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Geoscience and Decision Making for Geothermal Energy: A Case Study

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Geoscience and Decision Making for Geothermal Energy: A Case Study

by

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Dedication

This work is dedicated to the people of Chile who have always welcomed me and my colleagues with open arms and supported us in our research.

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Abstract

Geoscience and Decision Making for Geothermal Energy: A Case Study

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In September 2009 exploratory testing of an old geothermal power well caused a blowout at the El Tatio geothermal field of northern Chile. El Tatio is the largest geyser field in the southern hemisphere. The blowout was a paradigm-shifting event for the management of the El Tatio geothermal field and drew attention to the disparity and critical nature of scientific information sharing.

This study uses the El Tatio incident as a case study for examining problems of common-pool resource management and geothermal energy development. It explores how differing valuations of geothermal resources resulted in a breakdown of coherent regulation and negative outcomes for all stakeholders. Contingent valuation methods were used to create an elicitive interview process in order to assess how differences in valuation drove these conflicts and negative outcomes. The sharing of scientific information through Decision Support Systems (DSS) is identified as an important element in resolving these conflicts and creating new policies for common-pool resource management.

These methods are presented as tools that can be used by stakeholders to find common ground and seek mutually beneficial outcomes. In addition, these tools can help

with the critical issue of social perception of scientific data and science driven solutions to these problems. This study posits that the path forward is to ensure not only that scientific data is communicated in modes appropriate to the community and problem at hand, but that the acquisition and interpretation of this data is informed by stakeholder needs.

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Introduction

The El Tatio geothermal complex, located in the II region of northern Chile[1], is the largest geyser field in the southern hemisphere. This geyser field is an important geological, hydrological, and cultural resource for Chile's high desert region. Containing more than 100 documented thermal features, the geyser field is a major tourist attraction and a unique geological and geochemical laboratory (Glennon and Pfaff, 2003). It attracts more than 100 thousand tourists per year (Rojas and Campos, 2009) and has been the focus for important scientific inquiry. It is also home to a potentially large, renewable geothermal energy resource. Starting in the 1970's, El Tatio has been intermittently explored for geothermal energy, including deep wells drilled into the periphery of the field (Lahsen, 1988) as well as an abandoned desalination project. While the extent of the geothermal resource was confirmed, the technology available in the late 1970's and 1980's was not economical enough to justify further development. In the 21st Century, Chile's recent economic boom—much of it underwritten by the mining industry in the II region—demand for energy has continued to increase, creating economic feasibility for alternatives like geothermal to be exploited.

In September 2009, nearly 30 years after the initial exploration, a joint partnership between two Chilean state owned companies and an Italian developer was on track to develop a 40MW power generation plant in El Tatio. Using the existing exploration wells, the joint company Geotérmica Del Norte (GDN) planned a series of tests to quantify the flow-rate and other characteristics of the geothermal reservoir. In early September of that year, an operator error during the flow-test resulted in damage to one of the old well-heads causing an uncontrolled geyser of steam from the well—referred to

[1] Chile's regions are numbered I to XV beginning in the north and proceeding south.

in this study as a "blowout" or loss of well control incident. The 60m tall man-made geyser raged for nearly a month before being brought under control. This raised concerns about the potential environmental, ecological, and geological impacts of the geyser and put further development in El Tatio in jeopardy.

The reaction to this accident from both the public and the Chilean government was swift. The local community, which had been suspicious of the project since its inception, rose up in protest and petitioned the national government to halt the project, which the government did in short order. The event was termed a "blowout" by the national and international media and provoked immediate backlash against GDN and the nascent Chilean geothermal industry. GDN was ultimately fined and censured by the government, the project was shut-down, and a semi-permanent moratorium on geothermal development in El Tatio was put in place.

But what was the actual impact on the geothermal system and the environment? An inquiry by the United Nations Development Program (UNDP, 2010) concluded that the geothermal system itself suffered little damage. In fact, when the wells were first drilled, they had been opened completely for months at a time with no lasting pressure reduction to the overall system (UNDP, 2010). The discrepancy between previously reported response in the wells and geothermal system prior to the blow out event and after does raise many questions about how science can and should be incorporated into policy decision making for energy development. In El Tatio, all stakeholder groups faced negative outcomes: the local community felt betrayed and abused, the government's regulations were shown to be inadequate, and the developer lost a viable project and millions of dollars. How could this result have been avoided and what lessons for energy development can be drawn from the failure in El Tatio?

OVERVIEW/PURPOSE

Chile is not unique in its growing energy demand. Over the last decade, global energy consumption has grown by more than 25% and is projected to continue increasing at a rapid rate (EIA, 2012). As this demand continues to increase, new technologies and sources of energy are rapidly being developed. However, these technologies have often outpaced society's ability to understand, control, and implement them. From the boom in the renewable energy industry to the dramatic increase in offshore drilling, technological developments in the energy industry have continued to present complex problems to the public and to policy makers. The dilemma of how to balance the need for increased energy availability and concerns about safety, environment, and economics has created ongoing tension and conflict over energy. The El Tatio case is one of many current examples of conflicts over how to manage and develop finite energy and earth resources.

At the core of the conflict over these resources is the technical and scientific knowledge that makes innovation and implementation of energy and earth resource technologies possible. Rational policy and regulation seeks to balance technical data and expert opinion with political realities—energy policy is no exception. However, the energy industry has repeatedly struggled to reconcile scientific and technical data with policy-making priorities. The result of this disconnect can be disastrous; British Petroleum's 2010 Deepwater Horizon oil spill in the Gulf of Mexico was a dramatic example of the potential impacts of policy failing to keep pace with scientific and technical innovation.

The energy industry's position is further complicated by long-standing problems of common-pool resource management and inadequate stakeholder engagement, which even under traditional development circumstances is a complex and often frustrating process. As it was the case in the El Tatio incident, disagreement among stakeholders can lead to conflict and negative outcomes—since the 2009 well control incident geothermal energy development is at a complete halt in the region.

Finally, this tension is further complicated by the large gap in access to scientific understanding and differences in value systems between these different stakeholder groups. Not all groups have a similar level of access to nor understanding of scientific data or modes of inquiry. Local stakeholder groups may perceive science as a "weapon" or an impediment to creating consensus instead of a shared tool. When this is combined with a vastly different valuation of resources, conflicts over energy resource development can become intractable. A local indigenous stakeholder group may perceive value—both economic and cultural—very differently than a project developer or a government agency. In the end, these tensions result in energy policies and practices that often ignore these differences in valuation and understanding of scientific data leading to inefficient and sub-optimal outcomes for energy projects.

RESEARCH QUESTIONS AND PURPOSE

This study examines how a promising, yet historically underutilized, energy technology has successfully addressed or has failed to deal with the tensions described above. The El Tatio blowout incident is a case study for how these conflicting priorities resulted in a breakdown of coherent regulation as well as negative outcomes for all stakeholders. Through policy analysis, fieldwork, and engagement with stakeholders involved in the 2009 blowout at El Tatio, this study has three core purposes:

1. To formally document the events that occurred in September 2009 and provide analysis of the political and economic context for these events. This includes

identifying stakeholder groups and compiling a set of reference literature for future studies.

2. To present new geochemical and infra-red data taken before, during, and after the event that confirm the findings of the UNDP commission.
3. To identify key lessons for stakeholder interaction from the El Tatio event and present new methodologies for initiating and sustaining stakeholder dialogue. Specifically, work was completed to develop sustained dialogue methods for groundwater and energy resources, including the design of a pilot cyberinfrastructure project.

OVERVIEW OF CHAPTERS

The study is divided into five primary chapters. First, a literature survey on resource management and applicable theories, followed by a chapter covering Chile's economic context and a chapter providing detailed background on the El Tatio event in 2009 as well as characteristics of the region. The penultimate chapter details the process of interviewing and interacting with stakeholders. The final chapter provides potential solutions and recommendations for the way ahead.

Chapter one surveys the current literature and background on common-pool resource management problems, decision support theory, and incorporation of scientific data into energy project regulation. This first chapter focuses primarily on geothermal energy and is not meant to be a comprehensive survey of energy technologies or conflicts over all types of resource management. It also provides a background on different methodologies for stakeholder engagement and decision support systems, which are presented as a possible alternative to the current structure for stakeholder engagement in Chile.

Chapter two presents geothermal development in El Tatio in the larger context of Chile's energy, environmental, and economic policy situation. The El Tatio event is tied to many other macroeconomic and political trends currently taking place in Chile. The position of geothermal energy in Chile is linked to understanding how these events have impacted the country's management of energy projects. This chapter also presents the background of the stakeholder groups involved, with emphasis on the unique factors brought by the indigenous communities of the II region. The involvement and role of indigenous communities—and their approach to resource valuation—is critical to understanding the root of the conflicts in El Tatio and the possible solutions for facilitating dialogue.

Chapter three documents the events leading up to and after the blowout event in El Tatio and provides a geological and hydrological overview of the El Tatio system. This chapter also includes geochemical data taken before, during, and after the blowout even—which represent the only independent data taken during all three phases. This chapter also presents a technical assessment of the impacts to the geothermal field and the local environment.

Chapter four presents the full results of interviews and interactions with local communities in Chile based on the methodologies explored in chapters one and two. This chapter has been published independently as an article in the Journal of Contemporary Water Research & Education and has been adapted here as a formal summary of results.

Chapter five summarizes the initial efforts to apply the results of the geoscience and social science research through creating a cyberinfrastructure platform for sharing data. This included experimentation with and design of custom multi-touch user interfaces for facilitating stakeholder interaction. This chapter presents the key lessons learned in applying these technologies to the El Tatio case and other analogue cases, finishing with recommendations for further work.

Chapter I: Literature and Methodology Review

This research was conducted as part of a dual-degree program between the Jackson School of Geosciences and the LBJ School of Public Affairs at The University of Texas at Austin. As such, it is explicitly a piece of interdisciplinary research which relies on a broad set of literature and theory, ranging from fundamental geology and geophysics to economic theories of community engagement and common-pool resource management. The core of this study focuses on modes of stakeholder engagement and the successful or failed attempts to incorporate stakeholder feedback in energy and environmental policies. The majority of the studies reviewed here focus on groundwater management and other related common-pool resource problems. As there is a limited amount of research specific to stakeholder interactions in geothermal energy, this study offers a baseline for future studies.

The primary methodology for this study comes from the fundamental assumption that good governance exists when socially efficient management of common-pool resources is attained and when there is a social perception that this is the case; these two conditions are necessary for short and long run governance. If only one of these conditions is met no long run governance is guaranteed. The objective of this study was to seek solutions to both efficiently solving problems while engaging with stakeholders to enforce the perception of success through new formats of interaction. In order to do so, we first must define the nature of the problem.

COMMON-POOL RESOURCES

The case of El Tatio can be referred to in theoretical terms as a "common-pool resource" management problem. The fundamental problems of resource management are perhaps best articulated by the landmark article of Hardin (1968) "The Tragedy of the Commons." Hardin states that "Freedom in a commons brings ruin to all." That is, if men are enabled to develop common resources and property freely, it will ultimately lead to the destruction of these common goods and economic downfall because with free access to the resources, individual priorities and preferences often subvert communal needs. This is the underlying problem that is being confronted in El Tatio: there are a finite number of uses and resources available in El Tatio and not all uses can coexist, thus some of them must be excluded from using the resource. The loudest voices win, at first, but the results are unsustainable without consensus support

Hardin's argument also stated that economists and natural scientists could not invent their way out of these problems—they are fundamental and do not have purely technical solutions. Hardin's argument focuses on the fundamental "population problem" of growing numbers of people with growing needs for material goods. The case of El Tatio underscores this problem exceptionally well: since the day many centuries ago that humans first arrived in the Andean altiplano (high desert), resources have been scarce and overburdened. Hardin's provocative theoretical base has inspired generations of social scientists to grapple with how to confront and avert the tragedy of the commons. Among the most important of these theorists is Ostrom, whose 1990 work "Governing the Commons" presents a contrast to Hardin's dim view of the inevitability and intractability of the destruction of the commons. Put simply, Ostrom argues that society has organized itself into interest groups in such a way that negotiated uses of common resources have averted their complete collapse.

In the introduction to their 1994 book *Rules, Games, and Common-Pool Resources*, Ostrom. et. al (1994) use an example drawn from the field of geothermal energy. Using the gradual decline in steam pressure in the Geysers geothermal field in

Northern California as an illustration, the author's define the generic problem of common-pool resources as the following:

> "The incentives toward excessive resource extraction, illustrated by…The Geysers are not isolated or unique events. The temptation to over-extract fish, steam, or other resources units from a resource system shared with others occurs in many guises in diverse resource systems throughout time and space. As we define the term, common-pool resources (CPRs), where excluding potential appropriators or limiting appropriation rights of existing users is non-trivial and the yield of the resource is subtractable" (Ostrom, et al., 1994)

In the case of El Tatio, the problem of common-pool resource can be viewed in a broader lens. While not structured as an established geothermal power producer nor as simple as an extractive industry, El Tatio embodies many of the characteristics that concern Ostrom and Hardin: Local indigenous peoples view it as a spiritual resource, tourist operators as an economic resource, government as a nature preserve and potential national revenue stream, developers as a source of energy and miners as a source of water. This study seeks to highlight that such problems in the geothermal domain can lead to insights for resolving issues in any resource domain.

Problems of common-pool resource management are not limited to extractive industries such as fishing and mining; instead they can be broadly understood as the use of any finite resource which is non-excludable and rivalrous. Ostrom observes that governance of the commons is carried out efficiently largely because of people's inclination to self-align into distinct interest groups, in essence building strength in numbers. These interest groups then interact to determine allocations from the common-pool resource and in doing so attempt to negotiate a consensus. In modern democratic societies, this consensus is often put into action via government agencies and policies, though there are many examples of people jointly managing resources through internal cooperation without a centralized state (See Bailey 1982; Berkes 1982; Berkes et al. 1982; Steins and Edwards 1999; Wong 2004; Ostrom 2008; Gewali 2011).

These interactions present a new suite of problems and issues that demand a multi-disciplinary lens to begin to understand. Beyond the strict economic and game theoretical approaches of Hardin and Ostrom, there is the practical matter of planning and understanding both the social and the physical systems—the commons—that societies attempt to manage. The problems that arise in devising these plans have been described as "wicked" (Rittel and Webber, 1976). That is, they are problems that are not "tame" and do not have an explicit technical solution, they have no right or wrong answer, and often return, sometimes with further complexities. Rittel and Webber described wicked problems as problems that present a particular challenge to social planning, as they do not conform to a set pattern, meaning each instance even within the same field (water recovery, fishing quotas, geothermal steam) has different inputs that have significant impact on outcomes.

From a technical planning perspective, these inputs are complicated by scientific uncertainty, particularly with new or emerging technologies. Geothermal energy, despite having been utilized for electricity production for more than a century, still has many associated unknowns and risks. This is also seen in groundwater allocation modeling, where factors such as aquifer recharge--which operates on a geological timescale--must be estimated and correlated to human development timeframes. While science does provide benchmarks and data for planning, it also contributes to these wicked problems by adding complexity, which will be discussed in greater depth below.

CONTINGENT VALUATION AND METHODS OF ELICITATION

Before discussing the technical solutions and planning alternatives used to solve wicked problems we must understand the end goals of solving these problems. What is the benefit for society produced by solving a wicked problem? One of the root causes of wicked problems, as phrased by Rittel and Webber, is that there is no precise "theory that can locate societal goodness, nor one that might dispel wickedness." (Rittel and Webber, 1976) That is to say, even the solutions to these wicked problems do not adhere to a unified theory of "goodness".

Groups within society interpret the "goodness" of a solution based on their biased valuation of a given outcome. In the case of energy projects, which often have significant environmental impacts, standard economic market-based prices are often insufficient in capturing stakeholders differing valuations, which may have intangible values associated with proposed impacts. That is to say, the amount that consumers in the II region of Chile are willing to pay for electricity likely does not accurately capture the value they may place on the environmental impacts of generating this electricity. The public's willingness to pay (WTP) for electricity expressed by the market prices they pay for electricity neither captures the negative impacts that energy developments nor their associated environmental impacts on, for example, indigenous people's religious or cultural sites.

In order to estimate economic valuation of goods and services that are not traded in markets and to incorporate these estimated valuations in public policy decision making, economists have developed a method to value non-market goods known as contingent valuation (CV) (Haneman 1994). The need for economically valuing these non-market goods was first identified in the first half of the 20th century by economists and early scholars of public policy (Carson and Haneman, 2005). This field of inquiry was primarily built to augment and refine methods of cost-benefit analysis for use in the public sector, particularly by agencies involved in permitting and leasing of public lands (Thayer, 1981).

