PAST AND PRESENT HYDROGEOLOGY OF THE ATACAMA DESERT, NORTHERN CHILE: HUMAN AND NATURAL SYSTEM INTERACTIONS

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This work focuses on the past and present hydrogeology of northern Chile from 19ºS to 23ºS and on the research processes itself.

Chapter 2 is a study of the landscape evolution and paleohydrology of the northern portion of the Chilean forearc basin. During the Late Miocene and Early Pliocene, before the forearc basin was deeply incised, a lake existed in the western part of the forearc basin. New $^{40}Ar/^{39}Ar$ ages of volcanic ashes intercalated with lake and overlying fluvial deposits indicate that lacustrine deposition had begun by 10.86 ± 0.04 Ma, and the final stage of canyon incision occurred after 3.04 ± 0.03 Ma. The existence of a large, deep lake is consistent with, but not conclusive evidence for, a wetter than modern climate in the catchment region during the Late Miocene.

Chapter 3 presents an interdisciplinary hydro-economic aquifer model. This single-cell model incorporates groundwater outflows such as flow to rivers, wetlands and springs, that depend on the water table elevation. These outflows are modeled as providing economic, social and environmental benefits. The model is applied to a case history of groundwater extraction in the Ojos de San Pedro region.

Chapter 4 is a case study of a cross-disciplinary, intercultural research team that studied a water resource system in northern Chile. Such teams are necessary to solve many complex problems including how to manage scarce water resources. This study focuses on the interaction between cross-disciplinary diversity and cultural diversity during group integration. Results showed that translation served as a facilitator to cross-disciplinary integration of the research team. Cross-disciplinary barriers were found to be more difficult to overcome than intercultural barriers.

Chapter 5 presents a steady-state numerical groundwater model developed and calibrated using USGS MODFLOW-2005 based on subsurface geological and hydrological information, stream gauging data, and human water use. This model encompassed the Loa River topographic basin and part of the Altiplano Plateau. Model results indicate that groundwater flow to the region's rivers has likely decreased by ~20% due to human groundwater extraction. Hypothetical lower aquifer pumping scenarios produced reductions in simulated groundwater flow to the rivers and head drawdowns.

BIOGRAPHICAL SKETCH

Naomi E. Kirk-Lawlor, daughter of A. Theodate Lawlor and Robert E. Kirk, was raised in central Maine and attended Orono High School. In 2005 she completed her undergraduate education at Amherst College in Amherst, Massachusetts with a B.A. in Geology and Spanish. After college, she worked as a Wilderness Ranger for the U.S. Forest Service in the Wallowa-Whitman National Forest, as a geologist for a geotechnical engineering firm in Portland, Oregon, and as a naturalist for the Appalachian Mountain Club in the White Mountains of New Hampshire. In 2008, she married fellow Maine native, Ryan P. Gordon, and began her graduate studies at Cornell University. In May 2013 their daughter, Willa A. KirkGordon, was born. Naomi now lives with her family in Augusta, Maine.

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TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER 2

CHAPTER 3

CHAPTER 4

CHAPTER 5

LIST OF TABLES

CHAPTER 3

CHAPTER 4

CHAPTER 5

CHAPTER 1

INTRODUCTION

The modern Atacama Desert of northern Chile is the driest desert on earth with recorded rainfall of less than 2 mm/year in its arid core. The topography of northern Chile within the study area, from 19º to 23º south latitude, consists of north-south trending features. In the west a Coastal Cordillera mountain range separates the Pacific Ocean from the Central Depression. East of the Central Depression, the topography rises to the peaks of the Andes volcanic range, which serve as a regional topographic divide. East of the Andes volcanic arc mountains is the high elevation Altiplano Plateau. The climate in the study region has been predominantly hyperarid, with periods of arid and semi-arid climate throughout the past 14 Ma (Jordan et al., 2014). The work presented here focuses on the past and present hydrology and hydrogeology of the western margin of South America and on the interplay between the natural hydrologic system and human water usage.

Chapter 2 focuses on landscape development and lakes that existed in the geologic past (Late Miocene and Early Pliocene, from ~11 Ma to ~6.5 Ma). Chapter 3 presents a conceptual hydroeconomic aquifer management model and a case study of the water resource extraction history of Ojos de San Pedro region in the historic past (~1909 to present). In Chapter 4 the group development processes of a cross-disciplinary, intercultural research group that studied a coupled natural-human hydrologic system in northern Chile are investigated using qualitative research methods. In Chapter 5, a numerical groundwater model of the modern system is developed and used to understand modern groundwater fluxes and make future predictions about the likely outcomes of possible water management decisions. Taken together, the physical science studies presented in this thesis (Chapters 2, 3 and 5) investigate the changing availability of water in this region through time on both geologic and human timescales.

Scarcity of water in northern Chile has varied through time, due to climatic changes (Chapter 2), geomorphologic landscape changes (Chapter 2) and more recently, due to human use (Chapters 3 and 5). The region's aridity has had a profound effect on humans in this region by limiting the locations and amounts of water used for mining, agriculture and municipal use. Water availability is a limiting factor in the economic and population growth of the region. At the same time, the effect of consumptive human water use on the natural hydrologic system has also been profound. The natural and human systems are linked through complex feedback systems that are explored in Chapters 3 and 5. How scientists understand and study the natural system also ends up affecting the hydrology of the system indirectly because the results of scientific research can affect water users' and water managers' decisions. Therefore, researchers themselves are part of this complex hydrologic system. Chapter 4 of this thesis presents a study of a research team focused on the coupled natural-human hydrologic system of the Loa River.

The geology and hydrology of this or any region is extremely complex, with so many components hidden beneath the ground or obscured by time, that truly and completely understanding how it functions is impossible. Therefore, any of our concepts of a natural system are necessarily simplified models, most likely containing some factual errors. In developing these mental models we must decide how much to simplify the known complexity of the system in order to ask and answer the questions that interest us. The physical science studies presented here range on this scale from highly simplified to highly complex. The hydroeconomic conceptual model presented in Chapter 3 is very reductionist, allowing it to be useful across disciplines. It treats an entire aquifer as a simple bucket or bathtub with outflows at different heights. This allows for application of the natural system model to economic questions and for analytical solutions to those questions. The numerical groundwater model presented in Chapter 5 resides at an intermediate position on the simplicity-complexity spectrum. It greatly reduces the known complexity of the groundwater system but still incorporates a conceptual model of the topography, subsurface geometries, river systems and fluxes of groundwater. The paleohydrology and landscape evolution study presented in Chapter 2 incorporates even more complexity both in scale and with the incorporation of time as a studied dimension. This study involves geomorphologic, stratigraphic and sedimentologic methods and includes analyses done on a variety of spatial scales, down to microscopic observation of diatoms.

Since we each use our own simplified models to understand reality, how then do we work together towards a shared understanding of a natural system, or for that matter of any system? Through communication. When we communicate with one another, through academic publishing or in more intimate personal conversations, we attempt to share our individual cognitive models with one another. This is easier to do when we share similarities with our conversation partners and more difficult to accomplish when we are communicating across interpersonal boundaries such as differing disciplines, cultures or languages. All the research projects presented in this thesis attempt to describe a system (natural: Chapter 2, human: Chapter 4, or coupled natural-human: Chapters 3 and 5) by simplifying available information with the goal of communicating these models and conclusions that result from them to others. We call this scientific research.

This process of research is itself studied using qualitative methods in Chapter 4. This chapter presents a study of the research processes within an intercultural, cross-disciplinary research team (of which I was a member) that studied a coupled natural-human hydrologic system in northern Chile. This group process study stemmed directly from the research experiences that led to Chapters 3 and 5 of this thesis. The qualitative research results presented in Chapter 4 offer suggestions on how to make similar future collaborations more fruitful.

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CHAPTER 2

LATE MIOCENE TO EARLY PLIOCENE PALEOHYDROLOGY AND LANDSCAPE EVOLUTION OF NORTHERN CHILE 19°S to 20°S

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Abstract

Northern Chile's forearc lies in the hyperarid Atacama Desert. The northern portion (~150 km) of the forearc basin, known as the Central Depression, contains perennial streams that drain to the Pacific Ocean through canyons that are deeply incised within a pediplain. However, during the Late Miocene and Early Pliocene a lake existed in the western part of the Central Depression between 19.3°S and 19.7°S, indicating a forearc geomorphic landscape and paleohydrologic regime distinct from the present one. For approximately 2 million years, this lake was large (~375 km^2) and deep (up to ~120 m). The catchment area sourcing the lake covered an area of 2,900-5,200 km^2. New ^{40}Ar/^{39}Ar ages of volcanic ashes intercalated with the lake deposits and the overlying fluvial deposits indicate that lacustrine diatomite-rich deposition had begun by 10.86±0.04 Ma, and the final stage of incision of a canyon through the lake deposits is younger than 3.04±0.03 Ma. Additional published age constraints demonstrate that the expanse of the lake shrunk shortly after 9 Ma, yet the water balance in the western sector of the basin permitted lacustrine diatomite deposition until more recently than ~ 6.4 Ma. Even after the sediment-hydrology balance shifted from balanced-fill to overfilled, a near-surface groundwater table led to accumulation of salt pan (salar) evaporites until more recently than ~3.5 Ma. The existence of a large deep lake is consistent with, but not conclusive evidence for, a wetter than modern climate in the catchment region during the Late Miocene. The ultimate demise of the paleolake system is attributed to a kilometer-scale decline of the base level of drainages downstream of the paleolake. This study takes advantage of the unique characteristic of the drainage profiles in the study region, a spatial separation between areas of deep incision east and west of a prominent knickzone, to evaluate three end member scenarios of landscape evolution that could explain the base level fall event(s). The sedimentological, stratigraphic, and geomorphological data best fit

the interpretation that forearc tectonic uplift and tectonically driven coastal retreat both contributed to base level fall.

1. Introduction

The physiography of the central Andes Mountains is the product of millions of years of coupled tectonic and climate processes at work in an active convergent margin. The history of deformation, relief development, and climate of the Central Andes are active areas of research as tectonics, physiography, and surface processes are linked (e.g. Raymo and Ruddiman, 1992; Willett, 1999; Lamb and Davis, 2003; Oncken et al., 2006; Willett et al., 2006; Schlunegger et al., 2010; Ehlers and Poulsen, 2009; Norton and Schlunegger, 2011; Barnes et al., 2012). The formation of the Andes influenced climate through the creation of an orographic moisture barrier (e.g. Houston and Hartley, 2003; Strecker et al., 2007; Insel et al., 2009), while climate affected tectonic processes through the impacts on rates of erosion and denudation, which affect mass balances and stresses (e.g., Beaumont et al., 1992; Masek et al., 1994; Horton, 1999; Norton and Schlunegger, 2011). Rates of subduction and tectonic erosion may also be tied to climate state (Lamb and Davis, 2003).

Northern Chile is geologically renowned, for its Atacama Desert, volcanic arc, kilometer-scale coastal escarpment, Altiplano plateau, reserves of copper, and devastating earthquakes. Here key steps in the historical sequence of tectonic and climate events remain uncertain. Because surface processes are exceptionally slow in the Atacama Desert, and erosion is confined to a small fraction of the landscape surface (Hoke et al., 2004; Kober et al., 2007, 2009; Evenstar et al., 2009), there are exceptionally good opportunities to combine landform history and sedimentary history in a unified analysis of the interplay between tectonics and climate.

This study documents the landscape history and paleohydrology of a ~6000 km^2 region within the Atacama Desert between 19°25’S and 19°50’S. The analysis is based on Upper Miocene and Lower Pliocene lacustrine and salt pan (salar) deposits that occur in the forearc sedimentary basin, and on the geomorphology of canyons which traverse the basin. The facies and landscape evolution of this region illuminate the importance of base level control on the lake history, and demonstrate the ambiguity of extracting a paleoclimate history from a lake system (Carroll and Bohacs, 1999).

2. Background

2.1 Tectonic setting

The northern Chile forearc (18°S to 24°S) displays north-trending parallel topographic features (Figs. 1 and 2B) that reflect the tectonics of the South America – Nazca plate boundary system. The westernmost feature is a locally occurring, narrow marine terrace bounded on the east by a regionally persistent coastal escarpment with ~1000 m of relief. Inland of the escarpment is the Coastal Cordillera (CC), a mountain range 800 m to 2000 m in elevation that marks the western margin of a forearc sedimentary basin, the Central Depression (CD). East of the CD is the gently sloping, concave, low-relief Western Slope (WS), which is bounded to the east by the Western Cordillera volcanic arc of the Andes. Beyond the volcanic arc is the ~4000 m high Altiplano plateau.

Offshore of northern Chile, the Nazca and South American plates intersect at the Peru-Chile trench. The volcanic arc produced by the subduction has migrated ~200 km eastward from its Jurassic position to its present location (Western Cordillera) (Rutland, 1971), leading geologists to infer that the western edge of the continent has been tectonically eroded. As the coastline retreated eastward, exorheic river valleys would have adjusted their longitudinal profiles to the changed gradient.

The uplift history of the Altiplano Plateau and its change in elevation relative to the Andean forearc is known in general (Cembrano et al., 2007) but not yet well resolved in time (e.g. Victor et al., 2004; Farias et al., 2005; Garzione et al., 2006; Jordan et al., 2010). Tectonic relief development has been accommodated by a regional structural monocline between the CD and the volcanic arc (Isacks, 1988; Farias et al., 2005; Hoke et al., 2007; Jordan et al., 2010), which rotated and steepened the WS. Zeilinger et al. (2005) at 18°–19°S, Victor et al. (2004) at 20°–21°S and Farias et al. (2005) at 19°–20°S used structural and stratigraphic observation to reconstruct fault history, concluding that 2–2.5 km of relief development between the Altiplano and forearc basin occurred during the Late Oligocene and Miocene, prior to 7 Ma. Other work using oxygen isotopes and paleobotany as paleoaltimetry proxies has suggested that a greater magnitude of uplift (2.5–3.5 km) of the Altiplano occurred 10–6 Ma (Garzione et al., 2006). Jordan et al. (2010) at 20°–22°S document ~800 m of surface uplift of the Altiplano in relation to the CD between 11 Ma and 5 Ma, and an additional ~400 m of topographic relief development since 5 Ma.

