) 1 scene can cover the entire park, (2) the cost per scene is minimal ($600-$300), and (3) standard processing techniques can be used. The disadvantages of Landsat imagery are: (1) clouds or smoke may obscure thermal areas, and (2) low spatial resolution will mean that it could take 5 years to detect changes in thermal features.

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and the Advanced Visible/Infrared Imaging Spectrometer (AVIRIS), data offer advantages over Landsat's low to moderate spatial (80-15 m) and spectral resolution (5-8 channels). ASTER satellite images have 15 m spatial resolution in the 3 visible channels, 30 m spatial resolution in short wavelength infrared (SWIR) channels and 90 m spatial resolution in the thermal channels. Increased spatial *and* spectral resolution of these or other sensors will allow NPS personnel to detect changes in thermal features in 5 years or less. Airborne infrared imagery with a spatial resolution of 1 meter allows new thermal features to be detected on an annual basis.

In contrast to visible imagery, the longer wavelengths (3 cm, 6 cm, 23 cm), multiple polarizations, and all-weather capability of radar imagery complements the information provided by the visible, near infrared and thermal infrared sensors. Radar satellite imagery is useful in estimating soil moisture, mapping snow wetness, monitoring volcanic hazards within Yellowstone, generating detailed digital elevation models, and constructing maps of Yellowstone's faults, fractures, geologic structures and lava flows. Construction of an accurate digital elevation model of Yellowstone National Park from radar data will be useful for scientific modeling of surface hydrology and provide an accurate topographic base map that can be combined digitally with Landsat satellite images, ASTER imagery, and other digital data. Mapping Yellowstone's faults, geologic structures, and detailed flow structures within lava flows will assist the groundwater monitoring and chloride flux components of the Geothermal Monitoring Plan by defining areas of high fracture permeability. Estimates of snow cover also will provide valuable hydrologic information to the groundwater monitoring and chloride flux components of the geothermal monitoring program. In summary, a mix of various satellite (Landsat, ASTER, radar) and airborne (AVIRIS) imagery is recommended for the mapping and monitoring of Yellowstone's geothermal features.

Image Selection

Since 1972, nearly 1500 Landsat satellite images were taken over Yellowstone. Not all of those 1500 satellite images are useful for providing baseline and historic information about Yellowstone's ever-changing geothermal features. Eliminating images with greater than 10 % cloud cover would still leave a large number (900) of possible Landsat images. Landsat images with minimal (10%) or no cloud cover and appropriate seasonality (spring and summer) would enable the generation of baseline and historic maps for all of Yellowstone's geothermal features. An initial task will be to examine all existing Landsat images held by the EROS Data Center in Sioux Falls South Dakota and generate a list of images useful for mapping historic change. Given Landsat's low to moderate spatial resolution, 5 years may be required to detect changes. Because of the limited image resolution, changes in thermal area extent must be greater than 30 meters to be detectable. Because the exact time frame for detecting change in geothermal features is unknown, we recommend acquiring approximately 4 Landsat images per year.

ASTER images provide higher spatial and spectral resolution than Landsat images and complement the baseline information provided by the Landsat satellite images. A minimum of four to five ASTER images are required to generate an ASTER satellite mosaic of Yellowstone National Park. Because of ASTER's higher spatial and spectral resolution, it may be possible to detect changes in thermal features in less than 5 years. Therefore, the acquisition of satellite imagery to construct a minimum of 5 ASTER satellite composites for Yellowstone National Park is recommended and yearly monitoring in perpetuity will be accomplished to assess natural and anthropogenic change.

Several AVIRIS airborne images are required to generate an AVIRIS composite image for Yellowstone National Park. From 1996-2000, numerous low altitude and high altitude AVIRIS flights were flown over Yellowstone National Park and adjacent areas. The majority of the 125 AVIRIS flights were flown in 1998 and 1999. The first priority for AVIRIS imagery is the purchase of all existing AVIRIS images (104 flight lines) for 1998 and 1999. If new AVIRIS flights are needed there will be additional costs for AVIRIS imagery

Various types of radar images can be purchased for Yellowstone National Park: shuttle-imaging radar (SIR-C/X-SAR), shuttle radar topography, and Radarsat stereoscopic or interferometric satellite images. The relatively inexpensive SIR-C/X-SAR images from the space shuttle Endeavor will provide some useful spring and fall images for 1994. From 1995- present, Radarsat imagery from the Canadian Space Agency can be purchased and will allow the creation of an accurate digital elevation model for Yellowstone.