The contingent valuation method allows assigning monetary values to people's WTP for goods that do not have a market and therefore are not involved in market transactions. These values can include many different types of goods from the basic life support functions associated with ecosystem health or biodiversity, to the enjoyment of a scenic vista or a wilderness experience or the right to pass on these options to future generations. It also includes the value people place on simply knowing that places or animal species exist.

There is no controversy about the fact that people are willing to pay for goods that do not have explicit markets. However, these values are likely to be implicitly treated as zero unless their monetary value is somehow estimated. Since these values do not have markets, people do not reveal their WTP for them through their purchases or by their behavior; therefore, one option for estimating a monetary value of people's WTP for these goods is by asking questions to people.

CV is referred to as a "stated preference" method, because it asks people to directly state their values, instead of inferring values from people's actual choices, as the "revealed preference" methods do. Because of being based on asking people questions, as opposed to observing their actual behavior, CV is often severely criticized (see Diamond and Hausman 1994; Cummings and Harrison, 1995).

The core principles of contingent valuation are based on a rigorous elicitation process whereby consumers are surveyed regarding their fundamental WTP for those goods without explicit markets but whose people's monetary valuation we want to know.

Contingent valuation has evolved to include multiple formats of elicitation of valuation including surveys, questionnaires, tests, and games.

The goal of contingent valuation is to identify, in a repeatable and rigorous manner, the differences in valuations between different groups of consumers. An example of an implementation of contingent valuation theory is Deliberative Polling developed by Fishkin (1991). Fishkin's model of contingent value elicitation calls for a multi-stage process wherein stakeholders have access to data, information, and training between survey points, resulting in an approximation both of WTP and the impact of new information on valuation. Zarnikau, along with others, has used this methodology to estimate the willingness of electricity customers to pay additional costs for renewable energy (Zarnikau, 2003)

Contingent valuation remains an evolving practice and it is not without its critics. The chief concerns with applying contingent valuation theories are its consistency and basic validity (Venkatachalam, 2003), due to several technical requisites that need to be satisfied for a valid application of it. Erroneous implementation may result from mistakes in designing and elaborating the questionnaires, in constructing the hypothetical market on which the obtained valuations from the people surveyed is 'contingent' on, and in conveying the unbiased and necessary information to the interviewees to properly understand which is the exact WTP they are being asked to declare (see Carson et al 1996 and 1998)

Because CV has been implemented and used inconsistently across disciplines and cultural communities, reproducibility is often hard to prove. Moreover, the results obtained through CV can be difficult to validate and reconcile with conventional market-based valuation methods. In this study, CV theory and methodologies were used to support and give methodological framing to stakeholder interactions and interviews.

In this study, due to a small sample size and limited resources, a direct elicitation method was employed in field visit to the II region of Chile using principles developed by Pierce (2006). A set of common questions and topics regarding the El Tatio field and geyser incident was developed and presented to local stakeholders for freeform response. In subsequent visits, structured round-table meetings were held to refine responses and define boundaries for the respondents WTP or Willingness to Accept development or changes to the geyser field. The results of this direct elicitation is presented in chapter 4 of this study.

By eliciting specific information from the citizens of the region and of members of local communities about valuation of natural resources—in particular geothermal energy—the study aims to identify where differences in valuation exist. Do rural communities, like those close to the El Tatio geyser field, have a significantly different social/economic valuation of these natural resources? Is there something unique in geothermal energy development impacts that affect valuation? What are the differences in valuation between government agency representatives and business owners? By exploring these differences in valuation, this study offers a useful model for policy makers, electricity providers, and renewable energy developers to follow to better engage in dialogue with the public over issues of geothermal resource development. Additionally, this study will be useful for local communities and governments like those surrounding El Tatio in providing a methodology for documenting and addressing their concerns. Through the formal elicitation and the informal interview process, this study seeks to identify if and where a “middle-ground” for dialogue can exist.

DECISION SUPPORT AND APPLICATION OF FINDINGS

Having selected the guiding framework for identifying differences in valuation and methods, these findings can be generalized into technical approaches for confronting other wicked resource problems. As stated previously, the purpose of this study is not to propose a single methodology for confronting geothermal energy development problems; instead this study offers a trans-disciplinary approach to generating potential stable solutions. The chosen methodology for interpreting and applying these frameworks is through Decision Support Systems (DSS). First developed in operations research as a technical solution to facilitate decision making and planning for complex systems, the field of DSS focuses on how technology can make modeling complex systems faster and more efficient (Shim et. al, 2002).

Specifically, DSS can process and convey scientific data using a computer model and integrate this data with a decision pathway (Pierce, 2006). Emerging trends in DSS have recently attempted to integrate these discrete data based methodologies with non-discrete social science data—such as WTP profiles and assessments of social impact. As DSS technologies have advanced and improved, they show potential to serve as an aide to groups for discussing common-pool resource issues and enabling a process of social learning about complex problems, as well as deliberation and decision making.

English (1999) recognized that future research and work in the area of decision support development can be expected to flourish in areas that 1) develop new tools that are increasingly transparent to the user groups, 2) improve the integration of tools into daily use by decision makers, in other words keeping the tools off the shelf and in use, and 3) continue collection of input parameter data and improvement in data measurement. (Pierce et al., 2012)

CONCLUSIONS

In the last decade, Chile has struggled to balance its rapidly growing demand for energy with political demands for natural resource conservation. The political controversy surrounding the proposed HidroAysen dam project is the latest in a series of conflicts over how to best provide energy for Chile's growing economy.[2] These controversies have been worsened by a lack of communication and negotiation between interested parties. The sudden, extra-official way of terminating a private company's plans to build a thermal power plant in Barrancones, in 2010, is a key example of this failure to adequately frame the dialogue to include the value that stakeholders place on natural resources.[3]

The El Tatio event is useful as a case study as it represented the most advanced geothermal exploration project in Chile, yet differences in valuation and perceptions of environmental impacts resulted in a sub-optimal outcome across the board. All parties left the table feeling dissatisfied and a demonstrated economic demand for non-conventional renewable energy was not met. By studying the economic attitudes of the communities directly affected by the events related to the 2009 blowout, we hope to discover whether or not this conflict could have been avoided through dialogue or if attitudes are intractably distinct.

The II region as a whole is highly valuable as the venue for this study because of its unique balance of resource exploitation and conservation. Perhaps more than anywhere else in Chile, and due to harsh desert environment in which people reside, all

[2] This major dam project would flood a significant area of southern Chilean Patagonia in order to provide 2750MW of generation capacity.

[3] The Barrancones project was a proposed coal power plant on a coastal location in northern Chile. Despite having received full approvals from all relevant government agencies, the project was cancelled after public outcry.

residents of the II region are conscious of the need for balancing resource development and community concerns.

Chapter II: Geothermal and the Commons

Chile's struggles with management of geothermal systems offer a clear window through which to evaluate the pervasive problem of common-pool resource management. Methods of analysis and problem-resolution that have worked in Chile can be generalized to common-pool resource problems in other domains. Since the beginning of exploitation of geothermal systems for human use there have been conflicts over resource allocation and uses (Cataldi, 1993). Beginning with direct uses such as bathing and cooking, geothermal systems have always been valuable resources to the communities that have access to them. However the increased burden and activity needed to produce electricity from a geothermal field have provoked extended conflicts over these sensitive areas. While geothermal energy is a lower-impact form of power production than many conventional fossil fuel energy sources, there are still risks of adverse environmental and social impacts.

Moreover, geothermal resources in many countries, and particularly in Chile, can be characterized as typical common pool resource and, as it was highlighted in the previous chapter, this creates a set of problems regarding the use of the these resources and their long run sustainability. This section briefly presents a primer no geothermal power development, technologies, and their associated risks in order to provide scientific context for the El Tatio event. Two comparative case-studies from the United States and New Zealand are presented as examples of how conflicts over geothermal development impacts were confronted and resolved. The section also identifies where gaps in valuation of resources between different stakeholder groups emerged and how this contributed to resolution. Finally, the economic and political context to the struggle over development in El Tatio is presented and analyzed in the context of these larger trends.

INTRODUCTION TO GEOTHERMAL POWER GENERATION

Put simply, geothermal power is energy from heat in the earth's crust. Humans have used this heat for thousands of years, but only in the last 50 years has it been used extensively to produce electric power. Geothermal energy technologies can be broken into two general categories: direct use and electricity generation. As has been stated, direct use of geothermal energy for bathing, cooking, and heating is perhaps the oldest form used by humans. At present, geothermal direct use is typically a boutique industry that includes spas, exotic fish farming, tourism, and industrial heating and drying. As a proportion of energy consumption, direct uses far exceed electrical generation. These direct uses are difficult to precisely quantify, however, consumption and usage are often estimated (Geothermal Energy Association, 2012).

In the United States, approximately 2,200 MW of electricity are generated annually by geothermal energy, roughly the equivalent production of four large nuclear power plants. This production comes primarily from western states—with approximately 1,800 MW in California alone— electricity-grade geothermal are confined to locations where geological conditions are most suitable. Worldwide the total installed capacity of geothermal is approximately 11,000 MWe (Geothermal Energy Association, 2012). In Latin America and the Caribbean, only 5 countries have operational geothermal plants: Mexico, Nicaragua, El Salvador, Costa Rica, and the island of Guadeloupe. Despite many attempts and false starts, there has yet to be permanent, commercial scale generation from a geothermal reservoir in any South American country.

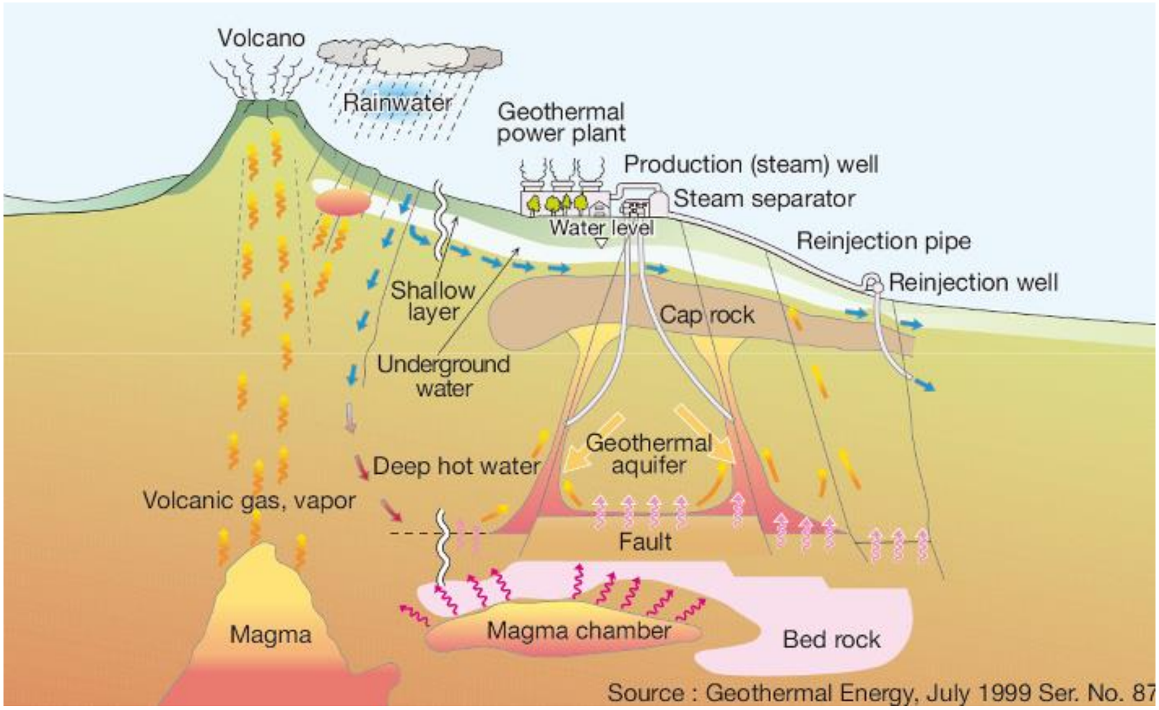


Figure 1: Schematic of a geothermal power system (Japan's New Energy Foundation, 1999)

The technical mechanics of geothermal energy are relatively straightforward. Figure 1 provides a good schematic overview of a geothermal power system. All geothermal electrical energy generation uses the heat, steam, or hot water from a reservoir to create the force needed to turn turbine generators and create electricity. The three basic types of geothermal power plants are dry steam, flash, and binary. In dry steam power plants, steam from the reservoir is piped directly from wells into the power plant and used to turn a conventional steam turbine. In flash power plants, hot water (ranging from 300° - 700° F) trapped in the geothermal reservoir is brought to the surface and the pressure change induces a phase change from water to steam. Because of the high water content, these systems typically require additional separation and management of fluids.

Binary power plants are used in situations where the geothermal reservoir is not hot enough to convert to an adequate amount of steam for power generation at the surface. In these situations, the hot water (ranging from 250° - 360° F) is pumped to the surface and passed through a heat exchanger. There the heat is transferred to a working fluid with a boiling point lower than that of water. As this liquid is heated it flashes to vapor, expands, and is used to power turbines. This system is also used as a secondary loop to capture efficiency gains in systems where steam is the primary driver.

Conventional Systems

Conventional geothermal systems or hydrothermal systems form in proximity to volcanic activity caused by tectonic plate subduction. These conventional systems—which are known for their prominent surface features such as geysers and hot-springs—are formed in very high temperature, permeable, young volcanic rocks. They are often associated with large volcanic calderas, such as Yellowstone National Park in Wyoming or the Geysers Geothermal Field in Northern California. These waters interact with magmatic heat sources, becoming superheated, chemically altered, and saturated with minerals. These conventional systems are the dominant form for existing geothermal power production and much of the existing technology and knowledge base has been built to use these high-temperature volcanic systems. In Chile, it is these volcanic systems that constitute the majority of geothermal potential along the Andes fault line.

Economic Viability

Key reasons why geothermal energy has not been exploited more widely are the economic challenges associated with drilling and reservoir development. Virtually all geothermal drilling technology initiatives come from the oil and gas industry. Unlike the oil and gas industries, however, rapid returns on investment are much lower in geothermal power production. Chronic financial issues for geothermal power projects include the high upfront costs and the long return-on-investment timeframe. These factors have continued to discourage private investors and created the need for geothermal developers to increasingly self-finance the early stages of projects. As we will see in the case of Chilean development, this heavy emphasis on private development can have dramatic consequences for policy choices.

The early project development stage of a geothermal power producing facility is extremely capital intensive. Unlike solar and wind, finding appropriate locations for geothermal requires expensive geological exploration, and many geothermal systems are completely invisible from the surface. In order to accurately quantify the potential of the field, developers must invest heavily in exploration technologies, as was the case with the El Tatio project. Furthermore, investment in exploration does not guarantee success, thus many investors are leery of inputting any capital until a resource is well defined and a return can be guaranteed. Figure 2 presents a geothermal risk cure from an evaluation of investment risk illustrating the typical risk profile of a geothermal electricity generation project (Deloitte, 2008).

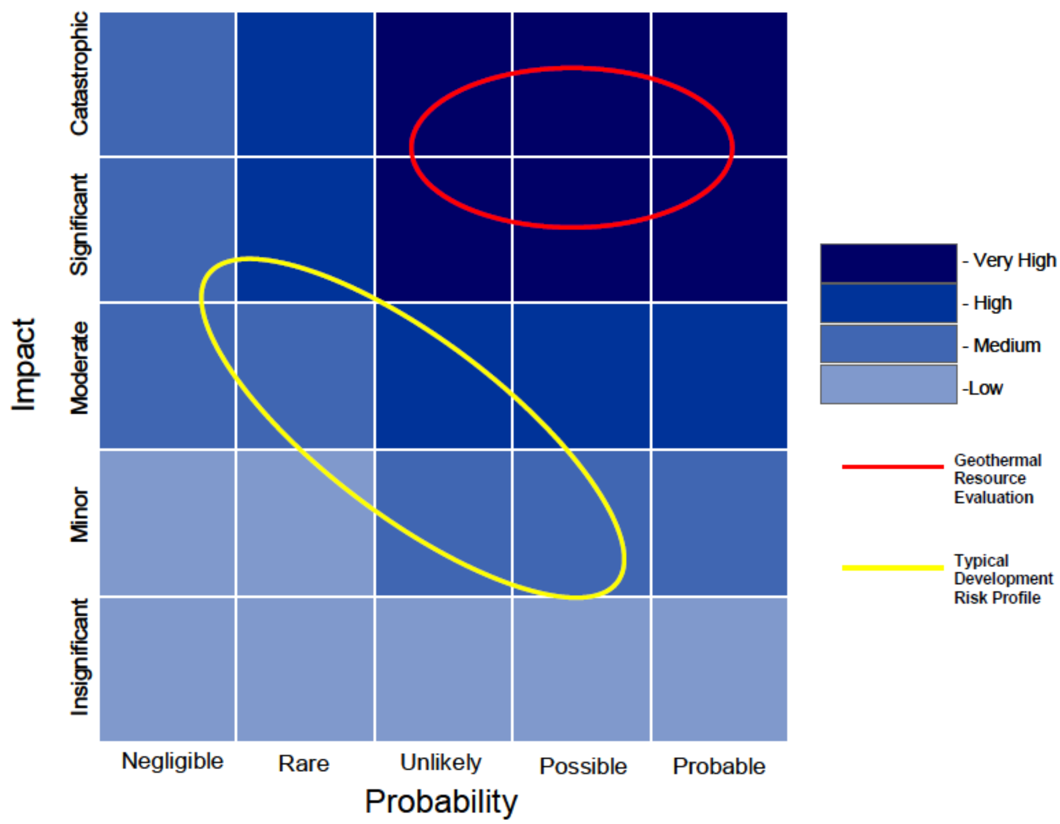


Figure 2: Risk matrix for investors in geothermal energy projects (Deloitte, 2008)

As a result of the private sector's aversion to the upfront risk of investing in geothermal, government investment has been pivotal in motivating development. The major driver of geothermal investment and research has historically been underwritten or subsidized by central governments in the few geothermal producing countries.