The CC is a topographic barrier that partially contains the forearc basin sediments, but the boundary is diffuse and there is no fault system has been identified that could account for large magnitude Neogene differential uplift between the CC and the CD (Parraguez, 1998; SERNAGEOMIN, 2003; Nester, 2008; Nester and Jordan, 2012). In contrast, the coastal escarpment at the western boundary of the CC is morphologically young, even though no known fault system accounts for the regional-scale topographic scarp. Pliocene internal deformation of the CC activated east-trending reverse faults and north-trending normal faults (Allmendinger et al., 2005.) Consequently, tectonic relief development within the CC, or of the CC relative to the offshore forearc, might have influenced the river valleys that cross the CD and thus might have influenced the paleohydrology of the CD.

2.2 Geomorphology

2.2.1 Regional geomorphology

The modern landscape of the CD and the WS consists primarily of a regionally extensive, low relief surface (slopes <2°; Fig. 2b), or pediplain, which abuts the CC. The pediplain is primarily a depositional surface within the CD and an erosional surface within the WS. The regional depositional-erosional boundary is north-trending and located where the pediplain surface slopes to the west at ~1.2º (Fig. 2B). Within the WS, the pediplain surface contains small scale, largely parallel paleodrainages with a maximum relief of 200 m (Hoke et al., 2004; Evenstar et al., 2009; García et al., 2011). North of 19°40'S, catchments that drain headwater regions at 4500–5500 m in the Western Cordillera and Altiplano feed canyons that incise the pediplain to depths ranging from tens to thousands of meters, and drain to the Pacific Ocean (Hoke et al., 2004; Schlunegger et al., 2006; García et al., 2011). The drainage systems south of that latitude and north of the Loa River (21.5ºS) do not reach the ocean. Those endorheic systems drain into the CD, where their final base level is ~1000 m above sea level.

2.2.2 Local geomorphology

The study area is located at the southern end of the region of deep canyons, bounded on the south by the endohreic Aroma drainage. The major incised drainages are the Tana and Tiliviche canyons, which converge at the eastern boundary of the CC and pass through the CC to reach the Pacific coast (Fig. 1). Compared with average topography, the Tana and Tiliviche canyons are more incised into the WS (600 m) and into the CC (900 m) than they are in the western CD (50–200 m) (Fig. 3).

In the Tana canyon a knickzone of ~1 km relief exists approximately 43 km upstream from the coast (measured along the drainage profile; Fig. 3). This Tana Knickzone is defined as the inflection point of the drainage profile. Within the Tana canyon the knickzone marks the boundary between areas of greater (west) and lesser (east) incision.

West of the confluence of the Tana and Tiliviche canyons, a strath (erosional) terrace at ~950 m elevation on the south canyon wall, sits ~480 m above the canyon floor (Figs. 2 and 3). Farther south, a valley referred to as the Pisagua drainage (Fig. 1) runs from southeast to northwest along the eastern border of the CC. The Pisagua drainage crosses into the CC and joins the Tiliviche/Tana canyon west of the strath terrace, ~7 km upstream from the ocean.

2.3 Current climate and past variations

Three long-term features of the atmosphere, Pacific Ocean, and landmass are the principal controls on hyperaridity in the Atacama Desert: i) the Southeast Pacific Ocean atmospheric high pressure system, ii) the cold Humboldt Current, and iii) the Andean rain shadow (Vuille and Ammann, 1997; Rech et al., 2002; Houston and Hartley, 2003; Vernekar et al., 2003). Precipitation in the study region is highly dependent on elevation, and only areas above 3500 m have a mean precipitation >5 cm/yr (Houston and Hartley, 2003).

The timing of initiation and the subsequent variability of what is today a hyperarid climate are debated (e.g. Hoke et al., 2004; Rech et al., 2006; Placzek et al., 2010; Schlunegger et al., 2010). Supergene enrichment of copper ore, which requires repeated infiltration of water, was active between 30 Ma and 14 Ma; the region experienced greater aridity thereafter (Alpers and Brimhall, 1988; Sillitoe and McKee, 1996; Bouzari and Clark, 2002). On the pediplain 20–30 km south of our study area, four out of twenty exposure ages of desert pavement clasts range from 14.6–14.8 Ma (Evenstar et al., 2009). This exposure age peak suggests that parts of the pediplain did not change thereafter (Evenstar et al., 2009). Similarly, changes in paleosol chemistry led Rech et al. (2006) to conclude that hyperaridity began sometime between 20–9.4 Ma. Furthermore, between approximately 14 Ma and 11 Ma, coarse gravels were transported and deposited widely as well-sorted gravel braid plains in the CD (Schlunegger et al., 2010; García et al., 2011), but ceased at approximately 11 Ma (García et al., 2011). In sum, all these features imply that hyperaridity became the mean condition regionally in the late Middle Miocene, and resulted in the cessation of deposition across the CD (Nester and Jordan, 2012). The abandonment of the depositional surface produced the Atacama Planation Surface (Evenstar et al., 2009) or the El Diablo/Altos de Pica Pediment (Hoke et al., 2007), referred to here simply as the pediplain.

Nevertheless, there is widespread evidence of climate variability from the mean hyperarid state, with related changes in vegetative cover, environmental chemistry, and erosive power of streams (e.g. Saez et al., 1999, 2012; Gaupp et al., 1999; Evenstar et al., 2009). Those second-order climate shifts produced a subtle geomorphic record and a stronger cosmogenic nuclide signal of intermittent reactivation of erosion and deposition on the pediplain. Cosmogenic nuclide exposure dates on pediment clasts that range from 10.1 Ma to 1.3 Ma near 19°40’S ((^{3}He; Evenstar et al., 2009) and that are younger than 6 Ma near 18°30’S (^{10}Be, ^{26}Al, and ^{21}Ne; Kober et al., 2007) reveal that some gravel was transported since hyperaridity began.

2.4 Cenozoic stratigraphic units in the CD near 19.5ºS

The forearc basin fill spans the lowland CD and lower part of the WS (Fig. 4). The Oligocene–Miocene strata onlap both the CC and the WS (Parraguez, 1998; Victor et al., 2004;

Farias et al., 2005), with a lens-shaped cross-sectional form up to ~1200 m thick along the basin axis (Nester and Jordan, 2012). The CC served as a western topographic boundary, at least since first deposition of lacustrine sediments ~19 Ma (Parraguez, 1998; Worner et al., 2000; Pinto et al., 2004). Three regionally extensive units comprise the Oligocene through Pliocene strata of the CD. While stratigraphic nomenclature varies by location, these widespread units are generally mapped as the Azapa, Oxaya, and El Diablo formations, in ascending order (Fig. 4). The lithological distinctions are clear in the eastern and central CD, but as a result of lateral facies changes workers disagree in the western CD regarding the identifications and boundaries between these formations (Schlunegger et al., 2010; García et al., 2011).

The Oligocene to Lower Miocene Azapa Formation overlies a regional, pre-Oligocene, unconformity (Victor et al., 2004; Farias et al., 2005). The Azapa Formation is an alluvial-fluvial deposit composed of red to brown conglomerate and coarse sandstone at its eastern extent, and transitions westward to fine grained, well bedded sandstone (Parraguez, 1998). The Azapa represents either Oligocene deposition (García et al., 2011) or Early Miocene deposition (von Rotz et al., 2005).. The Azapa Formation is thick in the east (García et al. [2011] report a maximum 500 m) and thins to the west (Fig. 5), extending at least to the CC (Nester and Jordan, 2012).

The Lower Miocene Oxaya Formation is rich in ignimbrite and volcaniclastic sediment (Parraguez, 1998; Farias et al., 2005; García and Herail, 2005). Farias et al. (2005) and Parraguez (1998) describe a conformable outcrop relationship between the Azapa Formation and the Oxaya Formation, yet seismic reflection data suggest that this boundary is locally unconformable (Nester and Jordan, 2012). Dating of numerous volcanic horizons demonstrate ages ranging from 20.9±0.7 Ma to 16.3±0.6 Ma Ma (Muñoz and Sepúlveda, 1992; Parraguez, 1998 and references therein), whereas magnetic polarity stratigraphy suggests a narrower range, about 22–20 Ma (von Rotz et al. 2005). Although 1000 m thick in the east near the volcanic centers (García et al., 2011), the Oxaya Formation thins westward and largely pinches out near the study area (Fig. 4). Schlunegger et al. (2010) attribute Oxaya deposition to ephemeral fluvial systems.

The siliciclastic Middle and Upper Miocene El Diablo Formation fines markedly toward the west (Parraguez, 1998). The El Diablo Formation lies unconformably above the Oxaya Formation (Parraguez, 1998; Pinto, 1999); the low relief pediplain of the eastern CD and the WS form its upper surface (Farias et al., 2005) (Fig. 4). Locally in the east the unit reaches 300 m thickness (Pinto et al., 2004), and it thins to the west (Fig. 4). Two members comprise the El Diablo Formation. The lower member is thick and widespread north of the study area (Camarones valley, Fig. 2) (García et al., 2011), where it is composed of sandstone, silicified limestone containing plant fossils, volcanic breccias, and reworked tuffs, interpreted to reveal lacustrine depositional conditions (Parraguez, 1998; García et al., 2011). It onlaps and is interbedded with volcanic facies to the east in the Precordillera (Farias et al., 2005). The upper member contains partially consolidated, dark gray sandstone and sand-supported and cobble-supported conglomerate, deposited by perennial streams (von Rotz et al., 2005; Schlunegger et al., 2010). The proximal facies are coarse, with well rounded clasts ranging from boulders to coarse sand, while distal facies are progressively better sorted, fine grained, and thinly bedded (Parraguez, 1998) (Fig. 4).

The El Diablo Formation is younger than the Oxaya Formation and its proximal sector is older than the 8.3±0.5 Ma (García et al., 2004) overlying Tana Lava. A lava that interfingers with the El Diablo Formation along the eastern margin of the CD indicates that deposition persisted until more recently than 11.7±0.4 Ma (García, 2002; Farias et al., 2005). Overall, the data bracket the end of deposition between 11.7 Ma and 8.3 Ma (García and Herail, 2005).

Traditionally, sandstone, diatomite, and evaporite deposits of the western CD, the focus of this paper, are mapped as part of the El Diablo Formation (Parraguez, 1998; Pinto, 1999; Farias et al., 2005; von Rotz et al., 2005). These poorly consolidated sediments onlap the CC (Fig. 4). Data presented below demonstrate that deposition of these sediments is either contemporaneous with or slightly younger than the youngest proximal facies within the El Diablo Formation.

3. Methods

Field observations of lithologies, sedimentary textures and structures, and stratal architecture of Cenozoic deposits in canyon exposures and in many 2–4 m deep exploration pits for diatomite mining were conducted during approximately 15 person-days. Representative lithologic samples were collected, disaggregated by scraping, and suspended in water for observation using transmitted and reflected light microscopy. Radiometric dating of biotite separates from two volcanic ash samples using the $^{40}Ar/^{39}Ar$ method was completed in the laboratory of Servicio Nacional de Geología y Minería in Santiago, Chile (Supplementary Material). The lithologic information was compared to remote sensing imagery (Landsat and Google Earth images), leading to spectral and visual interpretations of lithologies and stratal continuity in areas lacking outcrop observations. The 30 m resolution global digital elevation model from the advanced spaceborne thermal emission and reflection radiometer (ASTER) was used to analyze topography and extract longitudinal profiles of rivers. Remote sensing data (topographic and spectral) and outcrop observations were used to identify the original extent of the laterally continuous diatomite facies (Fig. 2).

4. Results

4.1 Western diatomite, sandstone, and evaporite facies

On the western side of the CD, interbedded diatomite and well-sorted sandstone, overlain by chemical evaporites, are exposed near the pediplain surface. Where exposed in the Tana and Tiliviche canyon walls, these facies are up to 70 m thick and overlie pre-Oligocene basement rocks and undated siliciclastic deposits that fill paleo-valleys carved into basement. At their eastern extent, these fine-grained siliciclastic, biogenic, and chemical sediment facies are overlain by unconsolidated fluvial sands and gravels (Fig. 6).

4.1.1 Diatomite facies

A laterally extensive diatomite facies can be traced within the Tana canyon over a distance of 16 km (70º05’W–69.95°W)(Fig. 6) and in exploration pits across the pediment; landslides preclude similar mapping in the Tiliviche canyon. The altitudes of the base of the diatomite facies indicate that it drapes a pre-existing complex erosional topography. The diatomite facies display a long wavelength 0.6° inclination to the west and onlap the CdlC, creating a large-scale concave shape in east-west profile.

A white subfacies of diatomite consists of more than 95% diatoms and diatom fragments by volume (Fig. 7A). The diatoms are predominantly elongate, bilaterally symmetric, and range in size from 5–300 µm. Diatom fragments less than 5 µm in length make up 40–75% of the facies. A pink subfacies of diatomite contains higher concentrations of mud and sand (15–25%) as well as 75–85% diatoms and diatom fragments. No root traces, evidence of plant matter, or paleosols were found associated with the diatomite facies.

At its extreme western extent, diatomite caps the strath terrace located 480 m up the southern canyon wall (Hoke et al., 2007) (Figs. 8 and 9). The diatomite is several meters thick and lacks any plant material (Hoke, personal communication, 2011). An interbedded ash layer yielded a U-Pb zircon age of 6.433±0.047 Ma (Hoke et al., 2007).

The diatomite facies is thickest near its western extent, where the elevation of the pediplain is lowest (Fig. 6). In the Tana canyon mine near the border of the CC and the CD (Figs. 7B and 8, location B), two subfacies occur, constituting a white lower interval of nearly pure diatomite (20–35 m thick) that is mined, overlain across a sharp contact by muddier, pinker diatomite (25–40 m thick) (Fig. 7B). The diatomite beds are massive and range in thickness from 0.2–2 m.

Along Rt. 5, in the middle of the Pampa de Tiliviche, another mine exposes a 5 m thick section of the laterally continuous white diatomite subfacies (Fig. 8, location D). The lack of the pink, muddy interval is interpreted to signify that siliciclastic detritus was confined to the topographically lower, western, part of the landscape adjacent to the canyons.

4.1.2 Siliciclastic facies

Road cuts where Rt. 5 crosses the Tana and Tiliviche canyons expose a ~70 m thick unit of alternating dark gray sandstone and light pink muddy diatomite (Figs 7C and 8, locations C and E) (see also von Rotz et al., 2005). The base of the section is covered. The dark gray sandstone beds range in thickness from 5–50 cm. They are well sorted and medium to coarse grained; occasional pebble beds are less than 3 cm thick. Some of the dark gray sandstone beds are cross-bedded and some are horizontally laminated (Fig. 7C). The muddy diatomite interbeds are 1–30 cm thick and contain varying amounts of mud-sized and sand-sized siliciclastic grains. Some of the light pink muddy diatomite beds contain within them 1–5 mm thick white, diatom-rich laminae. We interpret these light pink muddy diatomites to be laterally continuous with the western diatomite facies (Fig. 6). A 30-cm-thick volcanic ash interbed 15 m above the base of this alternating sandstone and muddy diatomite sequence yielded an $^{40}Ar/^{39}Ar$ date of 10.86±0.04

Ma on biotite grains (Supplementary Material). This date is consistent with a stratigraphically higher ash which yielded a Rb-Sr date of 8.2±0.1 Ma on biotite and feldspar grains (von Rotz et al., 2005). Rare interbeds are composed of limestone. This fine-grained siliciclastic facies is thickest in the east and thins to the west (Fig. 6).