Remote Sensing Deliverables

The primary deliverables will be analysis of thermal area extent, distribution and change. These analyses will be presented in map form. Initial products will include: (1) at least eight maps showing park-wide changes in geothermal features from 1972-2003 (2) a spatially-referenced inventory of all Landsat images flown over Yellowstone National Park (3) an inventory of ASTER satellite images (4) an inventory of AVIRIS imagery (5) an inventory of other satellite or airborne imagery for Yellowstone, and (6) a radar map showing geologic structures. These maps will provide the baseline data for assessing future change in Yellowstone’s thermal features. An inventory of all Landsat images covering Yellowstone National Park will be generated during the process of selecting historic Landsat scenes. A similar spatially referenced inventory for ASTER and AVIRIS satellite images also will be generated. These spatially referenced inventories will be added to the YNP Spatial Analyses Center GIS database and the Yellowstone Geothermal Database. In addition to the initial inventory of satellite and airborne images, the annual purchase of satellite and airborne imagery will insure that efficient, park-wide mapping of thermal features continues into the future.

Yellowstone Geothermal Database

Introduction

An important component of the Yellowstone National Park Geothermal monitoring plan is the archiving and dispersal of geothermal data. All information gathered must be readily accessible to park managers, scientists, and the general public. Data must be archived in a robust manner so that it will be easily and reliably retrieved in the future.

Methodology

All data that are gathered will have both spatial and temporal components. Initially, all information will be placed in a hierarchical site-file structure. The site files will range from data that cover all of YNP (such as remote sensing data), to river basins (such as hydrologic gauging stations), to thermal basins (such as some chloride flux measurements), and to individual thermal features (such as eruption times, temperature, and chemistry). The site-file structure will enable all data about a particular area or feature to be easily located. It will also allow historical data to be added. All information added to any site file will contain basic metadata concerning the source of the information.

Information will be retrieved from the site files using an Internet-based Geographic Information System (GIS). The Yellowstone Geothermal Internet Mapper will allow users to query site files for the existence of data using an interactive spatial search. Examples of this capability include a user clicking on a specific hot spring to determine what chemical, temperature, flow, and photographic data exist for that hot spring; or dragging a box over an area to determine what geologic maps or remote sensing images exist for the specified area. Base maps will be interactively created using data from YNP's Spatial Analysis Center. The user will be able to display the spatial locations of the data they have chosen as well as query the data. A download capability will also be available for selected data.

The Yellowstone Geothermal Mapper will link to other databases such as real-time hydrologic data from the United States Geological Survey, Controlled Groundwater Area data available from the Montana Bureau of Mines and Geology, and University of Utah Seismic Station information. By using a distributed geolibrary concept, users would only need access to the Internet to interactively display images of the park with known thermal areas, land use, hydrologic maps, seismic activity, or other digital maps.

BUDGET

Budgetary information is presented by program component in tabular format. Costs are estimated in 2003 dollars. Five new staff positions will be required for the five elements of the plan.

		First Year	Second Year	Third Year
Groundwater Monitoring				
	Instruments for 20 wells	$35,000	$0	$0
	Maintenance for well instruments	$0	$7,000	$7,000
	Personnel, GS-7, 1/2 time	$22,200	$22,650	$23,090
	Water analysis ($100 per sample)	$8,000	$10,000	$10,000
	Standards and supplies	$1,000	$3,000	$3,000
Chloride Flux				
	Installation of 8 gauging stations (USGS)	$290,000	$0	$0
	Maintenance for 12 USGS gauging stations @$17,100 per station.	$205,200	$205,200	$205,200
	Maintenance for 8 USGS gauging stations @$17,100 per station.	$0	$136,800	$136,800
	Analytical costs and supplies (480 samples per year)	$21,000	$30,000	$30,000
	Personnel, GS-7	$0	$45,290	$46,200
	Vehicle rental, per diem	$0	$11,000	$11,000
Thermal Feature Geochemistry				
	Personnel GS-11	$70,900	$72,320	$73,740
	Personnel. GS-7, 1/2 time	$22,200	$22,650	$22,090
	Water analysis ($100 per sample)	$5,000	$15,000	$15,000
	Instrumentation	$28,000	$3,000	$5,000
	Standards and supplies	$1,000	$3,000	$3,000
	Vehicle rental	$6,000	$8,000	$8,000
Remote sensing				
	Computer	$10,000	$0	$0
	Software	$15,000	$5,000	$5,000
	Images	$15,000	$40,000	$45,000
	Personnel, GS-11	$70,900	$73,200	$73,740
	Training and travel	$10,000	$10,000	$10,000
Yellowstone Geothermal Database				
	Computer	$0	$7,000	$0
	Software	$0	$15,000	$5,000
	Personnel, GS-7	$0	$45,290	$46,200
	Supplies (hard drives, back-up media)	$0	$5,000	$8,000
	Training and travel	$0	$10,000	$10,000
Administrative Support		$10,000	$36,200	$36,924
	TOTAL	$846,400	$841,600	$838,984