Geothermal Development Impacts

While there are a number potential negative side effects associated with geothermal projects, most have proven minor both in scale and in impact. The most significant impacts include gaseous emissions, water use and consumption issues, land use issues, drilling risks, seismic activity, land subsidence, and reduction of thermal features (Axtmann, 1975). In order to place the El Tatio incident in context, we must first understand the range of potential impacts and their relative severity.

Water Use

Geothermal projects require the use of water to facilitate multiple phases of the power generation process, and this water use can be of concern to communities. Water may also be needed for the condensation of fluids required for a plant's operation. The amount of water required to facilitate these processes, however, is generally small. Air-cooled binary plants use no fresh water, while other geothermal plants are highly efficient in their water usage and operate on a closed cycle. Nonetheless, geothermal heat sources within the United States are most commonly located in the western portion of the country where water is often a scarce resource. Water availability is also a concern for geothermal developments in the Chilean desert, as will be discussed in detail later in this section. In those cases located in water scarce regions in particular, it is essential to assure sound water conservation practices and management of water resources in conjunction with the local community.

Water produced during geothermal operations contains higher concentrations of dissolved minerals than water from cold subsurface reservoirs, and some of these minerals have the potential to contaminate ground or surface waters and to damage vegetation. In the case of El Tatio basin, naturally high levels of arsenic already present a public health hazard (Ferreccio and Sancha, 2011). Release of geothermal fluids into adjacent water supplies is currently very rare. Industry best practices have evolved so that working fluids are re-injected deep underground in order to maintain reservoir pressure, reducing the risk of negative externalities leading to contamination of ground and surface waters.

Land Use

The footprints of geothermal power plants vary by site, but they are generally much smaller than conventional fossil fuel power plants. Over a period of 30 years, the time frame typically used to measure the life cycle of various types of power plants, the total land per gigawatt hour (GWh) used by a geothermal plant is 4,350 square feet compared to 39,000 square meters per GWh for a coal-fired plant (EERE, 2006). Additionally, though the total area for well fields can be significant, from 3-6 square miles on average, the proportion of land actually covered by well pads is only approximately 2 percent of this area. Problems of infrastructure such as transmission lines and roads typically present a larger potential impact than the physical plant structure.

Seismic Activity

Induced seismic activity has generally not been a problem in conventional geothermal settings as these areas are already naturally seismically active. Opening fractures and injecting fluids at high pressure in order to access and stimulate geothermal reservoirs has the potential to induce seismic activity, but the magnitude of such activity is generally low. Seismic events generated through geothermal processes are known as "microearthquakes" as they measure below 2 or 3 on the Richter scale and are typically not perceived by humans. Additionally, induced seismic activity is a concern in all types of energy technology that involve extensive drilling and fracturing, including natural gas, enhanced oil exploration, and carbon capture geologic sequestration. In most cases, geothermal companies voluntarily measure seismic activity as it is a cause for public concern. The United States Department of Energy (DOE) has also developed a protocol that can be used for such purposes (Majer et al, 2012). In both cases, baseline data are taken at potential geothermal sites to aid in determining if future seismic disturbances are naturally occurring or generated by geothermal processes, and this information can be helpful in reassuring the public. The likelihood of future events can also be calculated, with possible effects of any disturbances on local infrastructure and communities taken into consideration.

Drilling Risks

The El Tatio loss of well control incident exemplifies a pre-production risk that is inherent in any drilling or well engineering project. Blowouts or loss of well control incidents occur in all types of drilling and well completion and often have catastrophic effects. In the case of geothermal drilling the release of potentially deadly hydrogen sulfide gases and caustic minerals are the highest risk for environmental contamination or injury to people. While this is an inherent aspect of geothermal energy, loss of well control incidents are generally related to operator error, as was seen in the El Tatio incident. The risks associated with drilling can be directly correlated to the quality of regulation and enforcement of the drilling industry.

Land Subsidence and Thermal Features

As extraction of steam causes the geothermal reservoir to depressurize, land above the reservoir may begin to compress and eventually sink or subside, ultimately causing a decline in surface elevation. This phenomenon was observed early in conventional geothermal development in New Zealand in the Wairakei field where subsidence rates in one area of the field reached as high as 1.5 feet per year (Tester et al., 2006). Since these initial incidents, geothermal operators have managed geothermal reservoirs more closely, particularly through careful reinjection of withdrawn fluids. From a public safety and potential economic damages perspective, subsidence is perhaps the greatest risk if the project is being developed in close proximity to a population center. In Taupo and Rotorua, New Zealand, several major sinkholes were documented soon after production began (Allis, 2000).

A decrease in surface activity of geysers, hot pools, and other thermal features typically accompanies this subsidence. Of all the potential impacts associated with geothermal development, it is this loss of features of cultural, historic, or religious value that presents the greatest problem in reaching consensus decisions for common pool resource management. For example, in New Zealand the initial production in the Wairakei field caused the extinction of all active features and the loss of approximately 240 hot springs (Scott and Cody, 2000), in addition to major incidences of ground subsidence (Steingesser and Marcus, 2009).

Surface uses—bathing, tourism, worship—present the greatest diversity of common uses and are where conflicts over development typically stall. As we will see in an examination of the policies surrounding the Yellowstone geothermal field in Wyoming and the policies for two fields in New Zealand, the other potential impacts mentioned above are usually not the core issues at stake. While the El Tatio incident centered on the loss of well control accident, the subsequent dialogue was not constrained to just this aspect of risk. Instead, the goal of preservation of the geysers in their natural state due to their value to the related tourism activities developed by the surrounding native communities was at the center of the conflict over common-pool resource use.

However El Tatio is not the first geothermal field to struggle with issues of common-pool resource conflicts. Because of the geological similarities of geothermal fields worldwide, wherever humans exploit them similar problems have arisen. The following sections compare and contrast significant geothermal basins with the development of El Tatio. This comparison of how other communities have dealt with managing geothermal energy resources was an important factor in community and government responses.

YELLOWSTONE ANALOGUE

While El Tatio is the largest geyser field in the southern hemisphere, the largest active thermal area in the world is Wyoming's Yellowstone National park. The park was created in 1872, long before any thoughts of geothermal power, and is strictly off-limits to any development. This is despite the significant potential for clean, renewable geothermal energy. Yellowstone represents the only other pure steam geothermal reservoir besides the Geysers geothermal field located in the state of California, U.S.A., and its total potential is an order of magnitude larger than the Geysers. The United States federal government, however, did not begin to directly regulate geothermal resources until the early 1970s. The first regulatory implementation was the Geothermal Steam Act in 1970, under which most federal geothermal oversight is still carried out. While both federal designations provide protection for Yellowstone's geysers within the boundary of the park, concerns have repeatedly been raised about development of neighboring geothermal areas that interact with Yellowstone's hydrothermal system (Barrick, 2009).

In the case of Yellowstone, the first major conflict occurred in 1991 when a church group in Montana uncapped an old well connected to a smaller geothermal system adjoining Yellowstone in protest to pending legislation that would prohibit such use. This sparked controversy both over the potential for private landowners to negatively affect the Yellowstone geyser system and the fact that there were no legal mechanisms in place to prevent such action (Kenworthy, 1991). This conflict led to the passage of a compact between Montana and the US National Park Service in 1994 which established a framework for monitoring and evaluating consumptive groundwater usage in areas proximate to Yellowstone. In the Yellowstone Compact, the federal government was given supremacy over water rights if they were determined to have an impact on the geysers (Barrick, 2009). This conflict ultimately was resolved through a purchase by the Department of the Interior of a conservation easement and all geothermal water rights on the property in 1999.

Concerns were so elevated in relation to Yellowstone that in 1995 the House of Representatives introduced the "Protection of old Faithful Act of 1995" which would have provided coherent rules for development of additional wells in and around Yellowstone. Though the bill stalled in the senate, it included a framework to develop rules similar to the Montana compact for other adjacent states. The net effect of this controversy and the strong action to prevent any type of development—even private individual use—in Yellowstone represents an extremely cautious and protective response to issues of common-pool resource governance. There is essentially little room for negotiation; Yellowstone is a fully closed system whose protection pre-dates geothermal development. In this context, this is a process that essentially eliminates stakeholder dialogue or negotiation, as it is trumped by longstanding public interests. While there are many known geothermal areas on the periphery of Yellowstone, the risk of uncertain water regulation and public backlash has kept developers away.

WAIRAKEI AND ROTORUA ANALOGUE

A contrasting example of approaches to resource management in the face of conflicting usage is the Wairakei and Rotorua geothermal systems in New Zealand. The Wairakei geothermal system near Lake Taupo and the Whakawarewa geyser field in Rotorua are both part of the massive Taupo Volcanic Zone of the North Island of New Zealand, which is analogous to Yellowstone in many respects. In both the Wairakei and Rotorua cases, competing uses for these systems resulted in degradation of thermal features and delayed regulatory intervention. These examples provide a pragmatic contrast to the type of resource protectionism exhibited in Yellowstone.

Beginning in the late 1940's, in part due to pressure from a drought which reduced the availability of hydropower, the New Zealand government began exploring for geothermal energy in the Wairakei field (Barrick, 2005). Much like the current state of affairs in Chile, the decision to undertake this exploration was partially due to demands on conventional sources of energy and the desire to innovate and tap an unused resource. In 1952 the first wells were drilled in Wairakei valley and power generation began in 1958—making Wairakei the longest continually running geothermal power plant in the world (see New Zealand Geothermal Workshop, 2008). Within the first years of drilling and active fluid extraction from the reservoir, thermal features immediately began to decline (Thompson, 1957 from Barrick, 2005). Later, due to the massive drawdown from the power plant, most of the major thermal features including the Wairakei Geyser valley were extinguished or had drastically changed (Simmons et al., 1992). In this case, little attention was paid to the associated drawn-downs from a public policy perspective. Incidences of subsidence and alterations to surface manifestations were noted and studied, but little was done at Wairakei to slow this change. In many ways these changes came as a surprise, as this was one of the first instances of major commercial geothermal power production in a water dominated reservoir.

The case of Whakarewarewa provides a more complex example of stakeholder interaction and interest groups in relation to geothermal resources. Rotorua, located in the center of New Zealand's North Island, is home to a percentage of New Zealand's indigenous Maori population. Since early settlement, the confluence of rivers, lakes, and thermal waters has made Rotorua a desirable place for settlement. Figure 3 shows the Whakarewarewa settlement in 1908, steam and thermal features be seen rising from the ground next to dwellings. The first settlers who arrived in Rotorua would regularly use the thermal waters to cook food and bathe. With the arrival of Europeans, the hot pools transitioned from being a shared resource that was governed under the princples of guardianship—Kaitiakitanga—into a tourist attraction. In fact, the thermal waters became valuable as one of the earliest tourist resources. Travelers would come from as far away as London to bathe in Rotorua's thermal waters and view its unique rock formations. This provoked some initial conflicts, as Maori who had historically occupied the land would block Europeans from entering or charge entrance fees (Rotorua Geothermal Museum, 2010).

Figure 3: The Whakarewarewa settlement in 1908 (Dannefaerd, 1908 – National Library of New Zealand)

However, the same principles were not applied to the subsurface waters. As Rotorua grew, the government began in the 1950's to allow its residents to drill and operate private geothermal wells for domestic heating. Although there was a permitting and licensing process in place that was designed to help manage the sustainability of the field, no licenses were issued and development continued without enforced oversight (Gordon, 2005). The result was a proliferation of backyard wells that were not monitored or inspected for safety or efficiency. While district heating systems—which provide hot water or steam to an entire community—using geothermal steam can be very efficient, Rotorua's development was decidedly wasteful. The result of this over usage was a steady decline in reservoir pressure that began threatening the Whakarewarewa thermal features. So rapid was the decline that the New Zealand national government declared a "crisis" situation and intervened through an enforced rulemaking process (Barrick, 2010).

Despite agreement that the decline of the geysers was linked to over-extraction, the decision to completely shut-in the existing wells proved extremely controversial. Many homeowners and businesses saw the direct use of geothermal as essential to their livelihoods and an essential part of the way of life in Rotorua (see Vercoe, 1987). While this curtailment of extraction was successful in stabilizing the field, many features have not returned.

These case studies from New Zealand are some of the most frequently cited examples of how energy development does inevitably alter existing geothermal systems and motivating the argument that elimination of surface features is highly likely. Moreover, these cases are an extremely useful comparison with new developments such as Chile, as they show the social tensions that exist between traditional uses that have perhaps never been challenged and new economic uses that have become an essential part of a local economy.

El Tatio - Scientific interests, Social Concerns, and Chilean Energy Policy

The cases of Yellowstone and Wairakei/Rotorua provide a baseline for understanding the concerns and evolution of the conflict over development of El Tatio. All three basins, in the US, New Zealand, and Chile, are respectively the largest and first to have been considered for development in their home countries. Examination of the lead-up to the development of El Tatio and the social and economic pressures that combined to produce the sub-optimal outcome after the event in 2009 can be compared with other international cases and common pool resource principles to design more socially acceptable results from their future use and/or conservation.

The El Tatio Geyser field is located in the II region of Chile, close to the Bolivian border in the high altiplano, as depicted in Figure 4. Located between two small townships—Caspana and Toconce—the site is accessible by an unpaved mountain road that traverses a 16,000 ft mountain pass. The geyser field itself spans approximately 10 km2 and is home to over 100 thermal features including 80 spouting geysers. Because of its variety of features and stark landscape, the field's primary function in modern times has been as a tourist attraction. Due to its elevation and isolation, there is little evidence of formal or regular human use. The original indigenous peoples—often collectively referred to as Atacameños—consider El Tatio to be a sacred place to be visited and used for spiritual reflection and ceremony. The Licakantay group of indigenous peoples believe El Tatio to be the "lungs of the earth (Ramos, personal communication 2009)." It is estimated that more than 120,000 people visit El Tatio every year from the nearby base of San Pedro de Atacama (Villa, 2013).