In the upper walls of the Tana and Tiliviche canyons, cross-bedded, well-sorted, light gray sandstones overlie the alternating dark gray sandstones and light pink muddy diatomites, separated by an erosional unconformity (Fig. 7D). This cross-bedded facies totals 8 m thick locally, built of 10–30 cm thick beds that are, in turn, built of 1–3 cm thick laminae. In the Tiliviche canyon near Route 5 (Fig. 8 location H), an ash interbed yielded a K-Ar date of 5.5±0.6 Ma (Naranjo and Paskoff, 1985).

Above the cross-bedded sandstones, separated by another erosional unconformity, are brown, well-bedded cobble gravels and coarse sands (Fig. 7E). These coarse siliciclastic deposits are trough cross-bedded and 1–2.5 m thick in the Tana road cut. They are associated with the canyons and not found in the pediplain exploration pits. An 8-cm-thick primary ash interbed collected in the Tana canyon yielded an $^{40}Ar/^{39}Ar$ age on biotites of 3.04±0.03 Ma (Supplementary Material).

4.1.3 Evaporite facies

Across the CD evaporites of three types overlie the El Diablo Formation. Most widespread are gypsic soils. Locally, halite nodules and cm-scale polygonally-fractured crusts occur in many natural deflation pits and anthropogenic depressions across the landscape. This halite seems to be related to wetting of evaporitic strata and soils by fog, and it is not further considered. This description focuses on the third type, found within the Pampa de Tiliviche (Figs. 1 and 2), composed of stratified gypsum beds that widely overlie the diatomite and siliciclastic facies (Fig. 6). .

The gypsum beds range from 1–1.2 m thick and contain centimeter-scale beds of gypsarenite cemented with gypsum and interbedded with siliciclastic sands cemented with gypsum and halite (Fig. 7F). The gypsum evaporite beds contain less than 10% fine-grained siliciclastic material, except in 1–2 cm thick sand-rich beds, which contain 30–50% fine sand. Horizontal lamination is common, defined by layers of mud-sized gypsum grains separated by 1 –mm-thick laminae of needle-shaped gypsum crystals (crystals ≤5 mm long). Up to 35% of the gypsum facies consists of diatoms or diatom fragments. In places the gypsarenite beds have fractures filled with gypsum-cemented siliciclastic sands (Fig. 7F). Locally, a 1–3 cm thick sandstone or mudstone bed separates the diatomite facies from the overlying evaporite facies.

An ash yielding an $^{40}Ar/^{39}Ar$ biotite age of 3.49±0.04 Ma is interbedded with laminated gypsum that caps a siliciclastic-dominated section ~3 km south of the Tiliviche canyon (Fig. 8, location G) (Allmendinger et al., 2005). The ash and the surrounding evaporite beds are folded by the Pisagua reverse fault and exposed by the incision of the Pisagua drainage (Fig. 8).

4.2 Eastern system gypsic soil

In the WS and CD, much of the pediplain surface above the El Diablo Formation is capped by hard gypsic soils composed of water-soluble minerals that are dispersed among silicate clasts from the El Diablo Formation parent material (Fig. 5). This gypsic soil is the dominant surficial material on the pediplain east of the eastern limits of the diatomite and evaporite facies. The soil-forming salts are primarily gypsum, anhydrite and halite. These well-developed gypsic soils are on the order of 1 m thick and are characterized by vertical fractures filled with downward transported clasts cemented by soluble minerals.

4.3 Relict drainage connections

The Pisagua drainage, which contains local wetlands, transects the area of the diatomite facies from southeast to northwest (Figs. 1 and 9). The topographic relief of the Pisagua drainage diminishes to the southeast (upstream) and eventually merges into CD sediments. Using surface textures and vegetation growth, a groundwater pathway that feeds the Pisagua drainage can be traced south from the limit of the Pisagua drainage surface expression (Fig. 9). Within the Reserva Nacional Pampa del Tamarugal, trees have been planted in a grid. The Prosopis tamarugo is a phreatophyte that taps groundwater to depths exceeding 12 m (Mooney et al., 1980), and the size and health of cultivated tamarugo trees depend strongly on the availability of groundwater (Mooney et al., 1980). Tamarugo trees that are located along the borders of channel-like pathways (Fig. 9) are healthier and larger than the others. The most southeasterly identifiable sections of interconnected groundwater pathways are aligned with drainages on the alluvial fan at the mouth of the Aroma valley.

Where the Pisagua drainage crosses the Pisagua Fault, evaporite beds of salar origin and the 3.49±0.04 Ma ash interbedded within them are folded by the Pisagua Fault (Fig. 8 location G) (Allmendinger et al., 2005). The Pisagua drainage cuts through the uplifted fault block (Figs. 7 and 11).

5. Environmental and landscape interpretation

5.1 Diatomite facies

Continental diatomite deposits can form in both lakes and wetlands (Bao et al., 1999; Saez et al., 2007). Following criteria summarized by Pigati et al. (in review), the Tiliviche/Tana diatomite facies are interpreted to be of lacustrine origin. The diatomite lacks bioturbation, root traces, and plant remains, which are common features of wetland deposits (Pigati et al., in review). The beds are up to 2-m-thick and massive, suggesting they formed during diatom bloom events with very little detrital input (Saez et al., 2007). Furthermore, the lateral continuity and extent across an area of approximately 375 km^2 is less common of wetland environments, which tend to occur in localized geomorphic settings or associated with faults where groundwater is forced to the surface (Pigati et al., in review).

The thickness pattern and elevation distribution of diatomite facies (Figs. 6 and 8) are consistent with deposition in a lake that was more consistently wet (allowing for deposition) in its topographically lowest part. In the western diatomite depocenter there are no paleosols and no other evidence of subareal exposure (e.g. mud cracks) within the diatomite unit, suggesting that the paleolake was perennial. However, the lake system may have transitioned eastward into a wetland system.

5.2 Siliciclastic facies

The alternating medium to coarse dark gray sandstone beds and light pink muddy diatomite beds are interpreted to have formed in a depositional environment in which conditions alternated between still water, enabling deposition of mud and diatoms on the lake bottom, and flowing water, when sand was delivered to the system. The high degree of sorting and predominance of horizontal lamination over cross-bedding in most of the sand beds suggest upper flow-regime transport by hyperconcentrated flows that would occur when dense, sediment-laden water entered a lower density water body, such as a lake (Sohn et al., 1999).

The repeated vertical alternation of sandstone and diatomite beds implies that hydrologic variability was an important characteristic of the eastern sector of the paleolake. The variations might relate to seasonal or multi-annual changes in stream-flow, enabling sand deposition when stream-flow was high, and mud deposition during drier periods when the rivers delivered only finer grained materials to the lake margin. Alternatively sediment variation could reflect short timescale changes in the size of the lake and associated horizontal shifts in the eastern shoreline position, stacking regressive (fluvial) and transgressive (lacustrine) deposits. Within the paleolake system, siliciclastic deposition was concentrated where the Tana and Tiliviche rivers emptied into the lake.

Both the light gray cross-bedded sandstones and the uppermost brown cross-bedded gravels and coarse sands are interpreted to have accumulated in fluvial environments. The grain size suggests that the latter interval of fluvial deposition experienced higher energy flow conditions than occurred during the first interval. This environmental succession from lacustrine with fluvial influence to a completely fluvial depositional system records the final regression of the paleolake.

Deposition of the alternating dark gray sandstone and light pink muddy diatomite sequence began before ~10.9 Ma. Von Rotz et al. (2005) present magnetic polarity analyses of 25 samples along the Rt. 5 Tana road cut section. The 10.86±0.04 Ma volcanic ash occurs ~15 m above the bottom of the von Rotz et al. (2005) magnetic polarity column. Re-interpretation of those magnetic polarity data, constrained by the newly dated ash and by recognition that major unconformities occur near the 70 m level of the von Rotz et al. (2005) section, suggests that the dark gray sandstone and light pink muddy diatomite sequence ranges in age from older than ~10.9 Ma to ~9 Ma. Thus this lake margin facies may have overlapped the age range of (von Rotz et al., 2005) or may immediately post-date (García et al., 2011) the proximal braided fluvial gravels of the upper member of the El Diablo Formation.

The unconformity that separates the fluvial light gray cross-bedded sandstones from the lacustrine-related interbedded dark gray sandstone and light pink muddy diatomite spans from ~9 Ma until prior to ~5.5 Ma. The subsequent unconformity represents a period of erosion bracketed between ~5.5 Ma (Naranjo and Paskoff, 1985) and ~3.0 Ma.. At the top of the Tana and Tiliviche canyon walls,. brown trough cross-bedded coarse sands and gravels overlie this unconformity. These gravels were undergoing deposition at ~3.0 Ma in a higher energy fluvial environment than the light gray cross-bedded sandstones.

Within the paleolake system, siliciclastic deposition was concentrated where the Tana and Tiliviche rivers emptied into the lake. The lake margin sediments preserved indicate that the depositional environment progressed from lacustrine with fluvial influence to a completely fluvial depositional system as the paleolake margin fluctuated and regressed. .

5.3 Evaporite facies

Bedded evaporites can form in marine environments, inland seas, and continental salt pans (salars), and evaporite-mineral dust generates gypsic soils in much of the Atacama Desert. The bedded evaporites of the study area are horizontally laminated and lack incorporated parent material, ruling out genesis as a soil. Rather, the evaporite facies is interpreted as a salar environment due to the presence of laminated gypsarenite and horizontal bedding (Fig. 7F) (Lowenstein and Hardie, 1985) and fracturing which is typical of subaerial exposure of salar deposits (Lowenstein and Hardie, 1985). The salar depositional system was active at ~3.5 Ma (Allmendinger et al., 2005).

5.4 Tiliviche paleolake boundaries, depth and catchment area

The spatial extent of the diatomite facies reveals the original minimum extent of Tiliviche Paleolake when diatom blooms occurred. The western paleolake boundary occurs where there is both an abrupt change in topographic slope (Fig. 2B) and a sharp change in the Thematic Mapper spectral characteristics of the surface materials (Fig. 2A). Without a clear topographic barrier to act as an embankment and with meter-thick post-lake alluvial and gypsic soil cover, the eastern border of Tiliviche Paleolake is less easily recognized. The documented facies and thicknesses suggest that the eastern border of the paleolake is located near but east of Rt. 5, where alternating lacustrine and fluvial sediments are exposed (Fig. 8, locations C and E). The northern and southern Tiliviche Paleolake boundaries are similarly uncertain. North of the Tana canyon, upthrown fault blocks within the Pampa de Tana (Fig. 1) do not expose diatomite facies (Caprio, 2007) and the Tana oil exploration borehole (Fig. 2, location A) encountered no diatomite (ENAP, 1983). Thus the northern border of the paleolake lies between those barren sites (~19º20’S) and exploration pits (Fig. 2, location F; ~19º27’S) that expose diatomite. To the south, the uncertainty on shoreline position is at least 15 km, bracketed by diatomite exposed in a road cut ~2 km south of the Tiliviche canyon (Fig. 2, location C) and by the Dolores oil exploration borehole (Fig. 2, location D) which lacks diatomite (ENAP, 1983).

The favored groundwater flow paths through the tamarugo tree grid and toward the Pisagua drainage suggest that paleo-channels once fed the Tiliviche depocenter from the south. The drainage integration of the southern area with the lake system leads to the tentative interpretation that the southern boundary of the paleolake was near Dolores (Fig. 2, location D).

For these geographic boundaries, the Tiliviche Paleolake was approximately 375 km^2 during the time of diatomite deposition. Using modern topography as a guide, we estimate that the paleolake maximum depth exceeded 120 m across what is now the pediplain and was deeper within the submerged, paleo-Tiliviche and paleo-Tana drainages. This depth measurement does not take into account any deformation since the deposition of lake sediments.

The eastern limit of the catchments sourcing the Tiliviche Paleolake was likely similar to the modern watershed boundary, as it lies along volcanic centers interpreted to be older than the paleolake (Wörner et al., 2000). Using the modern Tana-Tiliviche catchment as a guide, the minimum paleo-catchment was ~2,900 km^2. Given that the paleolake catchment may have included also the watershed of the Aroma drainage system (2,300 km^2) (Fig. 9), the total catchment area of Tiliviche Paleolake was 2,900–5,200 km^2.. If Late Miocene climate were like today's climate with precipitation strongly dependent on altitude, then the part of the total catchment area of the paleolake at elevation above paleo-3500 m may have contributed disproportionately to the recharge of the paleolake.

5.5 Gypsic soil

The gypsic soils of the eastern sector of study region formed while the pediplain was subaerially exposed, by accumulation of salts introduced to the system via coastal fog, dry atmospheric deposition, and/or aeolian transport of salts deposited elsewhere, such as in salars (Ericksen, 1981; Rech et al., 2003; Michalski et al., 2004). Soils like these cannot survive humid conditions (Ewing, 2006; Rech et al., 2006). The meter-scale thickness indicates that the pediplain upon which the soil formed was exposed to hyperarid conditions over geologic time spans (10^5–10^6 years) (Howell, 2004; Ewing et al., 2006; Rech et al., 2006).

6. Discussion

6.1 Paleoclimate

Carroll and Bohacs (1999) point out that paleoclimate variation is often not the primary control on a transition between underfilled, balanced-fill, and overfilled hydrological conditions of a lake, and therefore that a transition from diatomite-rich lacustrine facies (balanced-fill) to evaporitic salar facies (underfilled) may not reflect a climate change. Nevertheless, the presence of a ~375 km^2, 120 m deep perennial lake in the Atacama Desert during the Late Miocene would be consistent with a wetter climate than exists today. Today's hyperarid climate produces no lakes in the Atacama Desert at elevations lower than 3,500 meters, even where the CD is endorheic. Yet it remains unclear where in the catchment the wetter conditions existed. If the balance-filled paleolake was largely contemporaneous with the terminal stages of the El Diablo proximal facies (Schlunegger et al., 2010), then the paleolake is simply the distal environment associated with a time of widespread ample surface water. But if the ~11–9 Ma Tiliviche paleolake post-dates the cessation of deposition in the proximal El Diablo Formation (García et al., 2011; Nester and Jordan, 2012), then the paleolake was a spatially isolated feature in a broader valley that was so extremely arid that erosion and sediment transport largely ceased (Nester and Jordan, 2012). In the latter case, the Tiliviche Paleolake suggests wetter Late Miocene climate conditions in high elevation parts of the catchment, where most or all recharge occurs today. This might correspond to what Schlunegger et al. (2010) describe as a Miocene progression toward increasing precipitation on the highest parts of the Western Cordillera, even while climate trended toward intensified aridity at lower altitudes.