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APPENDIX A – Legal Mandates and Authorities

Specific legal mandates and authorities address geothermal monitoring in Yellowstone National Park.

The Geothermal Steam Act of 1970 as amended in 1988 seeks to preserve geothermal features in units of the National Park System. Specific lists of parks with geothermal features are provided. Yellowstone National Park is discussed separately: "the entire park unit is listed as a significant thermal feature" (Federal Register, v. 52, p. 28795). Specifically the law directs the Department of Interior to monitor significant thermal features (30 USC § 1026 Mineral Lands and Mining).

The National Park Service has developed policies concerning the role of research in management of geologic features. The following passage is from 1988 NPS Management Policies regarding geologic features. "Park geologic features will be protected. Certain fragile geologic features, such as geysers, caves, sand dunes, and arches, will be monitored to determine if measures are needed to prevent or stop human-caused damage."

The National Park Service has prepared specific guidelines for inventory and monitoring in NPS 75. According to the steps recommended in NPS 75, the first step is to define park objectives and management priorities. The 1995 Yellowstone Resource Management Plan outlines several specific steps including to "continue protection and interpretation of geothermal resources by regular patrol, visual monitoring, and informal and formal education programs" and "provide data and interpretations as requested to answer public and congressional inquiries on geothermal resources".

In 1994, the State of Montana and the National Park Service established a water rights compact and controlled groundwater monitoring program within Montana adjacent to Yellowstone National Park. The purpose of the compact is to protect Yellowstone's unique geothermal resources from groundwater or geothermal development that might occur within Montana adjacent to Yellowstone National Park. The inventory and monitoring of Yellowstone's geothermal features is a necessity for the success of the Montana Compact and will complement monitoring activities undertaken separately under the direction of the Compact.

Appendix B – Individual Thermal Feature Assessment Methodology

Introduction

Much of the following discussion is taken from "A Thermal Monitoring Plan for Yellowstone National Park" (Hinman 2001). In general, measurements would include some or all of the following parameters, depending on the specific area being monitored.

1. Measure temperature, pH, conductivity, and discharge.
2. Use temperature loggers to measure thermal feature and soil temperatures.
3. Survey tree-kills.
4. Remote sensing, overflights.
5. Collect water samples for anion and cation analysis.
    a. ion chromatography (IC)
    b. inductively coupled argon plasma emission spectrometry (ICPS)
    c. sulfide analysis
    d. ferrous/ferric iron analysis, if Fe is present
    e. silica analysis
6. Measure gas concentrations or collect samples for gas analysis.

Summary of Thermal Feature Monitoring by River Drainage

Gardner River Drainage

- Mammoth-Norris Corridor, Roaring Mountain, Amphitheater Springs – Obsidian Creek should be monitored for flow, chloride, sulfate, pH. Individual springs in the corridor should be monitored for changing redox conditions. Such changes will indicate whether more or less hot water, steam, or heated groundwater is moving through the corridor. Thermal surveys should include ground temperature via remote sensing or direct measurement. Aerial photography of tree kills and vents on top of Roaring Mountain.
- Mammoth – Mammoth outflow should be monitored (volume, pH, Cl, SO_4) but it should be recognized that this probably does not represent the entire outflow and some subsurface flow occurs. To identify subsurface flow, chloride flux measurements and stream gauging must be performed in the Gardner River to isolate flow from Mammoth. Individual springs (two springs: Narrow Gage and Angel Terrace or Jupiter Terrace) should be monitored for H_2S and SO_2 output to identify changes in redox conditions. Measurement of Rn should be considered in this area. Spring temperature and flow, spring patterns, and elevation changes should be mapped, possibly by aerial photos or photo points.