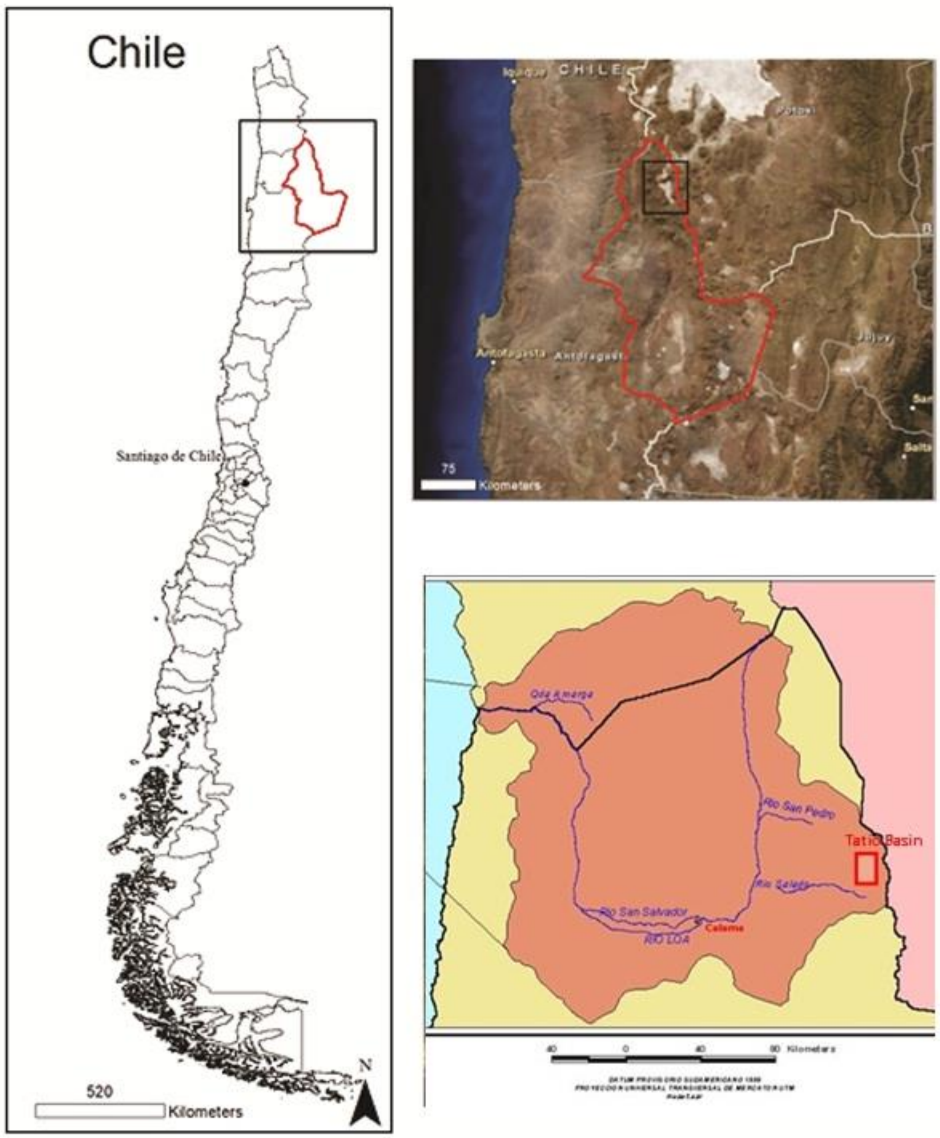


Figure 4: Map of Tatio and Calama basins, Loa Province, Chile with regional and local inset satellite image (modified from Markovich, 2012; DGA, 2003).

For these small communities, the economic importance of this tourist resource cannot be understated. Atacameño communities are amongst most socially disadvantaged in Chile. Most of the communities of local and indigenous people that live near El Tatio are isolated from major population centers and social services. Because of its extreme isolation, many of these localities lack basic services and only recently has road access to the towns been improved and regularly maintained. The continued growth of the tourism industry has created new opportunities for employment and has seen the area of San Pedro de Atacama grow at a steady rate for the past two decades, making it Chile's second most visited tourist area (SERNATUR, 2011). In 2006, shortly before the beginning of renewed energy development in El Tatio, these local communities organized themselves under a jointly sponsored project the "Tatio Mallku" tourist complex. This project formalized the ownership and operation rights of the indigenous groups and planned an investment of $82 million Chilean pesos to construct infrastructure and tourist facilities (Guajardo, 2006).

Scientific Interest and Value

In addition to these economic and social concerns, El Tatio is also of great scientific interest. The springs are home to unique microorganisms that are able to survive in the extreme temperatures, arsenic levels, elevation, and intense UV radiation present in the geyser field. These conditions and these organisms are thought to be analogues for early life on earth before the full formation of the atmosphere. Geochemical and geomicrobiological studies of El Tatio are responsible for much of what is known about the field's composition and life-cycle and have been ongoing before the most recent period of geothermal exploration.

Results of geomicrobiological studies confirm that the high altitude and low latitude of El Tatio makes UV radiation levels very high, and the shallow, saline waters makes it a good analog system to the Precambrian environment. Approximately 2.5 million years ago, oxygen-producing photosynthesis began, and oxygen levels in the atmosphere increased. The microorganisms that produced this oxygen had to survive very high levels of UV radiation, since the ozone layer did not yet exist (Phoenix et. al, 2006). Scientific investigations at El Tatio have provided new insights into potential survival strategies that cyanobacteria (photosynthetic bacteria) and other microorganisms evolved to survive in early earth conditions. For example, organisms at El Tatio precipitate silica to create a coating that may protect them from damaging UV radiation. The extreme conditions at El Tatio provide a rare opportunity for scientists to study conditions that may provide insight into the formation and survival strategies of early life on Earth.

Economic Interests

However, from a national perspective, entrenched extractive mining interests in El Tatio have largely overshadowed the economic importance of tourism growth and scientific merits for the region. Due to a confluence of ideal geological factors, the II region is home to some of the largest copper, gold, and lithium mines in the world. This industry is both the primary economic activity in the region and the largest consumer of energy and water. From the perspective of this important industry, geyser fields like El Tatio and other potential sources of energy and water are highly valued, with little regard for impact on indigenous populations. Most notably, the delicate playa lake basins—known as salars—have been heavily impacted by water withdrawals for mining activities (Markovich, 2012).

Global demand is driving the mining industry in northern Chile to expand with an increasing reliance on already unsustainable uses of energy and water in the region. Mining has been present in the region since pre-Incan times (Salazar, 2010) and the industry is tightly enmeshed with the national Chilean identity. But the relationships between Atacameño communities and the mining industry have been strained due to the environmental--particularly water resource related--impacts of mining (Larrain and Schaeffer 2010). In recent times, tensions over these resources have been exacerbated by the need to develop reliable energy generation to support mining. Contemporary events, such as the “Water War” of Bolivia in 2000 and the “Gas War” of northern Chile in 2004 are concrete examples of tensions among industrial, government, and indigenous entities in the Altiplano zones of South America. These have resulted in active conflict and resistance to water and energy infrastructure development (Orihuela and Thorp, 2012).

In the case of copper mining, this is a clear example of how the benefits of economic development are experienced at a national scale while the impacts are focused at the local and regional levels, particularly in cases with energy-water tradeoffs (See Scott et al., 2011). In the II region’s extreme water scarcity and energy insufficiency have created concern for the security of long-term water and energy supplies (Lloyd 1976, Figueroa et al. 1996, Madaleno and Gurovich 2007). This struggle has played itself out over many decades, with the perception among local communities that this development is inevitable, even if unwanted, due to industry’s strong relationship with the government.

Geothermal Development

The story of renewed geothermal development in El Tatio has its roots in the large structural changes in the Chilean economy and energy sector. Figure 5 shows the growth for various energy resources in Chile, highlighting the surge in imported natural gas in the late 1990’s, from Argentina and Bolivia that created a strong shift in the power industry towards natural gas fired power plants (CNE, 2008; Figueroa and Smith 2002). While this proved to be a temporary boon for the energy-hungry growing Chilean economy, it laid the groundwork for future conflict. Beginning in 2004 with the internal

“Gas War” in Bolivia, natural gas imports became increasingly unreliable. Adding to this tension is the fact that Chile is a signatory of the Kyoto protocol, and the rapid carbonization of its energy matrix through additions of coal and natural gas power plants has created a strong incentive to seek additional power from renewable sources. Recent legislation has set a national goal of increasing renewable energy generation from 5% of the current energy matrix in 2012 to 15% by 2020 (ACERA, 2013).

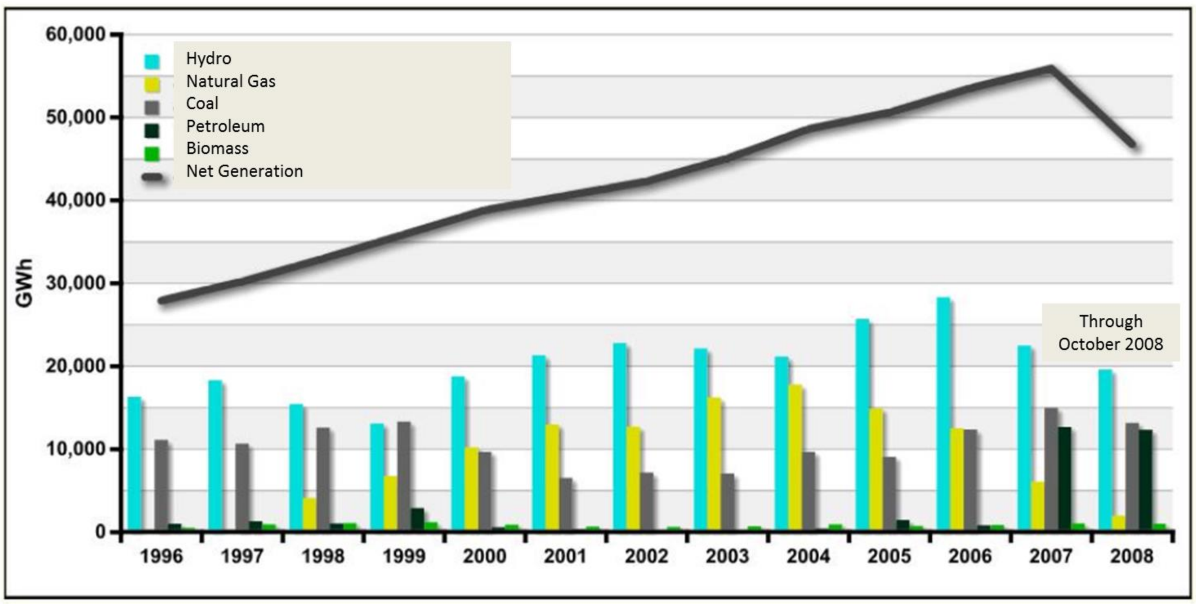


Figure 5: Net electricity generation for Chile’s two primary power grids—the SIC and the SING—by fuel source (modified from CNE, 2008)

El Tatio was first explored for geothermal power production in 1969 through a government supported project from the Chilean Government’s Production Development Corporation (CORFO). Between 1969 and 1974, six exploratory wells were drilled to gauge the characteristics of the reservoir. Further studies concluded that El Tatio could support a power plant with a capacity of between 15-30 MWe (Lahsen, Sepulveda, et. al, 2005; Glennon, 2003). In 1975, an unsuccessful steam-driven desalination pilot project was attempted in the middle of the geyser field, but was ultimately abandoned. These wells and equipment were essentially untouched for nearly 30 years before any further action for development was undertaken. This delay was largely due to economics—despite offering a world-class geothermal resource, El Tatio is extremely isolated with the distance from potential customers creating prohibitive issues for power transmission. Moreover, power plant and reservoir management technologies that have since made geothermal much more efficient were not yet available.

In 2000, after nearly a decade of being passed through the legislature, Law 19.657 governing geothermal exploration and exploitation permits was passed by the Chilean legislature. This action was largely a formality and between 2000 and 2003 only 12 exploration concessions were awarded (Vasquez, 2004). In 2004, the structure of the leasing process was further clarified in a ministerial decree from the Ministry of Mines, which established evaluation and bureaucratic procedures for assigning leases. The system of lease assignation is similar to a conventional auction for hydrocarbon resources, with open bidding on selected blocks—which has drawn criticism about risks of speculation (Saldivia, 2011).

This regulatory process has been further complicated by a rapidly shifting bureaucratic structure. Initially, the National Energy Commission (Comisión Nacional de Energia - CNE) was tasked with oversight of the leasing process. This was then passed to the Ministry of Mines, then finally to the newly formed Ministry of Energy. This shifting regulatory structure was also accompanied by shifts in the management of geological datasets related to geothermal energy, which are independently managed by the Chilean National Geological and Mining Service (SERNAGEOMIN). In addition, efforts to correct oversights in the initial geothermal law have been stalled in the Chilean Congress since 2009, though may be implemented as part of sector wide reform in the future. Geothermal regulation is very much still a work in progress in Chile, as evidenced by the formation of new institutions and legislation that is specific to geothermal development for the first time.

In 2005, a consortium composed of two state owned companies—the national oil company ENAP and the national copper company CODELCO—partnered with the Italian energy giant ENEL to create a joint venture named Geotérmcia del Norte (GDN). In 2006 this joint venture purchased the existing CORFO camp from earlier exploration and also acquired an exploration concession for the fields defined as Tatio II & III. As part of this process, they pledged to in an exploration and drilling program and had made initial plans for a 40 MW power plant, pending results of the exploration.

However, the proximity to the main geyser field presented additional regulatory requirements for GDN. In 2002, El Tatio was named a site of touristic interest, requiring an additional Environmental Impact Assessment (EIA). This initial process is where tensions between the community and GDN began to mount. The approval of the EIA was conducted through the regional environmental agency COREMA, which was responsible for documenting and overseeing the stakeholder engagement and environmental review process.

Almost immediately the proposal was met with opposition from the local community. Many disputed the validity of the EIA and claimed that the process was a rubber-stamp from the government which had a vested interest in the project. While GDN made assurances of safety, and the EIA was ultimately approved, many doubts remained about both the validity of the EIA and the motivations for the project.

The EIA process conducted by COREMA included a standard citizen engagement process, which consisted of six stakeholder workshops held over the span of two months in the affected communities. Exact of these meetings is sparse, but the objections of the indigenous communities and tourist operators to the execution of the project are noted in the final EIA document (GDN, 2008). This final document is an important primary document to understand the difference in valuation of the environmental impacts that exist within the local communities. The EIA is comprehensive in its inventory of the potential impacts of the drilling program on the El Tatio field and proscribes a remediation and impact mitigation plan. This included monitoring of geyser features flow, temperature, and physical characteristics on a daily basis and providing photographic documentation. This documentation was not made publically available or was not communicated in the aftermath of the event.

However the monitoring and concern for the geyser flow and overall system health in the EIA is essentially a bullet point—one of many potential environmental impacts that was studied and approved through an established process within COREMA. As has been discussed in this section, there are many environmental and social impacts to geothermal development, but the valuation of these impacts is highly dependent on local conditions. In the case of El Tatio, the local indigenous communities were so frustrated by the approval of the EIA that they appealed to the Inter-American Human Rights commission for relief, believing that domestic governmental protections had failed (Estrada, 2009). These extra-judicial appeals were not successful and with the receipt and approval EIA, the first phase of GDN's geothermal exploration campaign was slated to begin.

CONCLUSION

This section has described the common-pool nature of geothermal resources and their competing uses. By providing context for the potential environmental impact and economic drivers of geothermal energy development, we hope to provide a framework to understand the events of September 2009. In the three case studies briefly presented here—Yellowstone, New Zealand, and El Tatio—the common theme of perceived impact through hydrothermal features was a key factor in decision making.

However regulatory frameworks in all three countries have under-accounted for the importance of this perception of impact and its ability to dictate policy. In the Yellowstone case, the simple risk of reduced surface features has been a strong enough incentive to halt any development despite the huge potential of the geothermal resource. Similarly, in New Zealand, where actual damage has been done to the long-term health of geothermal systems, it was only when major thermal features began to wane that rapid regulatory action was undertaken.

This gap in regulatory oversight can also be seen when examining the EIA for El Tatio—while surface manifestations are identified as a potential impact, they are understood as one of many potential impacts. This is a fundamental reflection of wide differences in valuation between stakeholder groups. The stakeholder groups with strong economic interests are able to downplay these concerns and are receptive to data that show these impacts to be small. Conversely, local stakeholders are more likely to view these surface impacts as a call to action and a political cause around which to rally to oppose a project for diverse reasons.

Chapter III: The Event and Geochemical Investigation

INTRODUCTION

A pronounced outcry in the Chilean press was the immediate reaction to the loss of well control event at the El Tatio Geyser field in September 2009. Photos of the "artificial" geyser made the front page of newspapers and news reporters came to the region to quickly capture the sights and sounds of the artificial geyser. "El Tatio Muere" (El Tatio Dies) was the title of one widely circulated article lamenting the process that had led to the incident and the potential consequences. As in any crisis situation, public confusion reigned, which was worsened by a lack of communication from the company in charge of the operation, Geotermia del Norte (GDN), ultimately prompting the Minister of Energy to acknowledge that the company was "not up to snuff." (Santiago Times, 2009)

The damaged well was ultimately repaired and capped, ending the outflow of steam after nearly a month of uncontrolled discharge. By the time the well was finally brought under control an independent investigation had been commissioned by the Chilean government. The project was suspended, and the reputation of geothermal as an alternative energy resource was badly damaged. But what were the measureable impacts to the geyser field and the environment?

This section examines the perceived and measured impacts to El Tatio resulting from the loss of well control. A key document in this analysis is the findings of the independent expert report conducted by the United Nations Development Program (UNDP) regarding the impact of the event. As these documents have not been published on in English, the results and an overview of the loss of well control incident are presented here. In addition to summarizing these findings, this section presents new data and analyses that were conducted on the geothermal features of El Tatio. These new data were taken on field visits to El Tatio both before and after the "blowout" event.