The transition from deep water lake to salar environment occurred sometime between ~6.4 Ma, and ~3.5 Ma. This transition is coincident with the Pliocene warm period (e.g. Sloan et al., 1996; Zachos et al., 2001), which may have been accompanied by permanent El Niño conditions (Wara et al., 2005). Today El Niño conditions are associated with even drier conditions along the eastern margin of the Atacama Desert and in the Western Cordillera (Vuille et al., 2000; Houston, 2006b). By analogy, a transition to drier conditions in the high elevation recharge area during the Pliocene warm period may have contributed to the desiccation of the paleolake

6.2 Valley incision and lake history

Two major unresolved questions regarding the geomorphology of the northern Chile forearc region are the timing and cause(s) of the most recent major valley incision that resulted in bypass and abandonment of the large-scale interfluves that now constitute the pediplain surfaces (García and Hérail, 2005; Schlunegger et al., 2006; García et al., 2011). For the Tiliviche/Tana system, constraints on the timing of incision can be derived from the paleolake history, because the valley incision and paleolake history have been complexly related. On the west, the CC acted as the western lip of the topographic depression in which Tiliviche Paleolake formed. The Tana Knickzone is presently located east of the CC. If the paleolake existed when the Tana Knickzone breached the lake spillpoint, its continued eastward progression would have drained the lake. Thus, the location of the Tana Knickzone through time may have determined the youngest age of the paleolake. On the east, the lake itself raised the base level of the eastern drainages, and fluctuations in paleolake level were one control, among several (e.g., WS uplift events, climate variations, and bedrock properties), on incision rates of the canyons within the WS.

The Tiliviche/Tana system also offers more insight to the causes of incision than do other canyon systems of northernmost Chile (Suca-Camarones system, [García et al., 2011]; Lluta and Azapa canyons [García and Hérail, 2005; Schlunegger et al., 2006]). Because the sectors of the Tiliviche/Tana canyon with deep incision through the CC (west of the CD) and WS (east of the CD) are separated by a sector with less incision (Fig. 3) it is clear that they formed by separate events, not necessarily related to one another either temporally or causally.

6.2.1 Western base level fall event(s)

For incision to occur, two conditions must have been met: the base level must have fallen and climate conditions in the high elevation catchment must have been wet enough for the streams to have adequate erosional capacity. As Garcia et al. (2011) discuss, the base level fall event need not have been synchronous with incision. The region may have first been primed for incision by base level drop and then incision may have occurred at a later time when climate conditions were less arid. We focus here on the probable mechanisms for the western base level drop.

Hoke et al. (2007) quantified the base level fall magnitude that produced the Tana Knickzone by modeling Tana River profile segments. The profile segment now located upstream (east) of the Tana Knickzone grades to ~1 km above modern sea level (Hoke et al., 2007) (Fig. 10), which indicates that base level fell by ~1 km. A similar magnitude of base level fall is recorded in knickzones from southern Peru to the Loa River (Houston, 2006a; Hoke, 2006; Schildgen et al. 2009),

There are several possible causes of this regional base level drop, explored below. Although changes in eustatic sea level would affect the base level of drainages that reach the ocean, they are not discussed farther because the magnitude of Neogene sea level fluctuations (Miller et al., 2005) is an order of magnitude smaller than the change in base level in this system. A possible explanation is watershed re-organization within the CC (Fig. 11), here referred to as drainage breakthrough, that caused previously endorheic drainages to traverse the CC and become exorheic. These drainages would then have been subjected to the 1 km elevation drop of the coastal escarpment, initiating knickzone formation. Alternatively, as Allmendinger et al. (2005) showed, either uplift of the forearc or lateral retreat of the coastline, or a combination of these two factors, could be responsible for base level drop (Fig. 11).

6.2.1.1 Drainage breakthrough

The working hypothesis that stream capture and resultant drainage breakthrough of the CC were the only factors that caused the base level drop (Fig. 11A) requires the assumption that the Tiliviche/Tana drainage was endorheic initially and that a ~1 km drop in elevation existed west of the CC. We discard this interpretation for four reasons. First, the three-dimensional form of the contact between basement and lacustrine lithologies reveals that a stream valley was incised into the CC basement rocks in the position of the modern Tana canyon prior to the Tiliviche paleolake. Second, the position of the erosional (strath) terrace (950 m altitude) located west of the boundary between the CD and the CC (Figs. 2 and 3) indicates that a paleo-Tana River persisted west of the CD. Whereas one possibility is that the terrace was carved by a river flowing to the east that has since changed its direction due to stream capture (Fig. 11A, first and second steps), Hoke's (2006) analysis of the Tana profile showed that the terrace position is consistent with a westward-flowing paleo-Tana river (Fig. 10). Third, even if a drainage breakthrough might explain the available data for the local Tana-Tiliviche system, it cannot explain the regional 1-km-scale base level fall, especially because even canyons of southern Peru where there is no coastal barrier to exorheic drainages display the history of kilometer-scale base level fall. (Hoke et al., 2007; Schildgen et al., 2009). Furthermore, the hypothesis of stream capture and drainage breakthrough of the CC fails to explain drainage features on the western edge of the CC, where many small drainages that do not currently pass through a topographic high on their way to the coast are cut by the escarpment (Allmendinger et al., 2005).

6.2.1.2 Coastal retreat

Coastal retreat driven by subduction erosion is a strong candidate for a process that contributed to the base level drop experienced by exorheic rivers in northern Chile (Rutland, 1971; Kukowski and Oncken, 2006) (Fig. 11B). Evidence exists both locally and regionally that coastal retreat was an active process in the Miocene and Pliocene. Locally, nonmarine evaporite deposits exposed in the coastal escarpment near Pisagua, with an interbedded 22.2 Ma ignimbrite (Mortimer et al., 1974), reveal the Early Miocene existence of a closed drainage basin whose western boundary was later destroyed . Likewise, 100 km to the south (near 20.6ºS), Allmendinger et al. (2005) concluded that nonmarine strata, incised channels, and the evolution of local-scale fault scarps were best explained by the existence of higher topography west of the modern coastal escarpment at 5.62±0.10 Ma and that, since then, the late Miocene highland has been removed. Similar reasoning can be applied to the Pliocene Alto Hospicio nonmarine gravels, exposed by the coastal escarpment 75 km south of the Tiliviche canyon (20.3°S). There, a large volume of material originally deposited west of the modern escarpment was removed through coastal retreat since 2.77±0.03 Ma (Marquardt et al., 2008).

It is unlikely that coastal retreat alone can account for the entire 1 km of base level fall. East of the Tana Knickzone, the longitudinal stream profile has a <1º gradient (Fig. 10). If the drainage were exorheic and graded to an oceanic base level when Hoke et al.'s (2007) erosional terrace was cut, the coast must have been hundreds of kilometers west of its present location (Hoke, 2006). Laursen et al. (2002) estimate coastal retreat to have progressed at a rate of 3 km/Ma during the past 10 Ma, accounting for a maximum of 18 km since the end of lacustrine deposition on the high terrace. The mismatch between 18 km of tectonically driven coastal retreat and hundreds of kilometers of modeled distance to the coastline (Fig. 10) implies that additional mechanisms must have worked in concert with coastal retreat to produce the inferred base level drop.

6.2.1.3 Uplift of the continental forearc

If the CC were uplifted as a broad crustal block (Cembrano et al., 2007), there would be important consequences to the base level of valleys traversing the forearc, and knickzone migration would be expected (Fig. 11C). Near the study area, Regard et al. (2010) note that coastline planation surfaces exist approximately 50 m above sea level. Regional evidence of uplift of the coastline is stronger, revealing uplift at a rate of 0.3 m/1000 years (Regard et al., 2010) during the late Quaternary. That this coastal uplift applied to a broad forearc block and not only the coastline, and that it persisted over millions of years, is demonstrated in southern Peru's Ocoña canyon (~16.3ºS, 480 km north of the study area) (Fig. 1), where the CC does not exist as a topographic barrier. At a distance from the coast comparable to the width of the CD of northern Chile (40 km), a layer older than 23 Ma containing marine fossils occurs at ~1700 m above sea level (Cruzado and Rojas, 2007; Schildgen et al., 2009).

6.2.2 History of the Tiliviche paleolake and salar

An interpretation of the initiation of the paleolake must be consistent with the following geomorphologic and stratigraphic features. The location and elevation of the strath terrace within the CC (Figs. 2 and 8 location A) suggest that the Tana/Tiliviche paleoriver drained across the CC to a base level west of the modern coastal escarpment (Fig. 12A) when the terrace was carved. The diatomite beds on top of the strath terrace show that the paleolake postdated carving of the terrace. The pre-paleolake morphology reflected by the base of the diatomite unit shows the Tana and Tiliviche paleo-valleys to have been broader and shallower (~50 m) where they crossed the CD than they are today (Fig. 13). Finally, the paleolake formed sometime before ~10.9 Ma.

Therefore the basic paleolake history must have started prior to ~10.9 Ma with an event or a series of events that raised the drainage profile elevation west of the strath terrace, creating a topographic depression in which water could accumulate (Fig. 12B). This pre-10.9 Ma event may have been the formation of a drainage spillpoint or sill within the CC that raised the CD base level. Such a sill could have resulted from west-side-up movement on a fault that crossed the paleo-valley, or from landslide deposits. Although at least three faults cross the canyon between the modern coastline and the Tana Knickzone, none of these faults is a clear candidate for the formation of a sill. No landslide scarps have been identified in the CC adjacent to the valley. Moreover, it seems unlikely that canyon damming by landslide deposits could sustain a lake for millions of years. An alternative explanation for a rise in drainage profile elevation west of the strath terrace is a regional eastward tilting or folding in the CC, which could have created a spill-point behind which the paleolake formed. Were there a regional tectonic mechanism for CC tilting that dammed this river system, it might have affected other drainage systems to the north and south.

The hydrologic budget of the lake system between ~10.9 Ma and <3.5 Ma would have been sensitive to changes in the local climate, climate at high elevations in the catchments, base level, and surface drainage patterns. As noted by Schlunegger et al. (2010), some growth in area of the high altitude catchments may have occurred during the last 12 million years. Yet a more dramatic change could be related to shifts in the drainage network in the lowlands. Specifically, whereas surface flow from the modern Aroma catchment feeds the endorheic CD south of the study area, a groundwater connection from the fan at the mouth of the Aroma valley to the Pisagua Drainage suggests that, in the past, the Aroma catchment also fed the paleolake system.

An interpretation of the termination of the paleolake is bound by age and facies constraints. Diatomaceous deposits on top of the western strath terrace indicate that the western sector of the Tiliviche Paleolake persisted until more recently than ~6.4 Ma. In contrast, the lake retreated from its eastern zone beginning shortly after ~9 Ma (Fig. 12C). Sometime between ~6.4 Ma and ~3.5 Ma the hydrological balance of the lake changed from balanced-fill to underfilled (Fig. 12D), even though the general morphology of the lake system did not change. In this time interval the lake level fell below the surface water spill-point but the water table did not fall far below the surface, allowing the accumulation of evaporites through the capillary migration and evaporation of groundwater.

The final chapter of the Tiliviche salar, which terminated deposition, could be explained in two ways. The water table may have fallen due to a decrease in the regional precipitation-evaporation ratio caused by climate change or surface drainage shifts. Alternatively, the water table may have fallen due to a drop in base level. Progressive downcutting of the lake's spill-point or migration of the Tana Knickzone into the lacustrine-salar system would have caused a succession of base level drops. Although today the Tana Knickzone is located east of the eastern boundary of the paleolake (Fig. 10), it is not clear whether it first breached the western lake boundary when the deep-water lake existed, when the salar existed, or after the paleolake system no longer existed.

Post-dating the termination of the salar environment in the western CD, there is a clear record incision that led to the modern canyon morphology. Younger than ~3.5 Ma, a region that had once been the western part of the salar was deformed by the Pisagua Fault (Fig. 12E). Thereafter the Pisagua drainage cut through the uplifted fault block (Fig. 8), which is evidence that the Pisagua drainage was erosionally active younger than 3.5 Ma. More broadly, incision followed salar evaporite deposition where the Tana and Tiliviche canyons traverse the western CD. This period of incision likely post-dated the ~3.0 Ma deposition of coarse brown gravels near the top of the Tana Rt. 5 road cut section. Other indications of renewed sediment transport and incision since ~3.0 Ma include cosmogenic exposure dates of 2.8, 1.3, and 1.2 Ma near the Aroma canyon, which indicate re-activation of the pediplain surface, and down-cutting of the Aroma canyon (Evenstar et al., 2009) (Fig. 12E).

7. Conclusions

In the northern portion of the Central Depression a deep-water lake and subsequently a salar existed from before 10.86±0.04 Ma to more recently than 3.49±0.04 Ma. At its maximum extent, the area of the lake was ~375 km^2 and its depth up to ~120 m. The presence of a lake that maintained this large size for at least 2 million years in the Late Miocene is consistent with a wetter climate and greater recharge in the high elevation parts of the catchment area. While its surface area declined after 9 Ma, a small water body persisted in the western sector until more recently than ~6. 4 Ma. The transition to a salar environment prior to 3.5 Ma coincided with the Pliocene warm period (Sloan et al., 1996; Zachos et al., 2001), which should have been a time of lower precipitation rates in the Western Cordillera based on the modern relations of Pacific sea surface temperatures and precipitation (Vuille et al., 2000; Wara et al., 2005; Houston, 2006b).

Prior to the formation of the Tiliviche Paleolake, the Tana and Tiliviche drainages were exorheic, incised ~50 m beneath the surface of the CD, and flowed to a base level west of the modern Coastal Cordillera. Incision of the Tana and Tiliviche drainages across the CD resumed more recently than ~3.0 Ma and resulted in down-cutting of the canyon another 200 to 400 m, to its present depth.