Gibbon River Drainage

- Norris – The current monitoring efforts at Norris should be expanded. Specifically, the discharge and chemical characteristics of the distinct drainages of Tantalus Creek should be monitored. Shifts in heat flow are dramatic at Norris. In addition, thermal imagery should be used, along with remote sensing data to identify heating and cooling areas. Tree kills should be carefully monitored. Fumarole and diffuse gas chemistry should be monitored as well. The features should be selected randomly.

- Gibbon Geyser Basin, Geyser Creek – (includes area with Avalanche geyser). These areas have well-defined outflows that could be monitored for discharge, temperature, chloride, silica and sulfate. Further, there are fumaroles that should be monitored for gas and temperature changes. Soil temperature surveys should be undertaken periodically to monitor for change in heating and cooling areas.
- Monument Geyser Basin, Sylvan Springs – Monument Geyser Basin is a high elevation field that at one time had geysers but such activity has ceased. Fumarole temperature should be monitored here. Sylvan Springs has several self-sealing features and combined acidic and alkaline activity.
- Beryl Spring and other features – Beryl Spring releases water from the deepest source. It is important to monitor its temperature, discharge, chloride, Na/K, as well as the distribution between gas and water discharge. Both the spring and the adjacent fumarole should be monitored. Numerous other springs exist in the Gibbon Canyon. The temperature, location, flow, and chloride content of these springs should be monitored. Terrace Spring should be monitored. This usually nondescript pool has unusual water chemistry for its location. It precipitates both travertine and siliceous sinter. The presence of travertine suggests significant amounts of dissolved CO_2. Temperature, flow, pH, silica, CO_2, bicarbonate, chloride should be monitored.

Firehole River Drainage

- Upper Geyser Basin – Temperature, chloride, sulfate, anions, cations, gases, and discharge should be measured in selected features.
- Midway Geyser Basin – Temperature, chloride, sulfate, anions, cations, gases, and discharge should be measured in selected features.
- Lower Geyser Basin - Temperature, chloride, sulfate, anions, cations, gases, and discharge should be measured in selected features.

Yellowstone Lake and River Drainage

- La Duke – temperature, chloride, sulfate, and discharge should be measured.
- Hot Springs Basin – Thermal area is located near the proposed recent magmatic injection. Because of its location over the youngest magma injection, this area should be monitored for impacts.
- Brimstone Basin -Thermal area is located just outside the caldera rim to the southeast of Yellowstone Lake. Because of its location, this area should be monitored for impacts.
- Mary Bay – This thermal area is located in a presumed former explosion crater in which thermal activity continues to this day. The road is built though the thermal area and is subject to harsh environmental conditions of high heat and high acidity. At present, the road has capped over some former discharge areas and is likely functioning as an insulator preventing heat from escaping. This area would be expected to exhibit significant changes in heat distribution and several soil and gas temperature surveys should be made.

Snake River Drainage

- Heart Lake – Heart Lake has thermal features near the lake and up through the Witch Creek drainage. The features nearer to the lake (e.g., Rustic Geyser) are generally more alkaline than those up Witch Creek and do precipitate some, but not significant amounts of silica. The activity in this area is probably constrained by faults. In that respect, there are several radial faults through this area outside the caldera. Heart Lake warrants attention similar to Norris Geyser Basin and should be treated as one of the significant extra-caldera heat-flow routes. Water and steam discharge and chemistry should be monitored year-round.
- Southwest Corner (Bechler, Boundary Creek, Mountain Ash Creek, etc.) – The southwest corner of the park is another area like Heart Lake, except that the area lies in the path of the caldera instead of along its leading edge. Water and steam discharge and chemistry should be monitored year-round.
- Smoke Jumper Hot Springs – This group of highly acidic thermal features sits atop the Pitchstone Plateau. This area and Phantom Fumarole should be watched closely. They probably tie in with the features in the Boundary Creek area and with features in the Hillside Group. Water and steam discharge and chemistry should be monitored year-round.