GEOLOGY AND CONTEXT

The El Tatio Geothermal Field (ETGF) is situated within the physiographic province of the Cordillera de Los Andes (or Andean Mountain Belt) shown in Figure 6. The geyser complex is located within the larger altiplano volcanic region of northern Chile at approximate latitude of -68.0168 and longitude of -22.3372 (Y. Hauser, 1997). The high altitude, approximately 4,250 meters above sea level, and relatively high temperatures at the geysers, between 78-86 °C create an extreme environment (Lahsen, 1970). In addition, ETGF is one of the largest reported geyser fields in the world with approximate 67 documented geyser features (and potentially many more, unreported) with a total estimated area of 30km2 (Glennon and Pfaff, 2003; Jones and Renaut, 1997).

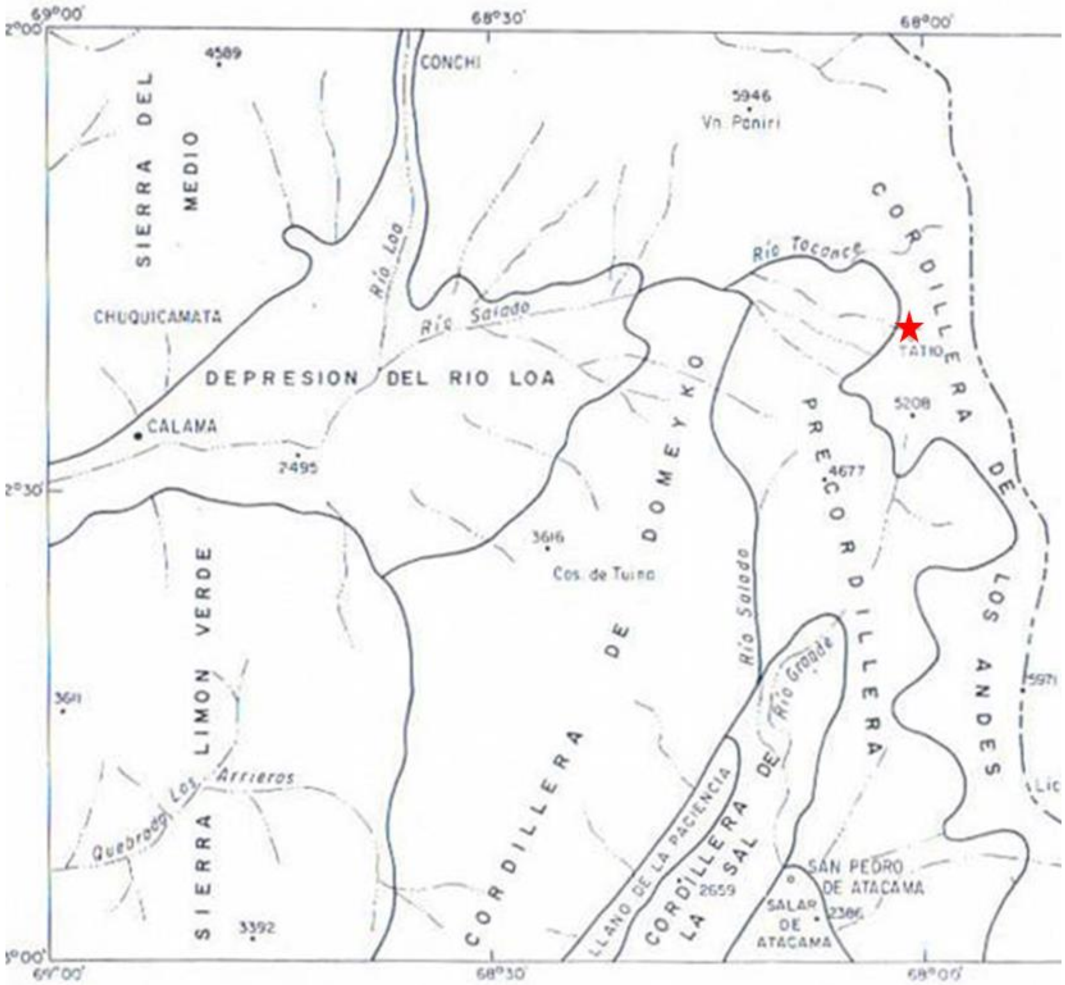


Figure 6: Physiographic Provinces of the Second Region, Chile (modified from Marinovic and Lahsen, 1984)

At the same time, the geyser basin discharges and contributes to the Rio Loa Depression making it an important water resource for the downstream agricultural activities. El Tatio and El Loa (or Calama) hydrologic basins are located within the greater Antofagasta region. Administratively the Second Region of Chile provides the governance structure for the area. While surface water and groundwater flows from high altitude precipitation and eventually recharge the Loa River, which is a major river basin within the country that provides a significant portion of the water demanded by industries, as well as potable water for the more than 400,000 inhabitants of the region (M. Salazar, C. et al, 2003).

The Cordillera de Los Andes (The Cordillera) is made up of a north-south trending series of volcanic cones with intermontane basins that constitute the altiplano (or high plains of Chile) (Marinovic and Lahsen, 1984). The Cordillera is characterized by Cenozoic volcanics with Cretaceous and Tertiary intrusives. The Tatio geyser complex is located within a graben that is part of a larger regional system of normal faults (Marinovic and Lahsen, 1984).

The downgradient Rio Loa Depression is covered primarily by sedimentary sequences of Miocene and Pliocene age, overlain in some locations by unconsolidated Quaternary age sediments (Marinovic and Lahsen, 1984). The arid climate limits recharge from seasonal precipitation largely to the upper elevations of the Cordillera (M. Salazar, C., 2003). Surface water occurrences within the Tatio Basin are generally limited to a 10 km2 area subject to superficial thermal activity. The central portion of the basin demonstrates anomalous resistivities of less than 10 Ohm/m (Marinovic and Lahsen, 1984). Additionally, surface water temperatures at the geyser expressions are generally greater than 70 °C and do not tend to exceed the 86°C boiling point for the altitude, yet geothermal exploration conducted in the mid-1970's demonstrated that subsurface temperatures ranged between 160°C and 265 °C (Lahsen, 1988).

CHRONOLOGY OF THE INCIDENT

The UNDP report provides a comprehensive overview of the causes of the release of steam. However it is only available in Spanish and through a formal information request from the Chilean government (UNDP, 2010). This section is intended to summarize the UNDP findings and provide context for the statements and analysis provided in the report regarding the environmental impact of the release of steam.

The primary well involved in the incident was the existing well named ET-10, one of the six original wells drilled in the late 1970's. The incident included a network of wells connected through a piping system (ET-7, ET-10, and DT-1 shown in the general location in Figure 7, the prefix is inconsistent between data sources, but well numbering is consistent). As part of a testing procedure for the newly drilled DT-1 well, GDN personnel were conducting a flow test whereby steam from DT-1 was being routed through a piping system to the nearby ET-7 well, as depicted in Figure 8.

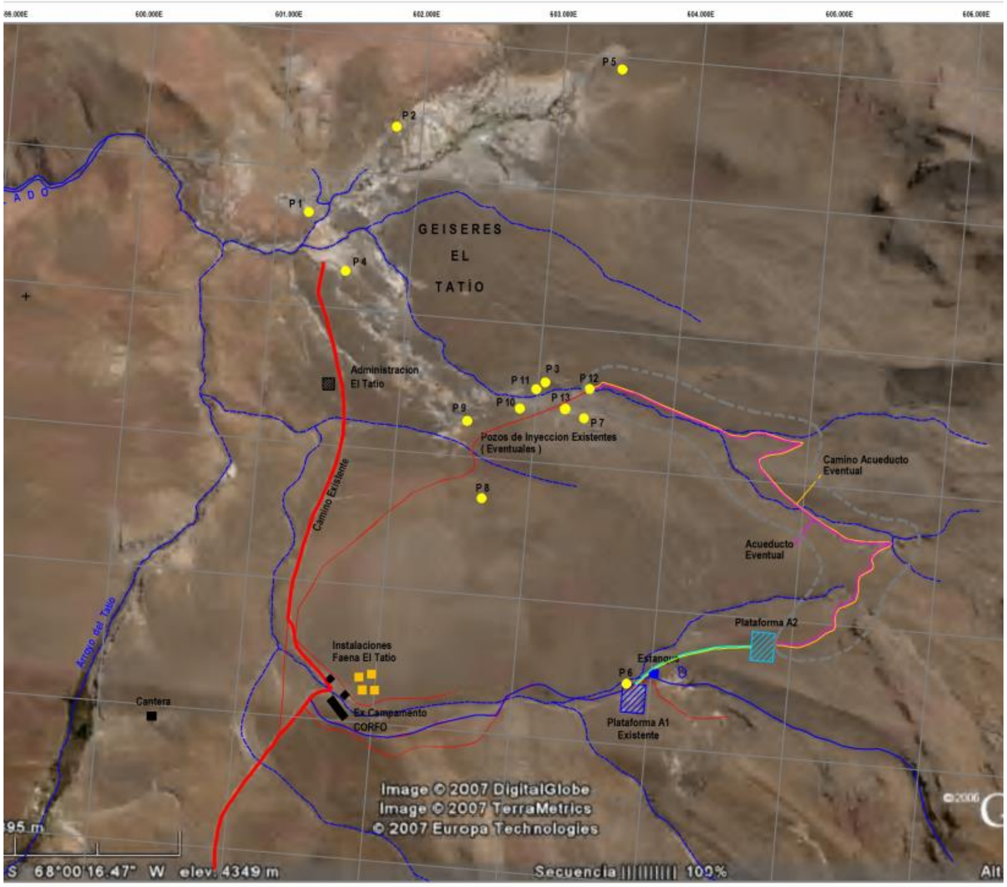


Figure 7: Location of original CORFO wells and road access to El Tatio (GDN, 2008)

Well ET-7 was monitored with a pressure meter which showed a vacuum, indicating that the well was completely absorbing all fluids being directed to it from DT-1. The piping system joining ET-7 to DT-1 also joined to ET-10. ET-10, which was drilled to a depth of 1000m, was assumed to have the same characteristics as ET-7, as both were classified as reinjection wells. ET-10 was isolated from the DT-1/ET-7 system via an isolation valve.

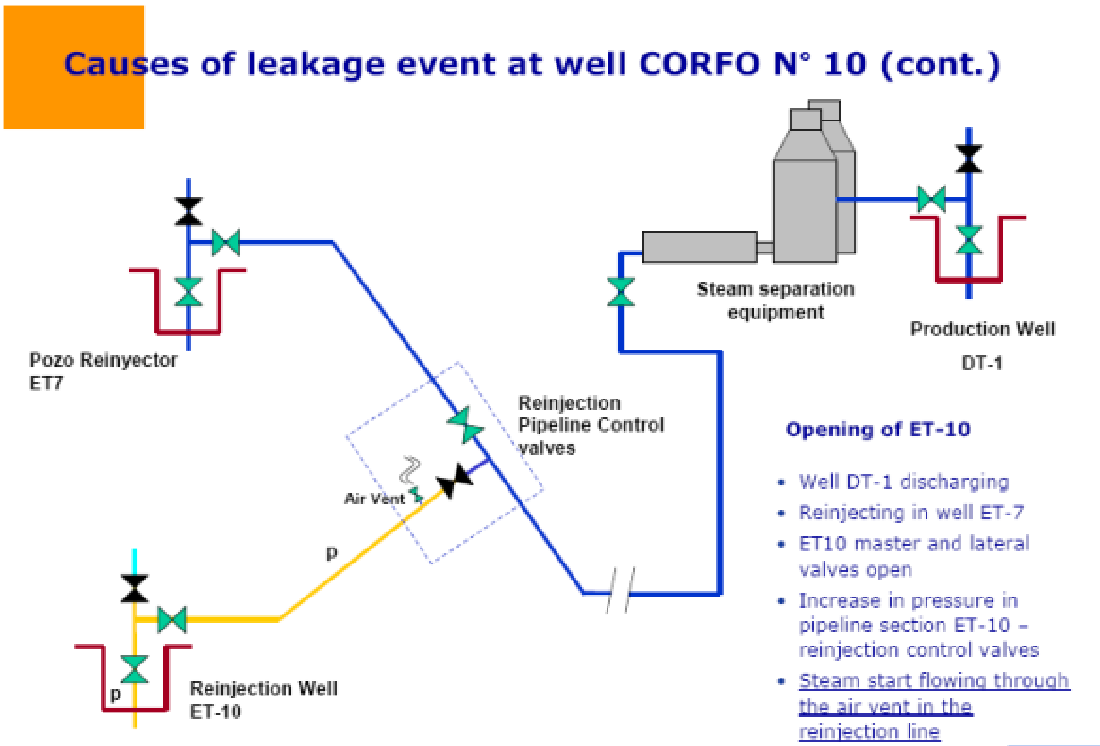


Figure 8: Schematic of flow testing system in place prior to loss of well control, (UNDP, 2009)

During the flow-testing procedure, the decision was made by GDN personnel to connect ET-10 to the system in order to distribute the fluid from DT-1 between ET-10 and ET-7. Upon opening the isolation valve to ET-10, steam rapidly flooded into the system from ET-10. This abrupt imbalance in hydrostatic pressure and temperatures caused a chain reaction through the reinjection system, causing the tubing to rapidly expand and crack in multiple places. The most severe damage was sustained by the wellhead of ET-10, which was the only movable piece of the system, as it was violently pushed laterally, resulting in a rupture.

At this point, GDN was unable to control the output from the newly live ET-10, which continued to release steam through the reinjection system air vents and the ruptured wellhead. In order to mitigate further damage to the infrastructure, GDN made the decision to fully open the wellhead of ET-10 to the atmosphere causing the highly visible 60m geyser. This sequence of events set the stage for subsequent social responses and policy decisions, which were completed without the benefit of a clear chronological description or adequate measurements regarding the actual state of the geothermal system.

MEASURING GEOTHERMAL SYSTEM RESPONSE POST-INCIDENT

This investigation collected information and data about both the geothermal system response and the human organizational system response. The following section presents results of field data collection and analysis from the timeframe immediately after well control and depressurization at well ET-10 had been achieved.

Due to the absence of any permanent monitoring system in the El Tatio field, much of the evidence provided about impacts has been anecdotal and no persistent monitoring program has been implemented since the event. The investigations completed for this study were completed in the same timeframe as the independent UNDP report and investigates the impact of the uncontrolled release of steam on the thermal and geochemical balance of major thermal features in the field. During the Environmental Impact Assessment (EIA) and immediately following the incident, GDN provided monitoring of the surface impacts of the drilling activities, but this did not include extensive analysis of stream flows or thermal feature activity. Moreover, this data would not be verifiable from an independent source. Fortunately, antecedent data from researchers at The University of Texas at Austin was available for comparison (e.g. Dunckel et al, 2009; Phoenix et al, 2006; Landrum et al, 2009).

Given the sudden nature of the uncontrolled release of steam and limited access to measure and sample the artificial geyser, a rapid method for acquiring thermal data over a large area was required. Thermal balance is an important indicator of the dynamic state of any geothermal system. Two field visits were completed in October and December of 2009 by investigators from The University of Texas at Austin immediately following the uncontrolled blowout event. The aim was to use antecedent FLIR data, that was collected for the El Tatio basin by a student research in 2008 for a comparative approach with conditions after the 2009 event to measure system behavior and potential impacts.

FLIR imagery and interpretation was selected as the preferred methodology. FLIR thermal imagery is an established technique for observing and estimating thermal budgets and eruptive activity in volcanoes (Spampinato, et al. 2011). Aerial thermal imaging has also been used in hydrothermal systems, primarily to identify thermal features for exploration or geothermal power project management (Einarsson and Kristinsson, 2010). However, to our knowledge FLIR imagery has not been employed as a rapid-response technology to measure changes.

Indications of basin conditions from the 2008 and 2009 FLIR datasets were compared with indications from geochemical datasets from 2006-2009, also collected by researchers from The University of Texas at Austin, to validate trend analysis and compare response indicators (Malin et al, 2011). Initial results indicate that there have been no significant long-term changes in thermal flux for the basin and assessment of short-term impacts remains inconclusive (Pierce et al, 2012). Without a continuous monitoring program, empirical assessment of impacts was not possible in the 2009 event. Results of this analysis support the use and value in further refining real-time FLIR monitoring to approximate conditions and corroborate the conclusions of the UNDP report.

FLIR imagery was acquired using a FLIR ThermaCam 660. Images were acquired from the northern end of the field of the upper geyser basin and the middle geyser basin. Each panorama image encompasses an area of approximately 1km2. FLIR data was analyzed for significant fluctuations in detected wavelength using analysis sequences conducted on micro-scale FLIR results from 2008, as shown in Figure 9 (Dunckel et al. 2009.) Basin scale images from 2009 were then compared to similar basin scale images from 2008.