In the Tiliviche/Tana system, the younger than 3 Ma incision west of the Tana Knickzone is the result of a 1 km base level fall event that was likely initiated by both continental forearc uplift and coastal retreat. This conclusion differs from García et al.’s (2011) attribution of late incision to short-lived climate changes, a re-interpretation enabled by the fact that the

Tiliviche/Tana drainage displays a regionally unique lack of continuity between the deep incision of the Coastal Cordillera and the deep incision within the Western Slope.

Since this base level fall event occurred, the Tana Knickzone has progressed at least 43 km up the Tana canyon and is currently located east of the estimated geographic extent of the Tiliviche Paleolake. Migration upstream of the Tana Knickzone would have progressively lowered the groundwater base level and drastically changed the depositional environment. In this way the existence and progression of the Tana Knickzone is a possible partial control on the nature of, and timing of changes in, the depositional environment of the forearc basin.

While the Tiliviche Paleolake existed, it served as the base level for the upstream segments of the Tana, Tiliviche, and perhaps Aroma drainages. Without discounting the significance of base level controls by WS uplift and climate change (e.g., Schlunegger et al., 2006; Hoke et al., 2007; Jordan et al., 2010; García et al., 2011), fluctuations in lake level would have been a partial control on incision rates of drainages cutting into the WS.

As cautioned by Carroll and Bohacs (1999), this study illustrates that the paleoclimate conditions within a sedimentary basin may not be clearly recorded in the sedimentary facies. A decoupling of facies from local paleoclimate can occur if catchments feeding a lake import water from a different climate belt, a situation that is common if the elevation range in the catchment is large, or if local geomorphic events affect baselevel. A detailed interpretation of paleoclimate history from fluvial and lacustrine facies requires understanding of the entire river basin, from headwaters to ocean. In this study, despite independent constraints on regional and local conditions and a complementary geomorphological record, the role of paleoclimate in controlling the history of lake hydrology and sedimentary facies is not clearly resolved.

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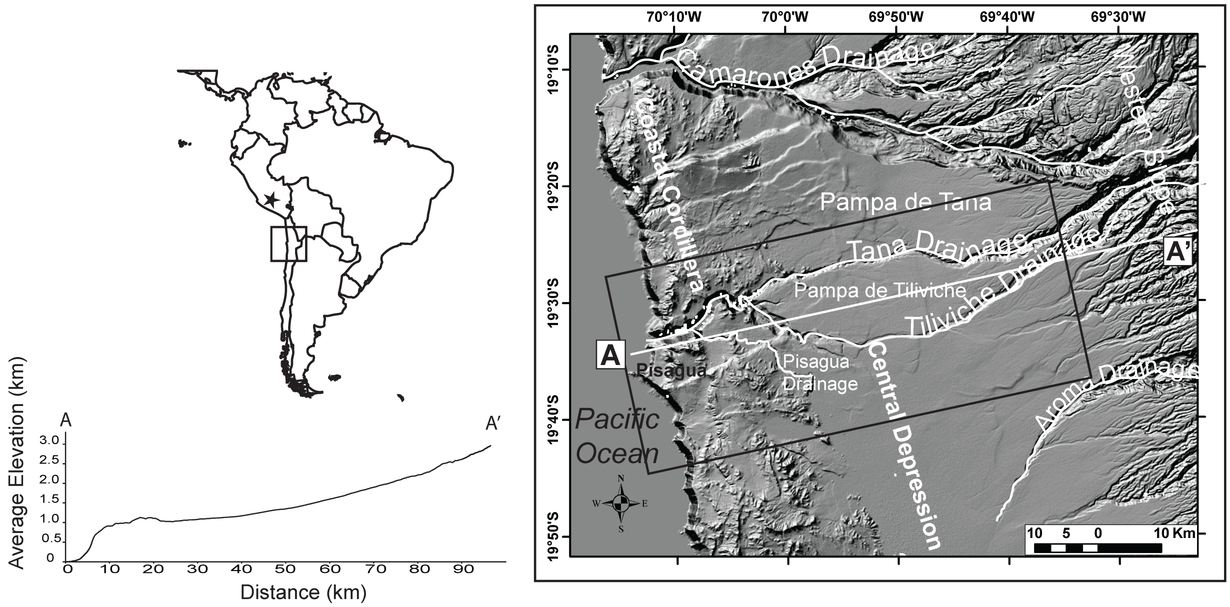


Figure 1. Shaded relief digital elevation model and topographic profile of study area (indicated by rectangle). Star indicates area where data are drawn from southern Peru. Topographic Profile from A to A' shows the average elevation along a 20 km wide swath.

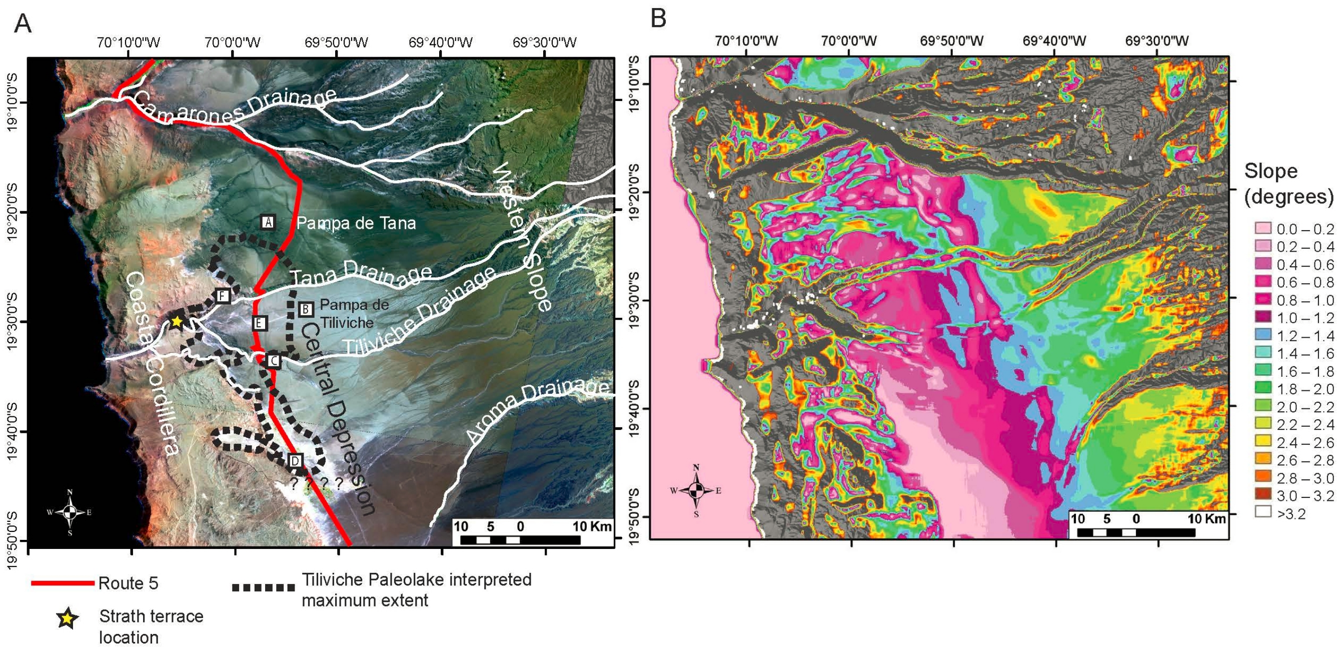


Figure 2. A) Landsat Thematic Mapper (bands 5, 4 and 2) image of study area (indicated by rectangle). A- Pampa de Tana ENAP oil exploration well location. B- No diatomite is present where gravel pit offers exposure. C- Diatomite exposed in road cut. D- Salar de Dolores ENAP oil exploration well location. E- Pampa de Tiliviche diatomite mine. F- Pampa de Tana diatomite pit mines. B) Slope map of are shown in part A created using the 90 m SRTM DEM averaged over 21x21 pixel squares, ~3.5 km^2. Pink colors represent areas of less than 1.2 degree slopes. Blue through red colors represent the Western Slope, where the inclination is greater than 1.2 degrees. Slopes greater than 3.2 degrees are not represented. The steepest slopes are found in the canyon walls.

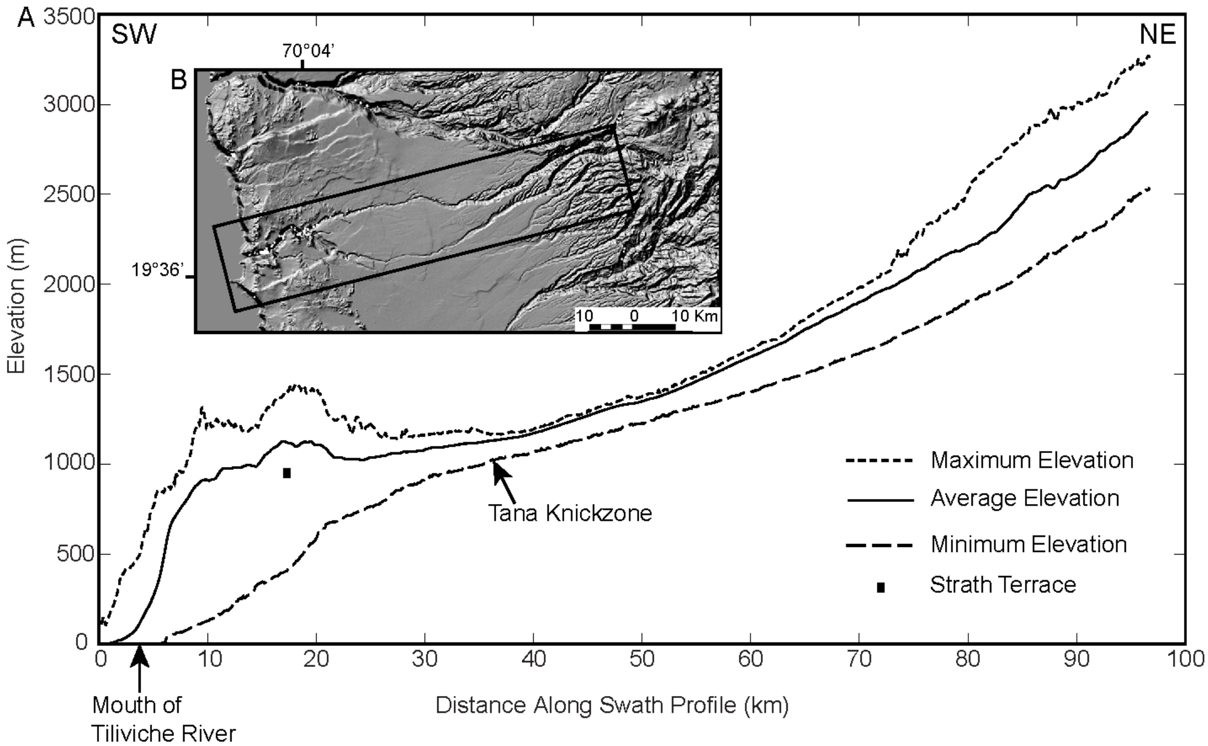


Figure 3. Swath profiles of study region from southwest to northeast showing maximum, minimum and average topography. The chosen swath, indicated with a rectangle, is 20 km wide and has an inclination of 13.5 degrees north of west. Profiles were made using 30 m ASTER global digital elevation model. The Tana Knickzone is located ~36 km along the swath profile from the west.

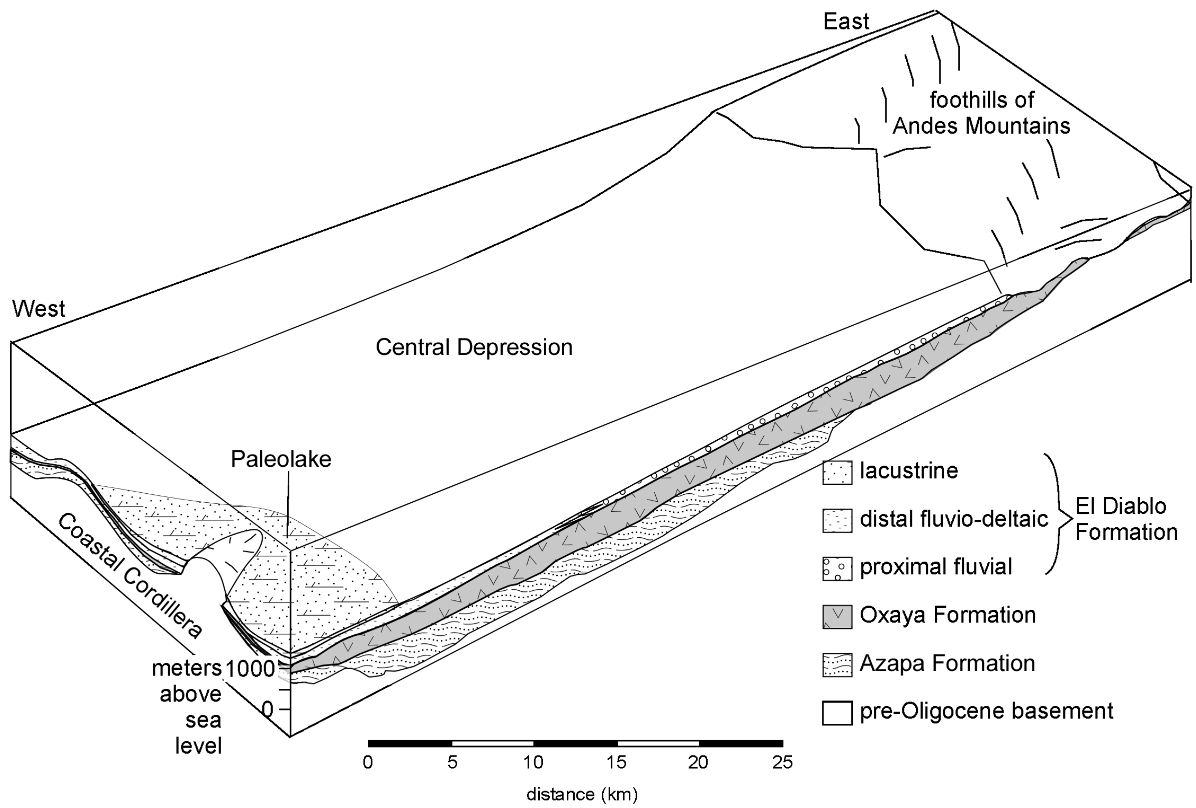


Figure 4. Block diagram showing the Oligocene to Pliocene strata of the Central Depression (CD) in positions between major canyons. The east-west face is constrained by seismic reflection data (Nester and Jordan, 2012) and exposures in canyon walls (Parraguez, 1998; Pinto, 1999; García and Hérail, 2005; Schlunegger et al ., 2010). The north-south face is more schematic, controlled by the Tana borehole, Schlunegger et al. (2010), García et al. (2011), and the authors' observations. The diagram does not differentiate the upper and lower members of the El Diablo Formation. Horizontal and vertical scales are accurate only near the SW corner.

Figure 5. Gypsic soil exposed in the study region. Here the soil is approximately 1.5 m thick and incorporates rounded dark gray gravels of the El Diablo Formation parent material. Arrows point to vertical bands of salt-cemented sand, about 20 cm wide and up to 130 cm long, that are representative of vertical cracks that form at the soil surface and into which detritus falls.

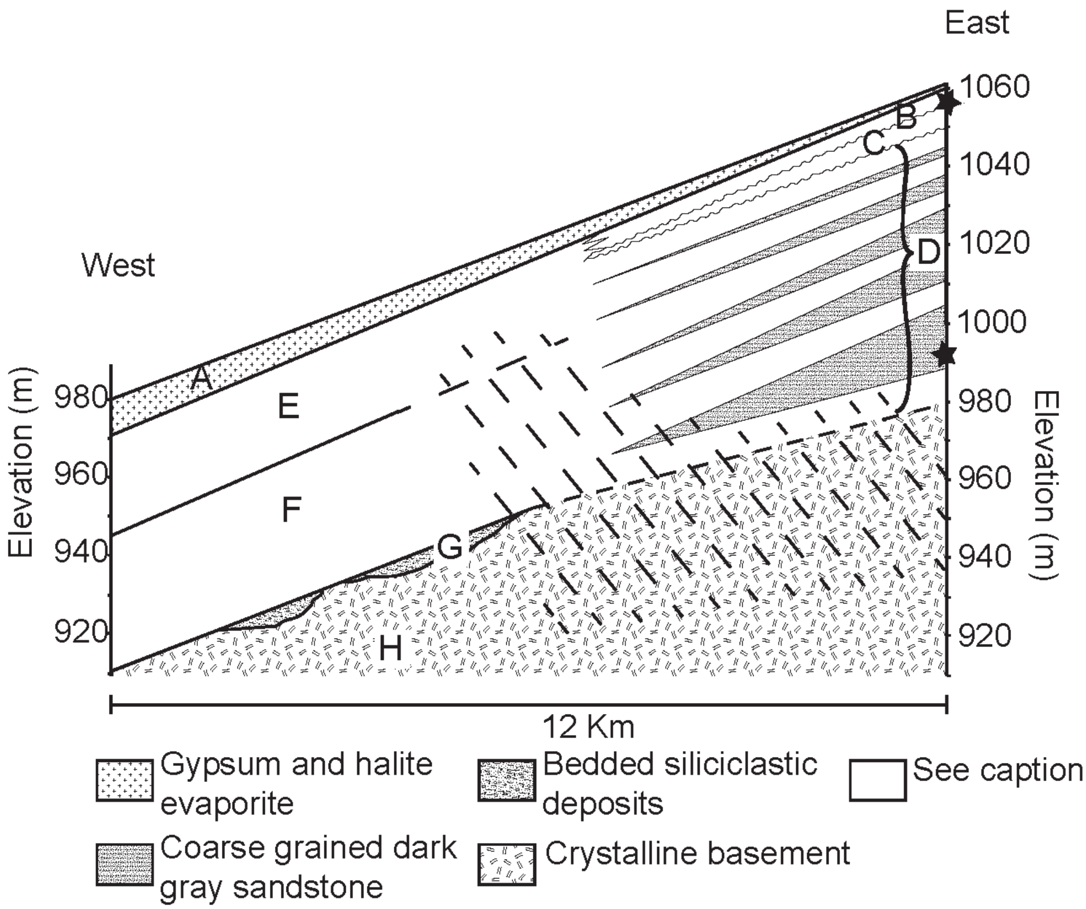


Figure 6. Schematic stratigraphy of Tana Canyon north wall, from the Tana Canyon Diatomite Mine in the west to the Tana Canyon Route 5 road cut in the east, 50 times vertical exaggeration. A) Gypsum and halite evaporite. B) Trough cross-bedded conglomerate. C) Cross-bedded fine to medium grained light gray sandstone. D) Coarse grained dark gray sandstone interbedded with mixed mudstone and diatomite, expressed schematically. Thickness of mudstone/diatomite layers increase upwards. E) Thickly bedded pink diatomite. F) Thickly bedded white diatomite. G) Bedded siliciclastic deposits. H) Crystalline basement. Black stars indicate locations of dated ash deposits. The stratigraphically higher ash yielded a date of 3.04±0.03 Ma, the stratigraphically lower ash yielded a date of 10.86±0.04 Ma. Diagonal dashed lines indicate covered areas.

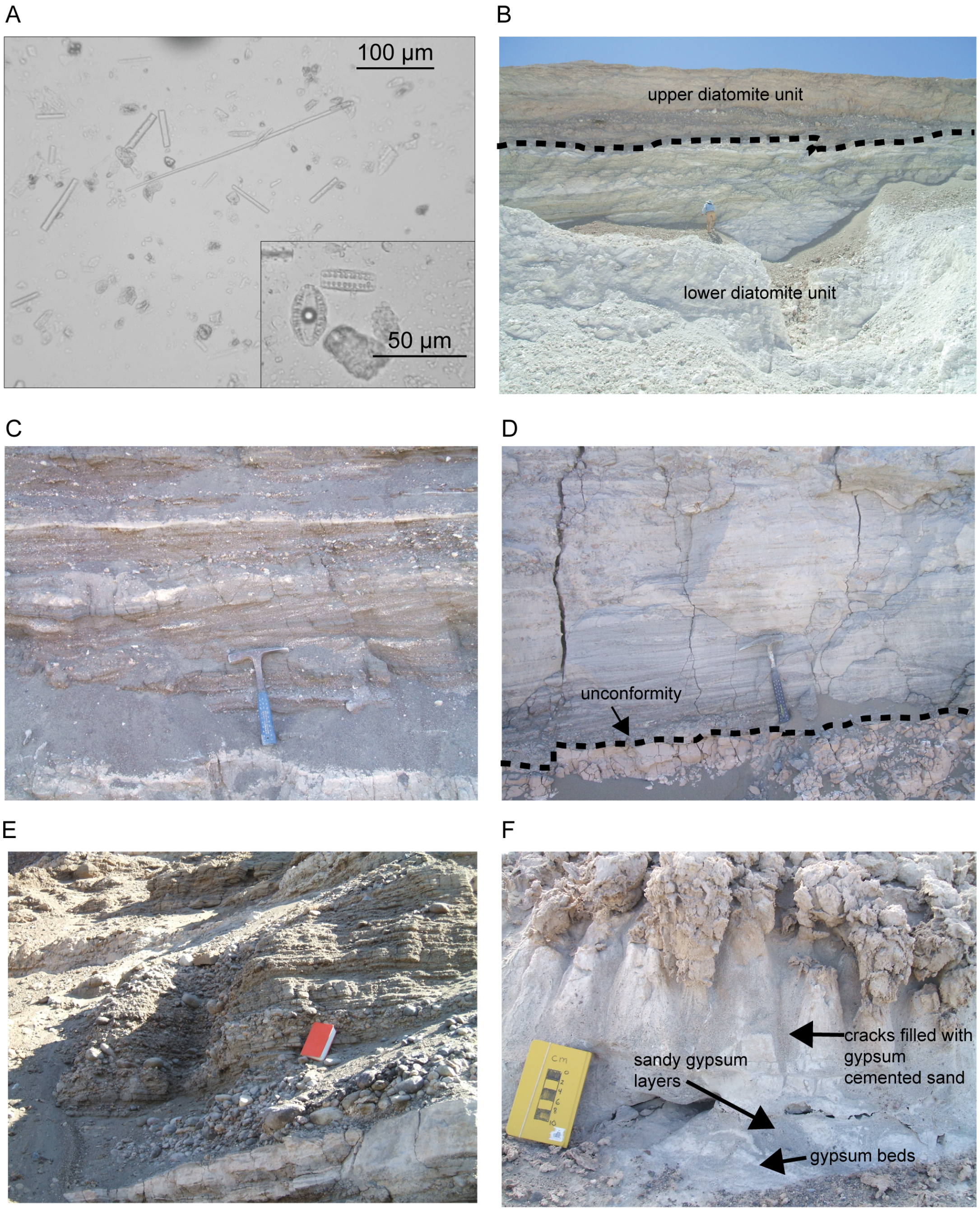


Figure 7. A- Photomicrographs of diatoms from diatomite samples collected at the Tana canyon diatomite mine site. B-White subfacies (lower) and pink subfacies (upper) of diatomite unit exposed in the Tana Canyon diatomite mine (Fig. 8B). C-Salar-formed gypsarenite covered by modern gypsum soils. D-Dark gray sandstones with pebble beds interbedded with light pink muddy diatomite. E-Cross-bedded light gray sandstone overlying the diatomite facies along an erosional unconformity. F-Brown trough cross-bedded conglomerate.

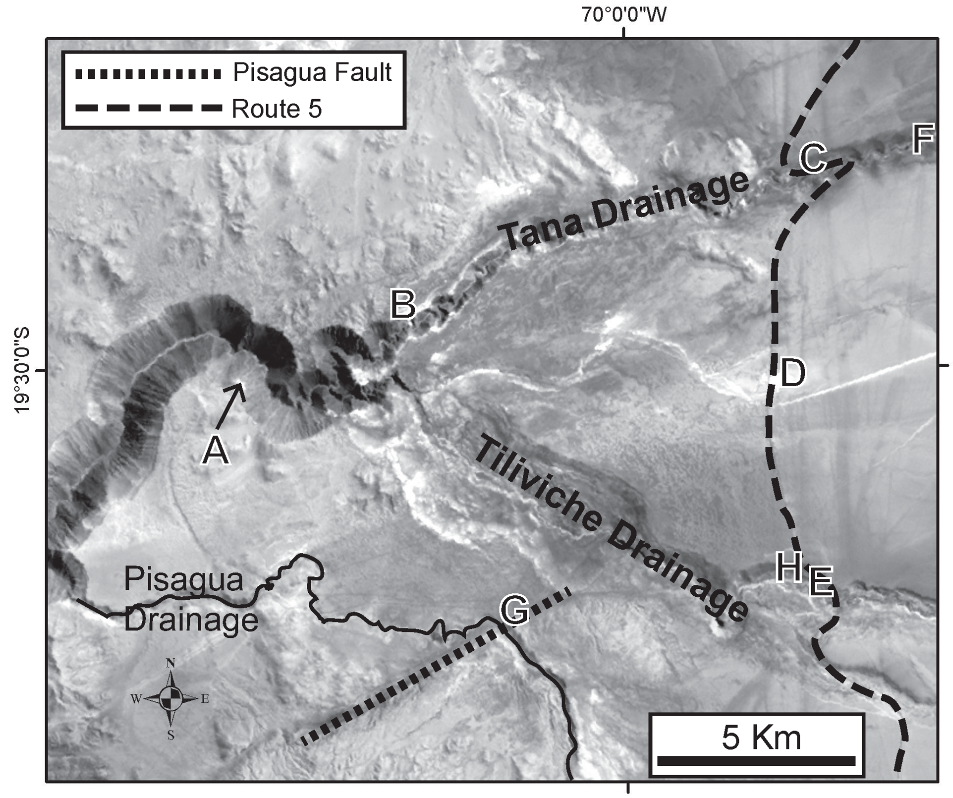


Figure 8. Locations of features mentioned in the text. A- Strath terrace and location of the 6.433+/-0.047 Ma ash interbedded with diatomite beds. B- Tana Canyon diatomite mine. C- Tana Canyon Rt. 5 road cut. D- Pampa de Tiliviche diatomite mine. E- Tiliviche Canyon Rt. 5 road cut. F- Knickzone location within Tana River profile. G- Location of 3.49+/-0.04 Ma ash interbedded with evaporates (Allmendinger et al., 2005). H- Location of 5.5+/-0.6 Ma ash interbedded with sandstones and siltstones (Naranjo and Paskoff, 1985).

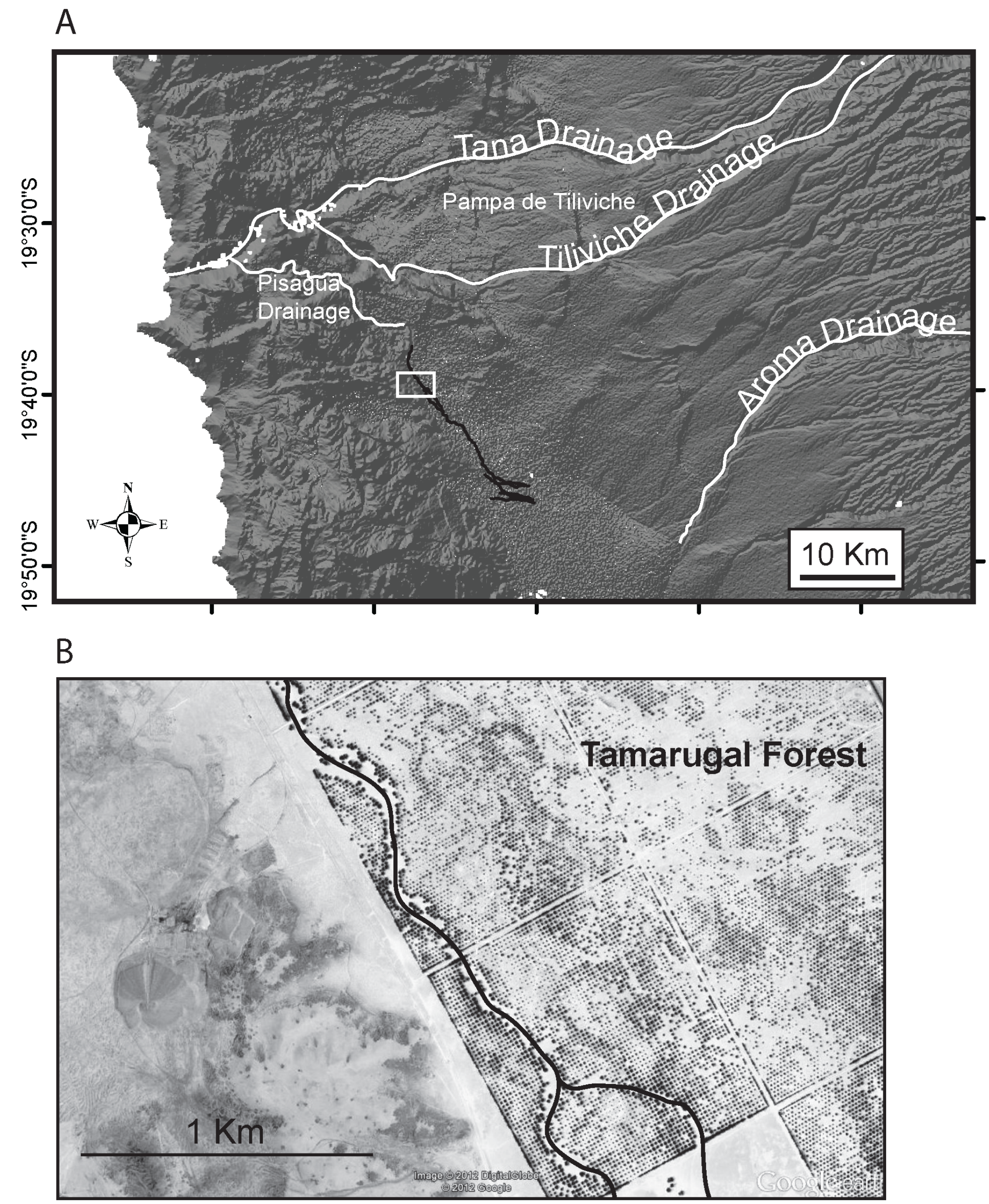


Figure 9. Modern groundwater is accessible to tamarugo trees, Prosopis tamarugo, along paleo-drainage flow paths (pink lines) indicating that the paleolake/paleosalar system may have once been hydrologically connected to the Aroma drainage. A- Digital elevation model shaded relief map of study area, black lines indicate regional paleo-drainage flow paths. B- Google Earth satellite image of tamarugo trees and paleo-drainage flow paths, location indicated by white rectangle in Fig. 17-A.