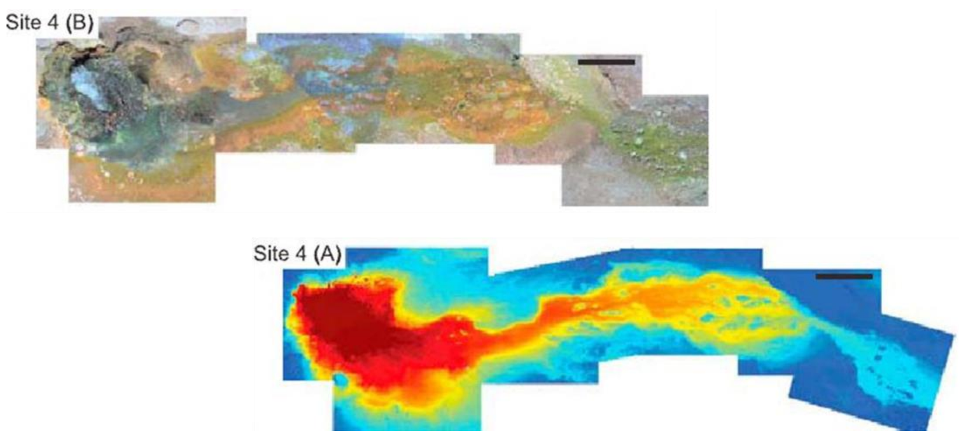


Figure 9: Detailed FLIR images showing microbial mat thermal activity (Dunckel et al. 2009)

In addition to the FLIR data, water quality data was collected for comparison with prior samples to assess indications of aquifer response to the discharge event. Geochemical water samples were collected at four major springs within the middle basin, as well as major spring and geyser features within the upper and lower basins (See Figure 10). One sample was also collected from a spring feature located in group M-III, a group of hydrothermal features closest to the damaged well. These samples were analyzed for cation, anion, and trace metals, as well as total carbon and dissolved gases including H2, O2, and CH4. Trace metals and cations were measured using Inductively Coupled Plasma Mass spectrometry (ICP-MS). Anions were measured using High Performance Liquid Chromatography (HPLC). Gas chromatography was performed on the water samples to calculate dissolved volume of gases.

Geochemical analyses had been performed over multiple years during focused field campaigns from 2002 through 2009 at the same sample sites, and geochemical data from measured features were compared with results from data gathered from the same springs in December 2006, March 2008, and/or June 2009. Arsenic, a toxic metalloid occurring in very high concentrations in El Tatio, as well as chloride were selected as key indicators of geochemical changes compared to the prior data.

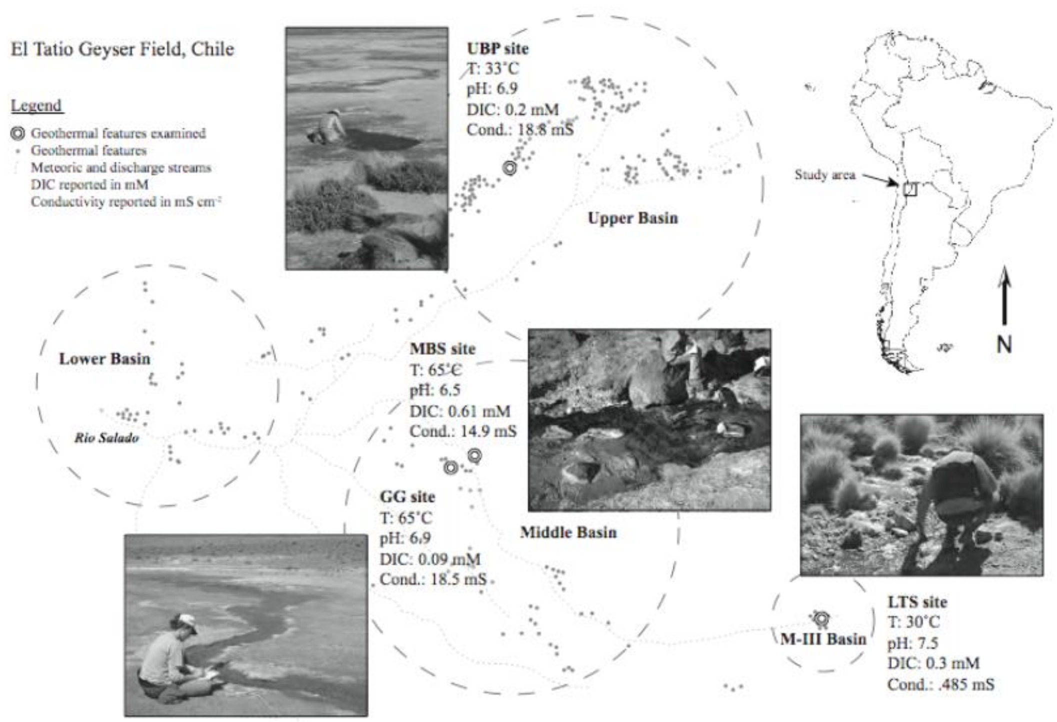


Figure 10: Map of locations of springs and geochemical sampling sites, modified from Franks, (2012)

RESULTS

The images obtained via the FLIR camera indicate a steady thermal output from El Tatio's major hydrothermal features. Images taken over a span of 2 field visits in 2009 yielded virtually identical results and correlate with imagery from the data prior to 2008. Figure 11 illustrates the limitations of the FLIR camera. Field complications prevented extended calibration and repeated measurements with the FLIR camera. Therefore images like Figure 11 are useful for comparing temperatures of features within a photograph, and between photographs, but thermister measurements must be used to calibrate this data to absolute temperatures. This aspect of the investigation was largely constrained to the realm of feasibility testing, because without this calibration quantitative analysis of these images was not possible.

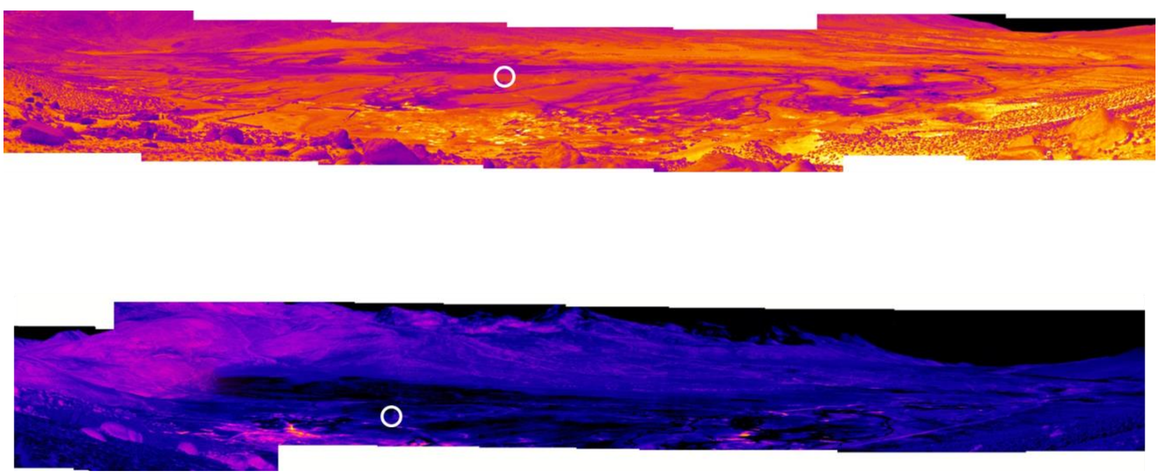
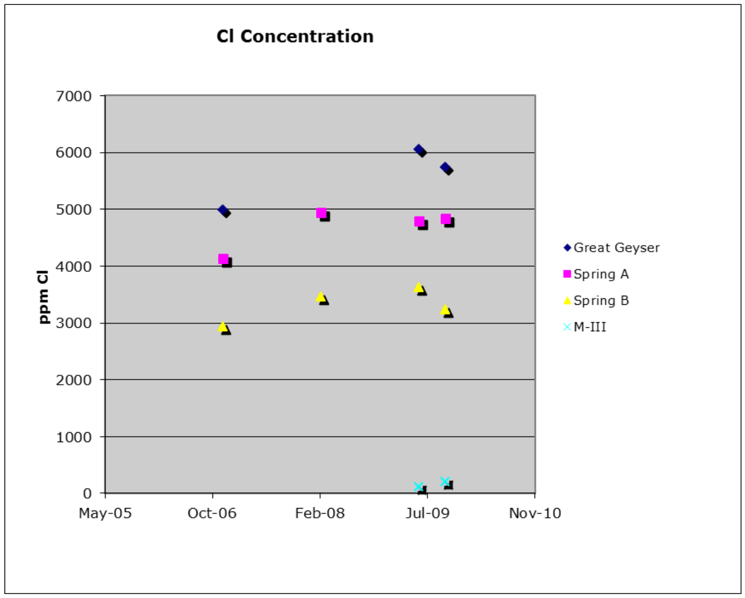


Figure 11: FLIR panorama of the upper field of El Tatio from two different angles, white circle indicates a fixed location, courtesy Anne Dunckel.

FLIR images from 2008 are very similar to those taken in 2010, which corroborates the results obtained from geochemical analyses showing slight variations in geochemistry that cannot be correlated directly to geothermal exploration. The charts in

Figure 12 illustrates the relative geochemical stability of the hydrothermal system, with no significant fluctuation in cations, anions, or trace elements.



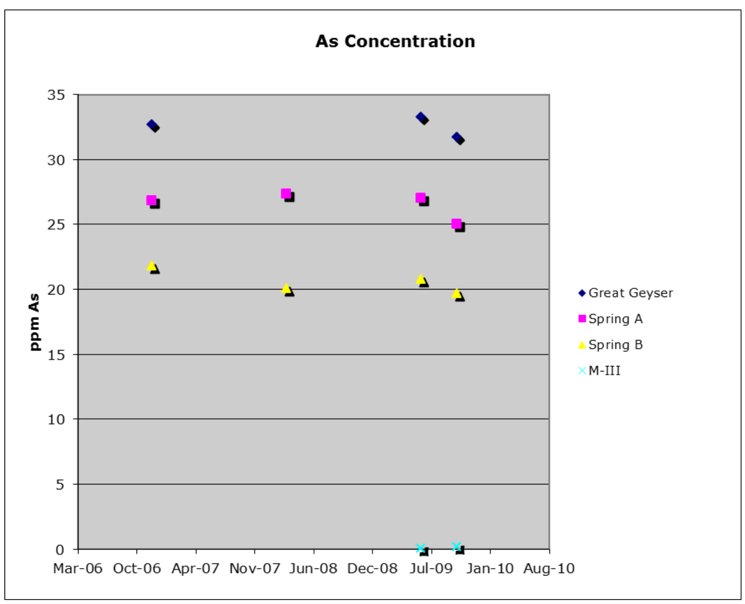


Figure 12: Arsenic (As) and chloride (Cl) concentrations (in ppm) for the four major features examined.

With the exception of the feature in group M-3, located nearest the artificial geyser the time series data indicate no significant fluctuations between the key periods of July and October 2009. These results indicate that the physical system response, as assessed using FLIR and geochemical datasets, recovered and stabilized relatively quickly.

CONCLUSION

The continuity of geochemical and FLIR results corroborate the findings of the official report by the United Nations Development Program's panel of experts (UNDP, 2010). The recharge cycle for El Tatio has been estimated to be 15-17 years (Lahsen and Trujillo, 1976) and the volume of water available from the recharge zone is likely orders of magnitude larger than the output of the geyser field, even with the uncontrolled release of steam (for over 30 days) from the damaged well (Malin et al, 2011; UNDP, 2010). Given these parameters, it is unsurprising that this study's independent analysis does not support claims for major shifts in thermal flux. The correlation of geochemical data adds an additional level of confidence to this conclusion.

The use of FLIR imaging as rapid response to crisis events, such as well control incidents in geothermal fields, presents a useful methodology and tools for inquiry and assessment. This investigation was conducted with a rapid-response philosophy, with limited antecedent FLIR data. As such, the results obtained from the FLIR imagery are preliminary indicators that are best assessed in conjunction with additional parameters such as the flow rate of steam, geophysical data, and in situ reservoir measurements, where these data are available

We anticipate FLIR methodology will be essential in determining anthropogenic and environmental impacts on hydrothermal features in the future. Future work in the development of robust methodologies for basin-scale assessment of geothermal flux using the FLIR camera and establishing a set of measured baseline conditions can provide improved understanding of system behavior and offer valuable information to aide long-term management, or protection, of the geothermal basin. Continued collection of geothermal data with the FLIR will also contribute vital knowledge for assessing potential for impacts related to either geothermal exploration or development on geyser fields.

Independent analysis of both publically available and new data on the El Tatio geothermal field supports the finding that the system rebounded rapidly from the blowout incident and no irreversible damages were incurred. While the long-term impacts of further development of El Tatio cannot be forecast based on the loss-of-control incident, the environmental and geological impact of the incident was likely negligible.

Chapter IV: Results of Interviews and Valuation Decision Support

INTRODUCTION

From a policy perspective the incident highlighted many shortcomings in current geothermal regulations and the need for more attention to oversight of well management practices. However from the larger perspective of common-pool resource management the official conclusion of the incident also leaves much to be desired. In order to move beyond reactionary measures and seek better outcomes, this study sought to test new methods for engaging stakeholders in substantive dialogue that can identify differences in valuation and how individuals and communities engage in dialogue around these issues. Building on previous work by Pierce, 2006, in the emerging field of Integrated Water Resources Management (IWRM), this chapter provides an overview of elicitive interviews conducted with stakeholders in Chile's II region in 2012. Much of this work was initially published in the Journal of Contemporary Water Research & Education (see Pierce et al., 2012).

MOTIVATION FOR INTERVIEWS

Available sources of freshwater and energy are critical to human and economic development. Frequently the benefits of economic development are experienced at that macroscale while the impacts are focused at the local and regional levels, particularly in cases with energy-water tradeoffs (Scott et al. 2011). Global development and population growth are spurring demand for base resources, such as copper and other metals, which requires secure stable sources of water and energy. In the Atacama Desert of northern Chile, regions of extreme water scarcity are also experiencing intense economic growth from mining, causing concern for the security of long-term water and energy supplies in that region (Lloyd 1976; Figueroa et al. 1996; Madaleno and Gurovich 2007).

Sustainability describes the rates of use for a resource that are considered appropriate for the current generation's benefit offset by preserving the viability of that same resource for future generations (Bruntland Commission, 1987). Global demand is driving the mining industry in northern Chile to expand with an increasing reliance on already unsustainable uses of energy and water in the region. Mining has been present in the region since pre-Incan times (Salazar, 2010) and the industry is tightly enmeshed with the national Chilean identity. Yet relationships between regional indigenous communities and the mining industry have been strained due to the environmental--particularly water resource related--impacts of mining (Larrain and Schaeffer, 2010). In recent times, tensions over these resources have been exacerbated by the need to develop reliable energy generation to support mining. Contemporary events, such as the aforementioned 'Water War' of Bolivia have impacted attitudes among industrial, government, and indigenous entities in the Altiplano zones of South America. These have resulted in active conflict and resistance to water and energy infrastructure development (Orihuela and Thorp, 2012).

Science can contribute to the topic of water and energy resource allocation by providing information about the workings of these IWRM systems and creating tools to quantify impacts or beneficial aspects of development. Yet, tools alone cannot deliver adequate decision support for the complex, ill-structured, and dynamic problems. To address the needs for application of science and planning, decision makers and community stakeholders need both computational tools or models and soft systems methodologies to support dialogue and deliberative processes to assist with the design, presentation and evaluation of water management alternatives.

This chapter presents a methodological framework to link decision-analysis tools with a sustained and facilitated dialogue process in order to establish the basis for transforming relationships across stakeholder groups and enable systematic evaluation of resource management and development alternatives. The decision pathways framework (Pierce, 2008) presented in Figure 12 shows the process flow between scientific data analysis, economic valuation, and policy development procedures. Dialogue processes are especially useful during the "Identification" stage, while deliberative process is well suited to "Evaluation & Choice Routines" as shown in Figure 12.

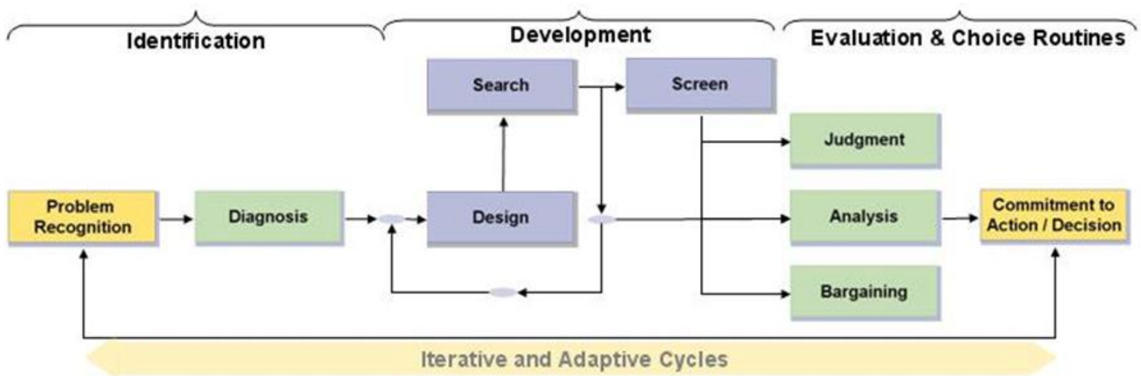


Figure 12: Decision Pathway framework identifies common decision making stages (from Pierce, 2008; modified from Mintzberg et al., 1976).

There are deep seated conflicts and interdependencies in many water and energy resource cases. Disputes can be compounded by social and political misunderstandings among the various interest groups in a basin, as well as misconceptions about the meaning of scientific models about how water resources interact and respond to management actions within a basin. The need to identify tough decisions and necessary tradeoffs makes it difficult to gain clarity on both the system behavior and interest group concerns that are critical to identifying possible solutions within a reasonable timeframe.

The overarching motivation for this work is to develop replicable IWRM approaches for this and other systems. These approaches should be capable of improving links between water resource problems and community concerns so that science-based information can be communicated in ways that are both meaningful and accurate. Research focuses actively on the use of Sustained Dialogue in the El Tatio case study to bridge the diagnosis phase of a problem from naming and framing the problem and analysis of cross-communication among different stakeholder groups.

IMPACTS

The 2009 incident in El Tatio created localized impacts to the environment, perceived health risks due to arsenic precipitates from the release, and concerns regarding the relative impacts to basin fluxes due to depressurization of the geothermal complex. Impacts from shifts in the geochemical, hydrological, and thermal fluxes in the basin may result in negative impacts for a range of industries and interests for use of the basin, such as geothermal energy development and international tourism.

The socioeconomic demands for the region can be generally divided into the categories described in the following categories.

Geothermal Development

As has been discussed earlier in this study, geothermal development of the Tatio geyser complex has been considered by Chilean government agencies since the mid-1960's. Early estimates of thermal energy production for three exploratory geothermal wells were capable of producing 18Mw of power (Marinovic and Lahsen, 1984) and reportedly 10 L/s of freshwater could be produced from each MW of potential power in the basin (Lahsen, 1988). Today, the Second Region has developed several power sources, including coal powered and natural gas imported from Argentina, but neither is secure and can suffer from international conflicts or transport issues. As the region's population continues to grow a safe, secure, efficient power source is desirable for continued economic success mostly rooted in mining activities.

Most recently geothermal exploration and development throughout Chile has become a focal point for conflict with indigenous communities along the Andes. Similar conflicts are emerging throughout the region, particularly in the altiplano regions of Chile and Bolivia (Orihuela and Thorp, 2012).

Agricultural Production

An estimated 1,503 hectares were under production within the Loa basin in 2002 with primary crops of alfalfa and carrots. Between both surface water and groundwater rights, approximately 5,861 L/s are used on average annually (DGA, 2003). Unfortunately, severe economic restrictions are placed on all agricultural goods produced in the region due to the high levels of arsenic in irrigation waters. Improved water quality discharge from the Tatio basin could have far reaching economic implications for the agricultural industry in the region if produce could be marketed outside the Second Region.

Mining Industry

The mining industry is recognized as the largest water resource demand component in the Second Region, yet the water ministry reports that it does not have complete information regarding the total water usage for mines in the area. Mining stands to benefit from geothermal development due to decreased energy costs for production, but the industry must also consider potential as yet undetermined benefits from conserving the geyser complex from international tourism, scientific discoveries in the extreme environment, or other sectors. The benefits of energy costs are directly quantifiable, but the unknown value of future research discoveries that can only be developed if the primary geyser site is preserved are difficult to predict.

Tourism Industry

The international tourism industry is thriving in the Second Region with the Tatio Geyser field providing one of the most enticing sites for destination travelers. In order to retain the current tourist industry that has developed in the San Pedro de Atacama area and is now expanding into other altiplano towns, such as Chiu Chiu, Toconce, and Caspana, the geyser field must be conserved in the future. This will be a strong offset to the economic drivers urging geothermal development.

Local / Regional / International Industries

Small enterprises, support industries for the larger mining sector, and international import/export activities in the Second Region are driven by the availability of both energy and water. Therefore geothermal development paired with water treatment could potentially result is positive benefits for most organizations within this category. Local indigenous cottage industries, such as an existing Ayquina Goat Cheese Factory, could be expected to increase with improved water resources. Regionally, a decrease in energy costs might encourage entrepreneurial investment and the existing port facilities in Antofagasta could also see increased business if the existing mine operations augmented production.

METHODS

This research develops an integrated approach to link science-based information to local knowledge for sense-making stages after a surprise event. Methods begin with elicitive interviews across stakeholder groups using open-ended elicitation and previously successful narrative analysis approaches (Pierce et al. in press) followed by focus group interactions based on sustained dialogue techniques (Saunders, 2011). Decisions about how to protect and/or use the Tatio geyser field will pit a myriad of interests (economic, environmental, scientific, cultural) against another. The conflict has intensified because of recent events creating conditions to observe how different stakeholder groups name and frame their concerns and understanding about potential consequences for the resource.

INITIAL INTERVIEWS

Initial socio-technical research for this case began with interviews conducted after the geothermal incident. These interviews were conducted with representatives from municipal governments, environmental interests, energy development, tourism industry, national government ministries, local pueblo community members, research scientists, and tourists about the perceived impact of the event and the impacts of future development on tourism and the local economy. Two field visits were completed in October and December of 2009 immediately following the uncontrolled release from the 4500m deep exploration well.

Interview results were used to collect preliminary data on how stakeholders perceive vulnerability and frame the possible consequences and solutions for the management of El Tatio. Stakeholder perceptions of the event were then compared with results of direct measurements of the hydraulic and thermal balance of El Tatio in October and December 2009. Post-event recovery measurements provided a scientific basis for evaluating the actual impact to the basin (flow, temperature, chemistry, heat flux) and interviews captured perceptions (varying from catastrophic impact to no impact across stakeholders).

Qualitative data was collected using open-ended elicitation with a set of participants from interested parties. Preliminary data were evaluated using Value-Focused-Thinking Techniques (Keeny 1992), sustained dialogue stages (Saunders 2011), and combined evaluation of collective sense-making (Weick et al. 2005) to describe possible science-based uncertainties that are integral to the dialogue surrounding long-term management and decision making for managing the geothermal basin. Results from interviews were captured with either handwritten notes and/or capturing comments using word processing tools on a portable laptop computer. Human subject involvement began October 26, 2009 and participants were asked to self-identify with an interest group category and then selected for inclusion or exclusion using the following criteria:

- Knowledgeable about the situation and/or geothermal basin,
- Willing to participate and give verbal consent,
- Available at the time of the field study and/or willing to participate via teleconference after the field visit is complete, and
- A member of one of the interest groups named above and/or another group with an interest in management of the geothermal basin.

Open-ended elicitation interviews lasted between 20 minutes to 1 hour depending on the length of participant responses to questions. Interview results supported the research design for a follow-on group dialogue forum as described in the next section. Questions during non-structured elicitation using open-ended questions related to:

- Historic connection with the geothermal basin,
- Perceived level of vulnerability in the basin to use and/or management options

- Description of primary concerns or objectives for resource management
- Description of primary controls for management
- Description of possible best and worst case outcomes or consequences for the basin
- Identification of the highest perceived values to society from the basin
- Perception of the impacts specifically related to the September 21, 2009 well release incident

SUSTAINED DIALOGUE AND GROUP FORUM WITH INDIGENOUS STAKEHOLDERS

Values that consider non-market aspects of resource problems, such as environmental and long-term sustainability (or intergenerational equity) values and economic forces associated with a problem are difficult to measure. Initial interview processes provide insight into the key concerns, objectives, and social constraints for any resource problem, but moving from identification to transformation of group dynamics is a challenging process. Sustained Dialogue is a descriptive framework that recognizes the phases that every group goes through to resolve a conflictive issues and it also sets out a set of principles and tenets that mediators or facilitators can use to inform group engagement (Saunders 2011; Stewart and Saunders 2009).

Sustained Dialogue formed through decades-long processes of conflict resolution conflict negotiation teams working on behalf of the US Department of State to broker peace in many of the most volatile situations around the world. Although readers are referred to publications by Saunders (2011) for more detailed information on this complex process, key elements include five general stages (shown in Table 1) that reflect the topics that groups need to address during any conflict resolution process. The discussion is not a linear process. In fact it is iterative, but any group seeking to achieve resolution must address each of the five stages.

The case described in this study is in the Stage I and II framing and early problem identification stages of dialogue. One tenet that Sustained Dialogue practitioners are urged to follow, is disallowing the group to discuss alternatives or solutions until they have addressed the first stages of any problem. These early stages are also the starting point to bridge science and society knowledge, because Stages I and II provide sound problem diagnosis for a scientist interested in constructing an IWRM model.

Table 1: Stages of Sustained Dialogue process with Stages I and II highlighted and showing primary concerns addressed in these stages of a process (Saunders and Stewart, 2009)

Stage I	**Stage II**	**Stage III**	**Stage IV**	**Stage V**
- Define - Who - Engage	- Identity - Interests - Power - Misperceptions - Interaction	- I to We - Alternatives	- Collaborate - Transform the Problem - ID Actions	- Communicate - Implement

INTERVIEW RESULTS

The results reported in this research present initial steps for creating a long-term engagement strategy with a community group. Initial problem formulation and fact-finding were completed through individual interviews across stakeholder groups. The results of interviews informed the design of a participatory process to engage with a target stakeholder interest group, in this case the indigenous community members of northern Chile. These initial steps provide early problem formulation and social learning opportunities in the broader process of decision support to long-term IWRM in the Second Region. As the process continues, additional stakeholder groups will be engaged and dialogue processes are expected to continue. The following sections discuss specific results of early engagement processes.

Results of the stakeholder interviews demonstrated several important considerations about the perceptions of scientific knowledge and conditions in the El Tatio and El Loa basins. This section focuses on perceptions reported by indigenous community members and government agency representatives, because analysis indicated that the greatest levels of misunderstanding and miscommunication exist between these two groups.

Results of interviews with indigenous community members highlighted their perception of severe impacts to the El Tatio basin during the and after the geothermal blowout event, which is directly at odds with results of scientific measurements after the event (Malin et al. 2011). Core concerns raised by indigenous community members demonstrated that they are firmly locked in the Stage I aspects of a Sustained Dialogue that represents a sense of direct threat to identity and power imbalances with all other sectors in the region.

In relation to scientific information participants reported that they see science as a ‘weapon’ that can be used against them locally, while international scientists are viewed as allies to help the group advocate for their case. Importantly, the indigenous community members indicate that they reject all government authority over environmental, water, or energy resources in the region. This is significant because these same community members led a protest march against government control of El Tatio that led to a moratorium on new leases for geothermal exploration in the country, through Senate action, several months.

Government representatives reported perceptions that are directly connected to Stage II aspects of Sustained Dialogue demonstrating that they feel they are in a top-down environment with control over activities and events in the El Tatio basin. Participants in this stakeholder category indicated that they needed more hydrologic information to make sound decisions and that from more technical information they would be able to craft a limited communication plan and control outcomes for El Tatio. This planned change perspective is at odds with the indigenous community's rejection of government authority.

Notably, the physical measurements and comparisons using forward looking infrared, geochemical, and flow datasets indicate that the El Tatio system recovered rapidly from the exploration incident in 2009 (Malin et al., 2011) and this corroborates the findings of the official report by the United Nations Development Program's panel of experts (UNDP, 2010).

These results provided important information to guide the next elements of the research so that sustained dialogue sessions could be initiated to bridge between science, policy, and communities. Because the indigenous group is squarely situated in Stage I phase, the research team decided to initiate a group dialogue using the Sustained Dialogue techniques to initiate and inform an early framing and problem diagnosis process and open opportunities to bridge a dialogue process with government representatives in the future.

FORUM RESULTS

The initial group dialogue session was hosted as a "Seminario Cientifico-Etnico" (Ethnic Science Seminar) with 19 participants from four northern regions in Chile over the course of 12-hours. See Figure 13 for a photo of participants during the forum, illustrating the seminar style setting.

The process combined narrative and deliberative approaches to generate substantive discussions among participants. Scientific participants provided brief capacity building lectures about available information sources for water data through the Chilean government, GIS and mapping resources, and the macroscopic context of water resources in the north of Chile.

Figure 13. Photo of sustained dialogue participants during January 2013 Seminario Cientifico-Etnico.

At the conclusion of the meeting, participants defined three initiatives to: 1) create an indigenous management environmental and water resource monitoring network, 2) develop a science-based training program for indigenous tour guides using water topics initially, and 3) explore potential for an indigenous-led alternative energy cooperative. Each of these initiatives is underway since the culmination of the group forum. Some important constraints were placed on topics by the participants, who refused to discuss geothermal energy and only allowed presentation of water resource information, which may indicate that water is an entry point for dialogue on more divisive topics for this region. Additionally the group agreed to clear actions in relation to the three initiatives and also requested a future seminar to discuss geothermal energy and groundwater.

The group forum supports scientists with an improved understanding of the level of knowledge about water resources in the region and the primary concerns of the indigenous community members. This new understanding can support the development of educational materials for future interactions and inform development of decision support models for IWRM efforts.

Conclusion

Truly sustainable water and energy resource management will not optimize a single indicator to define a long-term management regime. Rather, IWRM that takes into account the various biophysical, hydrologic, environmental, economic, cultural and legal factors can be expected to generate the most appropriate strategies for all parties concerned. Energy and groundwater management is a significant, complex real-world challenge that requires thoughtful consideration of scientific and social aspects before selecting a recommended course of action.

This study presents a replicable process for the early stages of decision problem formulation that may provide an avenue for addressing the areas identified by English (1999) and improve communication with regard to water resource conflicts, as demonstrated El Tatio geyser complex. At the same time community conflicts that involve complex systems with critical scientific information, are unlikely to be resolved without clarity in the naming and framing of issues to be addressed during a dialogic or deliberative process.

Chapter V: Decision Support Tools for Participatory Processes and Conclusions

The final chapter of this study briefly details efforts to design and implement socio-technical systems based on the findings derived from traditional geoscience and social science methods. This chapter presents the development of two socio-technical tools that are designed to improve the use of scientific information to inform decisions through participatory approaches. These tools include 1) a pilot cyberinfrastructure for data collection and accessibility and 2) a multi-touch decision support application. These two methodologies were trialed in the field in Chile and evaluated for both their practicality and their ability to support sustained dialogue processes.

Both tools are presented primarily for documentation purposes, as the development of these tools is still ongoing. The purpose of these projects was to conduct initial tests of their efficacy in decision support systems for aiding and creating sustained dialogue. The scope and initial activities are detailed her, concluding with a summary of initial findings and recommendations for future work.

Proposed Cyberinfrastructure

In response to the blowout incident at the El Tatio Geyser Field a rapid pilot project to integrate geoscientific and social science data was launched. The flowchart in Figure 14 illustrates the structure of the proposed system and provides the basis for the discussion that follows. A cyberinfrastruture can be defined as a federated set of digital tools for acquiring, organizing, interpreting, and sharing scientific information. Usually, this takes the form of a server-based solution with a common set of protocols for communicating data between devices in the field, laboratory, classroom, or community center.