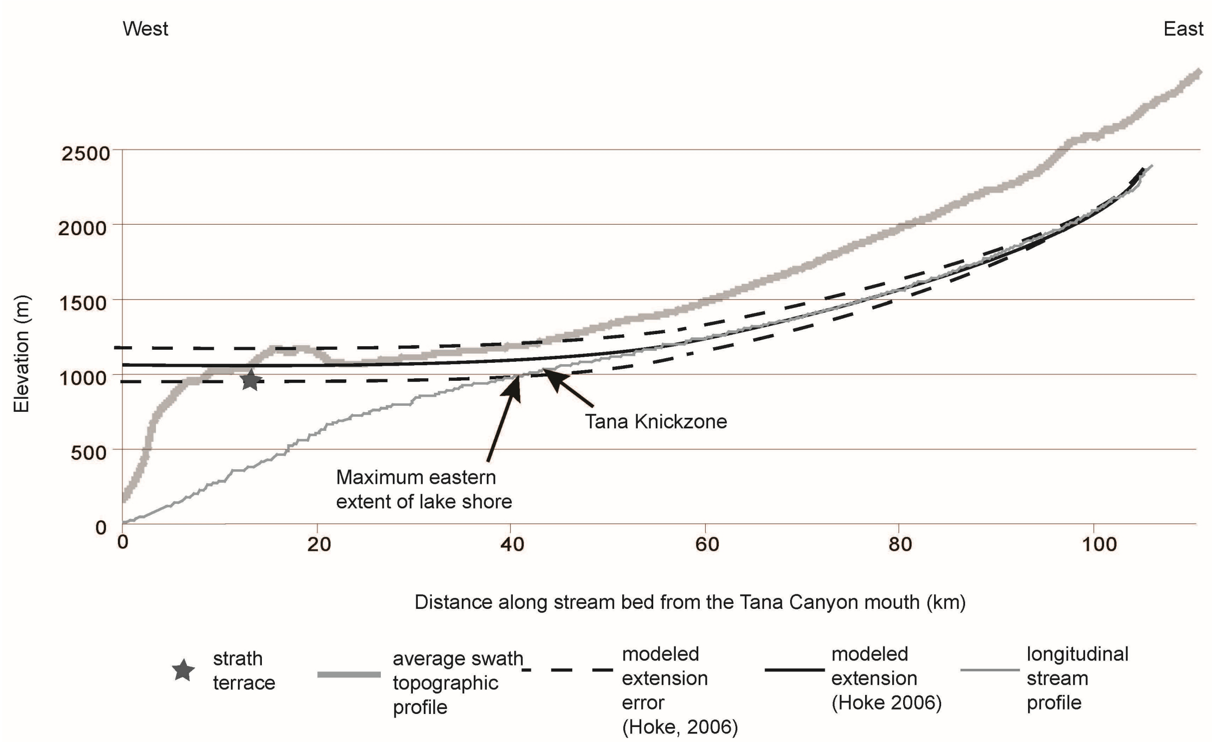


Figure 10. Tana drainage profile, modeled extension (with errors) of the profile upstream from the Tana Knickzone (Hoke, 2006). Strath terrace is within the error indicated on the modeled drainage profile extension. The Tana Knickzone is located ~43 km upstream from the canyon mouth. The eastern limit of the Tiliviche Paleolake shore intersects the Tana Canyon ~41 km upstream from the canyon mouth. An average topographic swath profile has been added for reference.

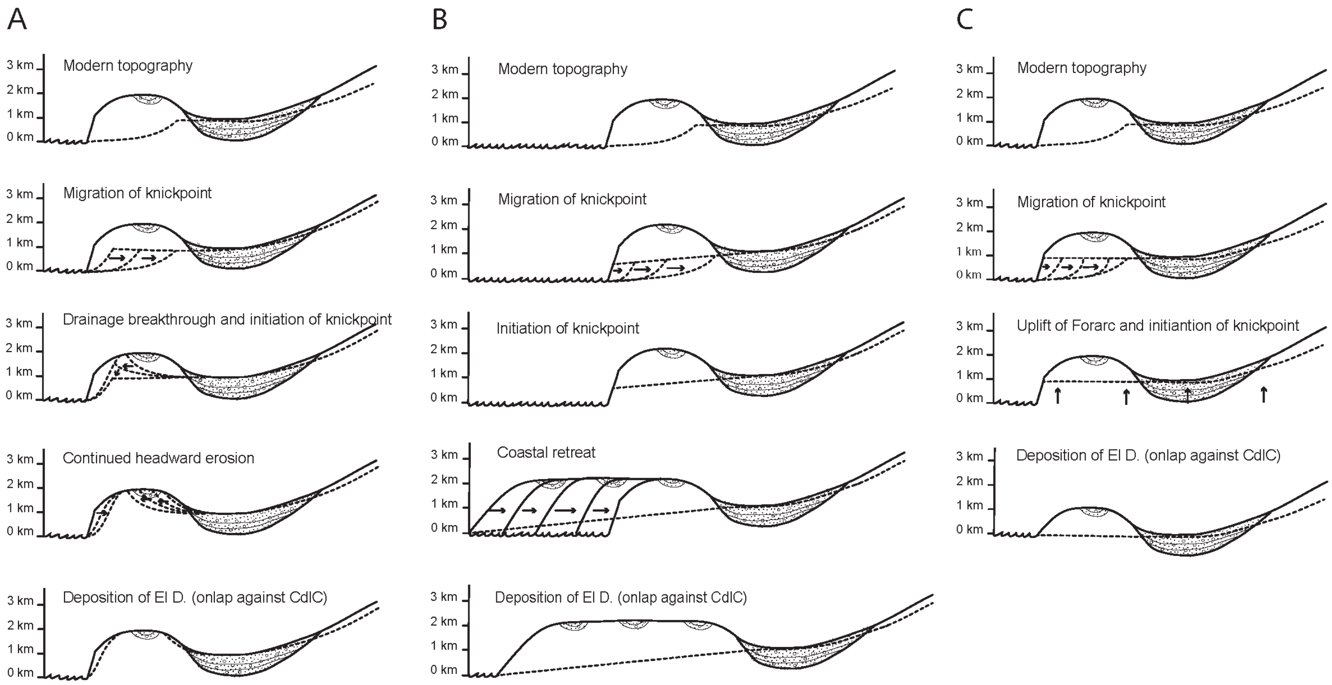
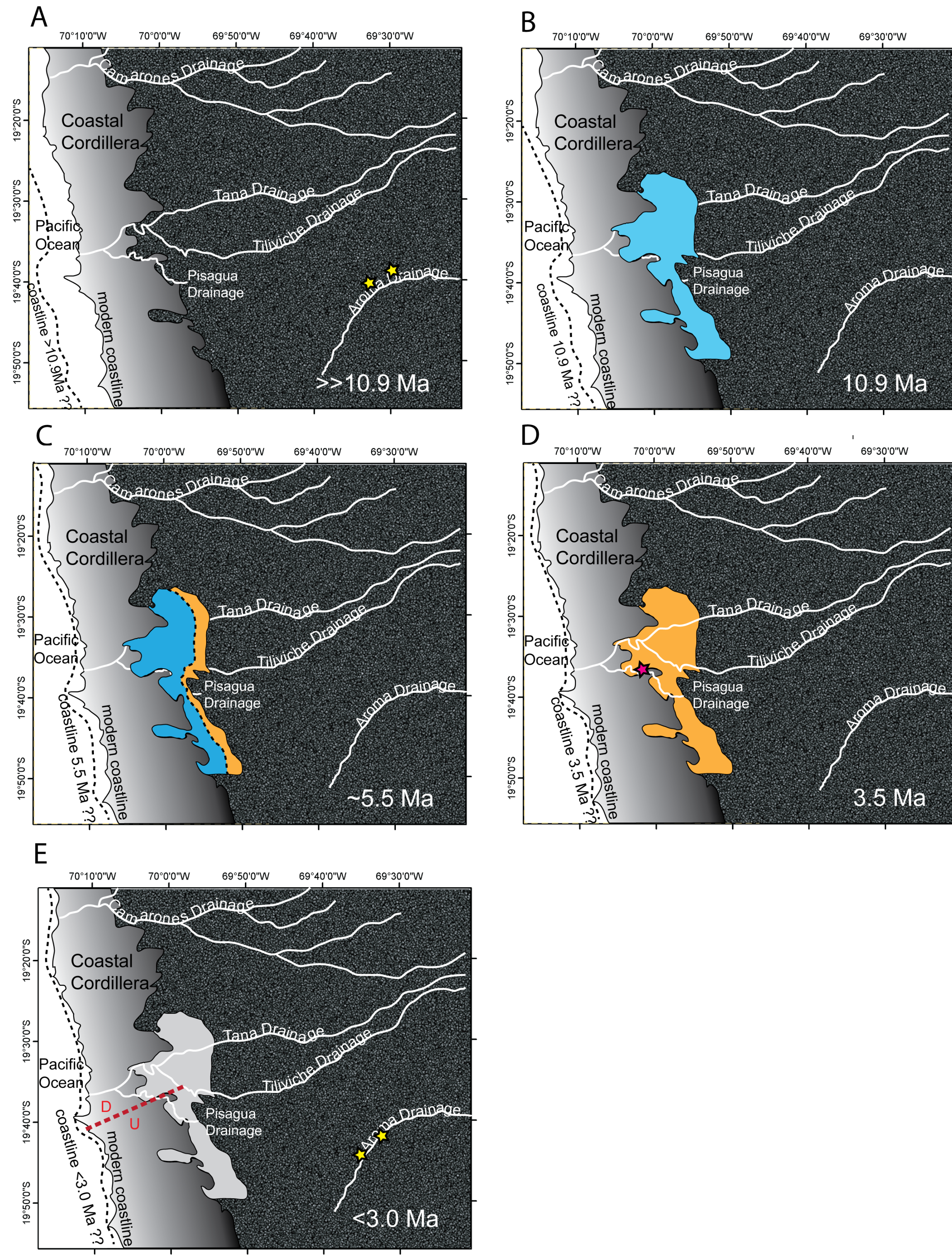


Figure 11. Cartoons of end-member hypotheses for the progressive decline in the western base level and corresponding landscape evolution . A- Drainage Breakthrough via Stream Capture from the West; B- Coastal Retreat; C- Forearc Uplift. Sequences begin in time at the bottom of the page and progress upward. Horizontal axis is not to scale.

Figure 12. Geomorphic and environmental landscape history of the study region. A) El Diablo deposition onlaps Coastal Cordillera before ~10.9 Ma (this work, Supplementary Material). Hyperaridity and large-scale abandonment of pediplain began ~14 Ma. Cosmogenic He exposure ages of 14.6–16.5 Ma on pediplain (Evenstar et al.,2009; yellow stars.) Before ~10.9 Ma the Tiliviche/Tana drainage is blocked within CC and a lake develops. C) By ~5.5 Ma (Naranjo and Paskoff, 1985) the paleoake had begun to shrink and transition to a salar environment in the east. Fluvial sediments were deposited over lake deposits at the eastern edge of the lake/salar system in the Tana and Tiliviche drainages. D) By ~3.5 Ma (Allmendinger et al., 2005) the lake had dried and a groundwater-fed gypsum-halite salar developed (dated ash; pink star). Groundwater remained near the surface within the salar. E) Movement on the Pisagua Fault occurred after ~3.5 Ma. The Pisagua drainage continued to incise during faulting. After ~3.5 Ma the groundwater level dropped, and the salars were abandoned. Renewed incision began after ~3.0 Ma (this work, Supplementary Material). Exposure ages of terraces and minor drainages in the Aroma drainage system range from 3 to 2.6 Ma (Evenstar et al., 2009; yellow stars).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Tana Drainage
Tiliviche Drainage
Pisagua Drainage
Aroma Drainage
Pacific Ocean
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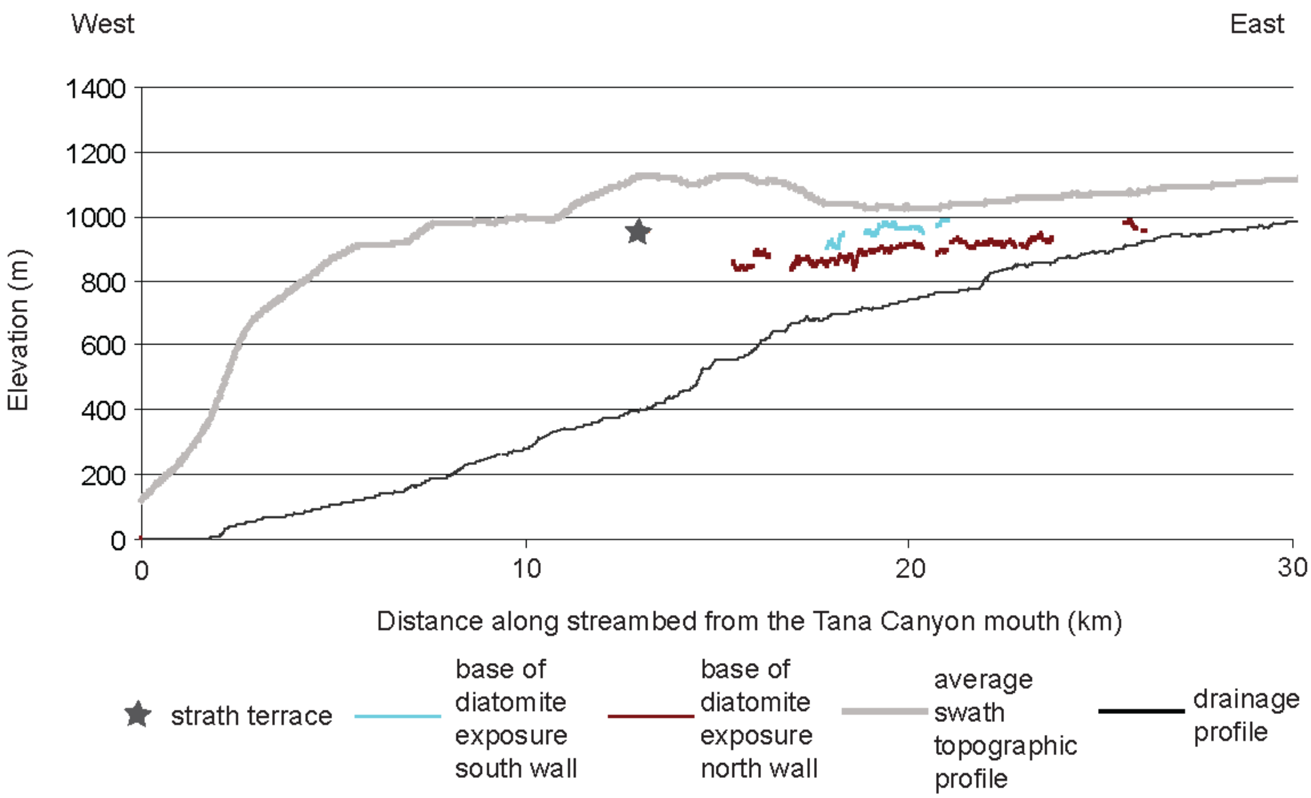