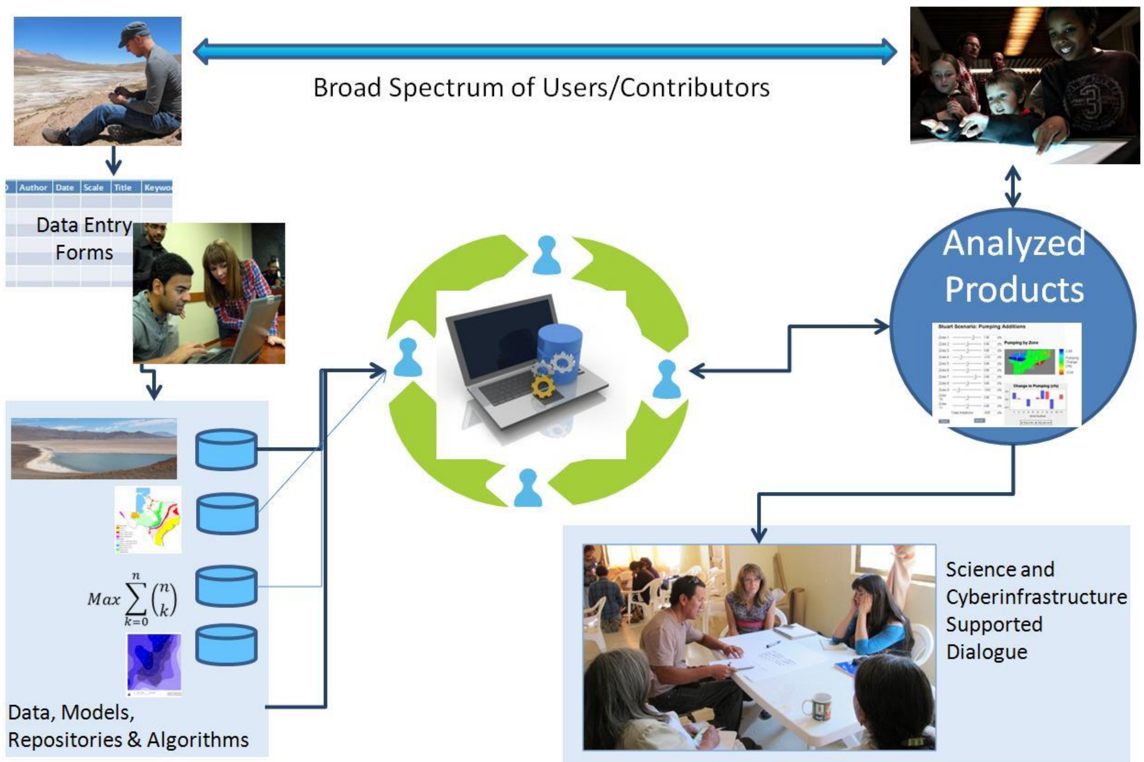


Figure 14: Conceptual schema of the ENCOMPASS project cyberinfrastructure system.

The pilot cyberinfrastructure—called the ENCOMPASS project—was designed to collect and present geoscientific information to support decision making processes by leveraging participatory tools. Essentially ENCOMPASS aims to engage both experts and the general public in the collection and interpretation of scientific data. For El Tatio, this system was proposed to be used to proactively share information, collect data, and provide community outreach. The pilot project called for basic parameters such as pH, spring temperature, geochemical content, and FLIR imagery to be collected in the field then combined using the cyberinfrastructure in order to conduct an ongoing assessment of the health and status of the geyser field. In El Tatio, the cyberinfrastructure system could provide immediate access for community members and decision makers, while also supporting rapid response during and immediately after an accident or unexpected event. The cyberinfrastructure includes the creation of a unified, multi-faceted mechanism for engaging communities with scientific information about physical systems before an urgent event occurs.

After the 2009 incident, the incomplete sharing of information resulted in negative outcomes for all parties—researchers, government, local communities, and developers. The pilot cyberinfrastucture project sought to bridge this gap by allowing collection of scientific datasets by hydrologists, geomicrobiologists, and economists and indigenous community members. To aid the collection of data in the field and rapid upload to shorten time between collection and reporting, the ENCOMPASS cyberinfrastructure was designed for use of handheld devices, or ruggedized digital field notebooks (handhelds) that enable flexible data collection with intuitive software and hardware. Figure 15 shows handheld equipment in use at the El Tatio field site in 2011. ENCOMPASS is designed to deliver of educational and visualization modules that inform sustained dialogue while also providing access to data for scientists and government representatives through a secure client. Over time, cyberinfrastructure platforms also improve potential for integration as a component of science research missions.

The ENCOMPASS platform was built from a preexisting groundwater modeling system or GWDSS (See Pierce, 2006). The GWDSS provided the basic data repository setup and loosely federated algorithm and modeling components. The pilot implementation for ENCOMPASS integrated the earlier GWDSS codebase into an open source enterprise portal, specifically the Liferay™ portal to moderate user access and social components of the system. This modeling and data portal was linked to a set of handheld dataloggers that were programmed to accept a variety of geochemical and geological data. These handhelds were designed and programmed to be flexible and could also be used to collect social science survey data. Most importantly, the devices are user friendly and can be used by students, community members, government agencies, or research scientists.

Figure 15: The author using a handheld digital field notebook in the upper El Tatio geyser field

Because the cyberinfrastructure application was envisioned as a supporting platform to streamline rapid data collection and capabilities for importing it into intuitive models, the handhelds were selected to automate the collection and upload processes. Using the handhelds, stakeholders and scientists can collect data in the field then directly upload to the cyberinfrastructure portal. The handhelds allowed us the flexibility needed to collect survey data and record geoscientific data in the field, while also digitizing and pre-formatting the data.

RESULTS

The cyberinfrastructure handhelds were used on three trips to northern Chile for data collection and stakeholder interviews. Digital forms were created, utilized and synched with GPS in order to create maps to document the impact of geothermal development on the geothermal field. The handhelds functioned well as a digital field books and enabled creation of georeferenced datasets which included images that were analyzed and processed into usable maps while still in the field. Normally this process requires manual data entry of geochemical data, GPS data, and attaching of photos. All of these elements were captured in a single entry form which was exported to an MS Access database for immediate use and later for upload to the ENCOMPASS platform.[4]

Limited funding and time prevented a full roll-out of handheld devices to the local community, however the initial field tests and use of the handhelds by scientists in the field proved the feasibility of using handheld technology as a primary interface and data collection method for a larger cyberinfrastructure. While the full implementation of such a cyberinfrastructure project was beyond the scope of this study, several key results from the use of the handhelds were identified as milestones for future development of the cyberinfrastructure projects.

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[4] Full documentation of the handhelds, software, and database structure is available on the project wiki: https://wikis.utexas.edu/display/dfii/Home

KEY FINDINGS FROM HANDHELD AND CYBERINFRASTRUCTURE TESTING

1. *Proprietary operating systems and code greatly restrict both the usability and appeal of digital systems*

   Users in the field in Chile and in other groups within The University of Texas at Austin reported that restrictions due to the Windows Mobile software platform on the ruggedized handhelds greatly reduced the usability of the devices. Users had a strong preference for open source based.

2. *Continuity of application and use must be very clearly outlined from project inception*

   Users of cyberinfrastructure portals can easily be overwhelmed by the quantity and diversity of applications possible in such a system. In the initial phases of application of the ENCOMPASS project to the El Tatio event, the scope for applicable services and data management within the system was in a state of flux. This lack of clarity undermined development and implementation of new capabilities. Both users and creators of these types of systems must be aware of their great potential. In addition, but the users and creators must be willing to commit significant time and resources to managing and interacting with the cyberinfrastructure system in order to realize the potential.

MULTI-TOUCH APPLICATIONS FOR DIALOGUE SUPPORT

The final application of the findings of this study was the creation of a multi-touch application to be used to support sustained dialogue among stakeholders. To do this a team effort was undertaken and used data for a field site in Idaho, while the site is not in Chile the application and use of data can be transferred to other sites. The research and activities related to the Snake River Plain case were focused on developing a multi-touch application to meet the recognized needs for tools to support science-based dialogue that emerged from the El Tatio case study.

From March to August of 2012 a team of four students participated in the annual Department of Energy (DOE) sponsored National Student Geothermal Competition. The 2012 competition focused on the Snake River Plain (SRP) in Southern Idaho. While there is a single commercially operational geothermal power plant on the southwestern periphery of the SRP, the central and eastern areas of the plain remain undeveloped. The stated goal of the competition was to investigate geothermal resources in the SRP, however the final application was also designed to be used globally and with any dataset.

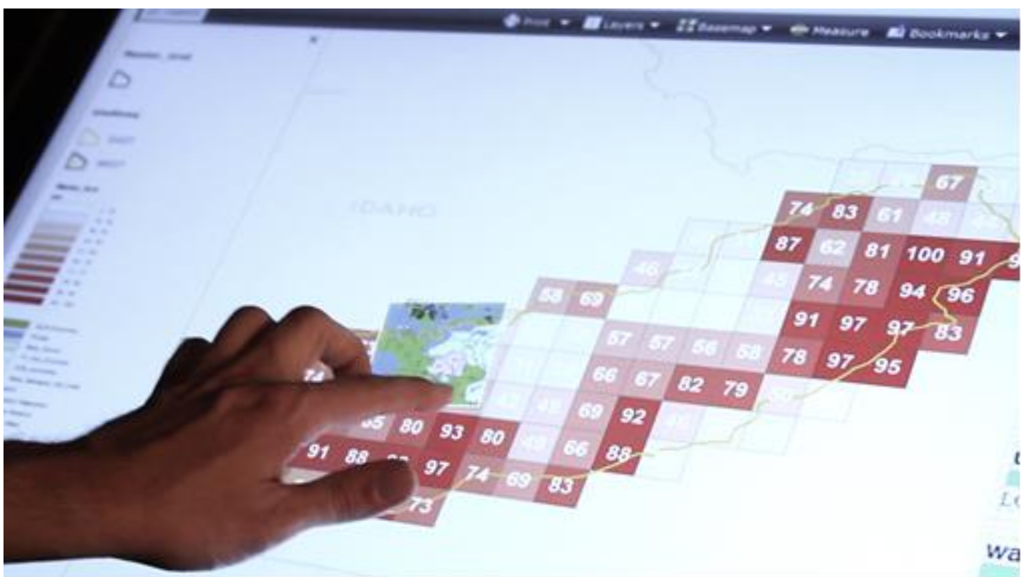

Figure 16: The multi-touch application displaying the results of a geothermal exploration model

For the case of the SRP exploration, tool the team examined how a traditional geothermal exploration campaign mitigates development risk by gathering geological, geochemical, and geophysical data about a potential site. In doing so, field surveys and technical geothermal system characterizations will ideally reduce the risk of costly drilling and maximize the chance of finding a useful geothermal resource through creation of more robust geological and geophysical models (Malin et. al, 2012).

However, this traditional model assumes that geologic information can be accurately assessed and does not consider other non-geologic factors that also have substantial impact on project siting decisions. Geographic suitability, land use restrictions, proximity to existing infrastructure, and other economic and physical characteristics have a significant impact on a project's viability. In the case of the SRP—due to its relatively unexplored nature and uncertain geologic characteristics—developers will need to begin evaluating a project from a broad, multi-attribute view to address these additional risk factors.

This multi-attribute model is useful for refining areas of interest and also addresses an often overlooked component of geothermal development: stakeholder engagement. Because geothermal energy continues to be a relatively boutique and less-understood form of renewable energy, developers often face upfront challenges in securing financing and explaining project constraints. The decision model is designed to be interactive and intuitive—equally useful for explaining to investors decisions about target areas for exploration and for presenting geoscientific data to geothermal experts.

The model uses an intuitive ranking system, whereby a set a predetermined variables can be dynamically weighted and reweighted to produce a final "favorability score" for grid cells on the map, illustrated in Figure 16. This map is displayed on a large multi-touch interface, which allows users to interact with and iteratively update the map and save scenarios for exploration and development. GIS based favorability analysis for geothermal development has been conducted in geothermal areas worldwide (See Noorollahi et. al 2007, Yousefi et. al. 2007, and Einarsson and Hauksdóttir, 2010) and is an evolving field for geothermal development. The application was designed to allow stakeholders to dynamically update their preferences and interact with data in a hands-on environment.

The primary advantage of a multi-attribute decision support tool comes from its ability to reflect and rapidly update user preferences. The elicative interviews revealed that certain variables are of greater importance to certain stakeholders—a multi-attribute decision model allows these users to update these preferences in an iterative sequence. For example, a government agency reviewing its land leasing policies may be primarily interested in land ownership status, whereas a developer may be more concerned with proximity to electric transmission infrastructure. Both stakeholders can use the model to analyze geological and geothermal potential and can also modify it to reflect their unique favorability preferences.

The ultimate goal would be to apply this multi-touch application tool to a situation like the development of geothermal in El Tatio. Figure 17 shows the initial testing with the indigenous community members in Chile from the seminario etnico-cientifico held in October 2012. That pilot use with indigenous community members demonstrated that gesture-enabled, or multi-touch, applications are effective natural user interfaces. Both prior to development or during a crisis event, like the one witnessed in 2009, decision support tools that allow users to directly interact with data are of great value for supporting sustained dialogue. This importance of accessibility to scientific data and interpretation—reducing the perception that science is only a "weapon"—was a key outcome of the elicative interviews and seminar conducted in Chile. Next steps in the Chilean case include populating the multi-touch application, that was initially created with SRP data, with information and data from Chilean sites for testing and use in a co-design process that will convene the scientists, indigenous community, geothermal energy industry, and mining industry representatives.

Figure 17. Initial testing of multi-touch and natural user interface with the indigenous community members in Chile from the Seminario Etnico-Cientifico held in October 2012.

CONCLUSIONS – KEY LESSONS FROM EL TATIO

The El Tatio case study demonstrates need for improved links between scientific information and decision makers. The case exemplifies common relational dynamics and the role of scientific information common to resource issues. The overarching motivation for this work is to develop replicable tools and sociotechnical approaches for addressing conflicts that arise out of the exploitation of energy and earth resource systems. These approaches should be capable of improving links between common-pool resource problems and community concerns so that science-based information can be communicated in ways that are accurate, meaningful, and useful.

From a policy perspective the El Tatio incident highlighted the many shortcomings in current geothermal regulations in Chile and the need for more attention to oversight of well management practices. Yet the policy implications and insights related to event response and the limited role that scientific information played in the communication with communities, media, and decision makers provides insights into broader patterns in scientific communication. Important lessons can be gleaned from the El Tatio experience to inform engagement practices and policy process. In addition, scientists, industries, and communities can gather new understanding and appreciation of the need and mechanisms for communication that is substantive and effective for creating mutual understanding. Ultimately, this study has attempted bridge the many disciplines, approaches, and stakeholder interests related to the issue of common-pool resource management.

Lesson # 1 – The data collection and accessibility imperative

Beyond the EIA phase of the geothermal drilling project, geoscientific data was not included in the decision making process about the development future of El Tatio. In part, decisions related to the El Tatio case could not be based on data or scientific observations for the specific site because data either did not exist or it was inaccessible.

A tenet of decision support is the need to assure access to sound data or information about the problem. As this study has highlighted, the availability of verified scientific data related to El Tatio needs to be addressed to better support dialogue about the unavoidable energy and water development decisions for residents of the II region.

Lession #2 – Assure scientific data relevancy

In the response to loss of well control incident, the UNDP report only included a short assessment of the geothermal system's health and the environmental impacts of the man-made geyser. The final assessment of the company's conduct and official sanctions were focused largely on well operations and the neglect of best-practices by the operator. The process and reports largely ignored the perceptions and preferences of stakeholders, both at the community and policy levels. Technical or scientific information should be communicated such that it is connected, or relevant, to stakeholder concerns.

FUTURE CHALLENGES

Using El Tatio as a case study, this study has taken a multi-disciplinary approach to creating solutions for confronting the "wicked" problems of common-pool resource management. The methods identified here—contingent valuation, decision support systems, and sustained dialogue—are presented as tools that can be used by stakeholders to find common ground and seek mutually beneficial outcomes. In addition, these tools can help with the critical issue of social perception of scientific data and science driven solutions to these problems. This study posits that the path forward is to ensure not only that scientific data is communicated in modes appropriate to the community and problem at hand, but that the acquisition and interpretation of this data is informed by stakeholder needs.

The proliferation of cyberinfrastructure tools is promising for the future of decision support systems; however developers of these tools should be conscious of needs beyond expert in an academic and laboratory environments. The tools described here were primarily trialed in this environment and had limited success and exposure to the general public and to stakeholder groups. In order for these tools to help reinforce the perception that science is being brought to bear in an efficient and effective way, they will need to move beyond the realm of scientific consortiums and into the mainstream.

As was stated at the beginning of this study, all methods used here are based on the fundamental assumption that good governance exists when socially efficient management of common-pool resources is attained and when there is a social perception that this is the case; these two conditions are necessary for short and long run governance. In the case of El Tatio, neither objective was obtained. Chile as a nation—and the residents of the II region in particular—continue to struggle with energy and water security.

Future studies will need to find ways to rapidly apply these methods in Chile to begin to affect change. It may be too late to strongly influence the ongoing protests and acrimony over the impacts of current projects like HidroAysen, but the laying the groundwork through proactive outreach to stakeholders will be important to avert future conflicts. Incidents like the El Tatio blowout are inevitable in the world's collective energy future. How well stakeholders are equipped to respond—and whether or not they can leverage science to seek efficient solutions and resolutions to these conflicts—will be the key factor determining the outcome.

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