Figure 13. Tana drainage profile, mean strath topographic profile, location of the strath terrace, and locations of the base of the diatomite unit in the canyon walls. The base of the diatomite unit is at a higher elevation on the north wall than the south wall, due to the concave shape of the unit. The base of the diatomite unit has an apparent westward dip within the canyon walls.

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Sarah Hale Wicker
Associate Dean for Administration, Graduate School
350 Caldwell Hall, Cornell University
Ithaca, NY

May 4, 2013

Dear Dr. Wicker,

I am writing to verify the collaborative nature of a project I have had the pleasure to work on with Naomi Kirk-Lawlor, which she intends to include as a chapter of her dissertation. The research and writing that went into the interdisciplinary manuscript, “The economic value of an aquifer with beneficial outflows” was a collaborative effort between myself and Ms. Kirk-Lawlor.

The listed order of our names as authors is alphabetical and not intended to represent differential contributions to the manuscript. Ms. Kirk-Lawlor has my permission to include this collaborative work in her Ph.D. thesis.

Best Regards,

Eric C. Edwards
Ph.D. Candidate

Email: eredwards@bren.ucsb.edu 2400 Bren Hall Phone: 208-301-0247

CHAPTER 3

THE ECONOMIC VALUE OF AN AQUIFER WITH BENEFICIAL OUTFLOWS

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Abstract:

Economic models of optimal groundwater management explore how the water table elevation should change through time in order to maximize an aquifer's value to society. However, economic aquifer modeling studies have typically used a closed single-cell, or bathtub, model with no outflows. In many groundwater systems, the elevation of the water table must be above certain thresholds for some types of surface flow to exist. Examples of groundwater outflows that depend on water table elevation include groundwater baseflow to river systems, groundwater flow to wetland systems, and flow to springs. We modify the traditional single-cell aquifer model by allowing for outflows when the water table is above certain threshold elevations. These outflows are modeled as being beneficial to society, providing economic, social and environmental benefits. We explore the tradeoff between maintaining outflows and maximizing the benefits of groundwater extraction. The value provided by outflows may warrant maintaining the water table at a higher elevation than if only the benefits and costs of groundwater extraction were considered. To illustrate the usefulness of the modified model in a joint economic-hydrologic context, we provide a short case study of the Ojos de San Pedro area

in northern Chile. Evidence indicates that a wetland and lacustrine environment and a village dependent on that environment disappeared due to water extraction for industrial use. We demonstrate how the key features of the model provide important insight in understanding the tradeoffs underlying the decisions made in this case.

1. Introduction

Groundwater management is becoming an increasingly important worldwide concern. Fourty-seven percent of the world's population will be under severe water stress by 2030 (OECD, 2008) and aquifers provide many water scarce regions with some or most of their freshwater. The extraction of water for economic activity in agriculture, municipal supply, and industry make aquifers an economically valuable resource. Many groundwater systems also have natural outflows, such as flows to springs and wetland ecosystems, which provide benefits. The rates of these groundwater outflows are positively related to the elevation of the water table or the piezometric surface. Because of this relationship a key management tradeoff exists between the extraction of groundwater and the maintenance of outflows.

In the economics literature, aquifer management decisions are modeled as a choice of water table elevations through time (e.g. Gisser and Sanchez, 1980; Provencher and Burt, 1994; Knapp and Olson, 1995; Rubio and Casino, 2001; Chakravorty and Umetsu, 2003). Optimal management involves finding the elevation path through time that maximizes the aquifer's value to society, which can include both direct monetary value and assigned social or ecological value. However, this work has typically used a closed single-cell, or bathtub, model with no outflow such as that shown in Figure 1a (Gisser and Sanchez, 1980; Rubio and Casino, 2001). This model does not represent a natural aquifer system in equilibrium because it does not include natural groundwater outflows. The model *requires* human groundwater extraction in order to balance natural recharge. This is a fundamental flaw in the traditional closed, single cell economic aquifer model. Because such a closed model does not include natural outflows, it implicitly sets the economic value of all outflow services to zero. However, the ecosystems and productive activity supported by outflows can provide economic value.

An important management paradigm, sustainable groundwater development or extraction, has emerged in recent years. Sustainable groundwater development has been defined in many different ways. When we reference sustainable groundwater development here, we mean that a steady-state water table elevation that is sufficiently high to preserve valued groundwater services is maintained. By steady-state, we mean that the water table is in equilibrium and not still adjusting to newly imposed changes in extraction rates. Examples of valued groundwater services include maintaining specific groundwater levels in wells, specific rates of groundwater outflow to rivers, springs, groundwater fed wetlands and riparian zones, and to regional groundwater discharge. In most groundwater systems, natural outflows are reduced as the water table elevation drops and cease entirely if the water table falls below a threshold. For instance, if the water table falls below the elevation of a spring (Figure 2), groundwater flow to the spring ceases. There are two major types of aquifers, unconfined or phreatic aquifers ,in which the water table is free to fluctuate without restraint, and confined aquifers, which are overlain by a low permeability unit and as a consequence are pressurized. For simplicity and ease of description, we refer to unconfined aquifers throughout the remainder of the paper, but these same concepts apply to the piezometric surface of a confined aquifer.

To implement sustainable development strategies, managers must determine lower bounds on acceptable groundwater outflow rates and maintain a water table elevation that sustains these flows. Sustainable management may preclude decisions that lower the water table below a given elevation, and so may not correspond with economically optimal management. The traditional economic representation of an aquifer as a closed bathtub with no natural outflows (Figure 1a) (e.g. Gisser and Sanchez, 1980; Rubio and Casino, 2001) underestimates the potential for economically optimal management to coincide with sustainable management because it doesn't include the economic value of outflow services. In this paper, we modify the traditional economic model by including natural outflows that depend on water table elevation. This provides key insight into the tradeoff between sustainable management that protects outflow benefits and the benefits of continued extraction sans outflow. We apply our model to a case study in the Ojos de San Pedro region in northern Chile's Atacama Desert to demonstrate the usefulness of this economic framework in understanding water management decisions.

2. Background

2.1 Hydrologic Background

Inflow to a groundwater system is generally referred to as recharge and may come from precipitation or from groundwater inflow from another aquifer. Natural groundwater outflows include groundwater discharge to rivers and springs, regional subsurface discharge, evapotranspiration from groundwater fed wetlands and riparian areas, and transpiration by plants accessing groundwater (phreatophytes)(e.g. Bradehoeft, 2002). A commonly held definition of sustainable groundwater development, which differs from the definition we provide, is that any development where extraction rates are less than or equal to recharge rates is sustainable (e.g. Gupta and Onta, 1997; Pfeiffer and Lin, 2012). This definition is based on the misconception that when extraction rates are lower than recharge rates, aquifer depletion and depression of the water table does not occur. However, in a groundwater system with natural outflows, extraction at any rate necessarily results in a decrease in the volume of water stored in the aquifer (Sophocleous, 2000; Bredehoeft, 2002).

In an undeveloped groundwater system in equilibrium, natural inflow or recharge rates are balanced by natural outflow rates. When extraction begins, an additional outflow is imposed on the steady-state system, perturbing its equilibrium. Immediately after development, system outflows are greater than system inflows, leading inevitably to a decrease in stored aquifer water. After a time lag, the duration of which depends on aquifer properties and on the spatial relationship between extraction sites and natural discharge areas, changes will occur in natural discharge rates (and sometimes in recharge rates as well) (Bredehoeft, 2002). Eventually, in most cases, a new steady state will be established, in which the sum of the new (lower) natural discharge rates and the extraction rate equal the recharge rate (Bredehoeft, 2002).

In the process of reaching a new steady state, stored aquifer water is lost, causing the water table elevation to decrease. If water table elevation decreases beyond certain thresholds, groundwater flows to rivers, springs, and wetlands will cease. In addition to ecological damage, falling below thresholds can harm certain water resource user groups who may only have access to surface water in specific locations. Loss of surface water flow can also matter economically if switching to pumped groundwater from surface water increases the cost of the water to the user.

2.2 Economic Background

The economics of a single-cell model were first studied by Burt (1964,1966, 1967, 1970) and Domenico et al. (1968) and ignored outflows, focusing on a closed groundwater system. This closed model has remained popular due to its intuitive display of the interactions of the physical system with groundwater pumpers (see for instance Brown and Deacon (1972), Tsur (1990), and Rubio and Casino (2001)). Although many aspects of this model have been studied, the general result is that maximizing the value of the aquifer requires some extraction that balances the benefits of current water use with the cost imposed on all future use by water drawdown (due to increased pumping costs). While much of the economic literature has ignored the outflow component, Gisser and Mercado (1973) provide a single-cell model with outflow, showing how the outflow changes the state equation, but do not explore how placing value on the outflow changes the economically optimal extraction. We do not know of any studies that explore economically optimal extraction when natural outflows are valued.

A good deal of economic literature has focused on the combined use of surface and groundwater, termed conjunctive use. Much of this work consists of hydroeconomic models that "represent regional scale hydrologic, engineering, environmental and economic aspects of water resources systems within a coherent framework (Harou et al., 2009). Because these types of models utilize full three-dimensional hydrologic modeling, they do include groundwater outflows, see for instance Pulido-Velazquez et al. (2006), but do so in basin-specific applications with little exploration of the general effect of groundwater outflow value on economic behavior. So, while groundwater outflows are shown to be important in these basin specific three-dimensional models, their results are not transferable to other basins. Other literature explores general economic solutions to conjunctive management problems, in which groundwater and surface water are managed together, for instance Chakravorty and Umetsu (2003), Provencher and Burt (1994) and Knapp and Olson (1995). To our knowledge, this literature has not addressed groundwater outflows and their economic benefits specifically and, therefore, the conclusion of Knapp and Olson (1995) that there is little to gain economically from managing groundwater extraction may be potentially missleading. Kuwayama and Brozovic (2010) have recently addressed stream flow reduction due to nearby groundwater pumping, focusing on the most efficient way to limit pumping, but not directly considering the tradeoff between the value of extraction and outflows.

Aquifer outflows may provide services that are not valued in a market, for instance maintaining ecosystem health or sustaining culturally significant water uses. Determining the values of these nonmarket services or ecosystem benefits, such as species habitat, human enjoyment of a particular ecosystem, or tourism that depends on the health of an ecosystem can be difficult (e.g. Costanza (2000); Heal (2000), Ludwig (2000), National Research Council (2005), Martina and Blossey (2009)). While some authors have questioned whether the valuation of resource services is appropriate at all (Ludwig, 2000), the insights gleaned from examining these types of tradeoffs can be useful, even if there is debate over their valuation.

3. Model

The model is based on the single cell or bathtub aquifer model that we will refer to as the traditional model (Figure 1a). We improve on the basic single-cell model to directly address the benefits provided by maintaining a given water table elevation that allows for a valued outflow to exist. We do this by incorporating natural hydrologic system outflows as 'holes' in the bathtub when the groundwater table is above certain threshold elevations.

Figure 1b depicts the revised model with a single threshold point. In this model recharge rate, R, represents hydrologic inflow to the groundwater system. Groundwater extraction is pumped at rate W from the elevation of the water table, H, to the elevation of the land surface, S_L. A portion of this extracted water, α, returns to the system. At the threshold elevation, H^*, a flow of water with a rate of Q=Q(H), also exits the system. The rate of outflow is an increasing function of water table elevation, when $H>H^*$. We assume that Q=0 when $H< H^*$ (it is possible that water flows into the basin once $H< H^*$, then Q<0 for $H< H^*$, but in an arid region this is unlikely to be the case and we ignore this possibility to simplify the analysis). This model does not consider inflowing surface water that comes from outside the model boundaries.

For our analysis we consider the groundwater system to be a linear reservoir in which the outflow rate(s), Q, is proportional to stored water volume, a common assumption in hydrology (e.g. Boussinesq (1903), Barnes (1939), Brutsaert (1994)). In this case, the outflow rate is linearly dependent on the water table elevation, H, a proxy for aquifer storage or thickness (e.g. Brutsaert (2010)).

For this system generally, the equation of motion is:

$$\frac{dH}{dt} = \frac{R + (\alpha - 1)W - Q}{S} \tag{1}$$

The change in elevation of the water table with time is related to the rate of recharge, R, minus the net extraction and outflow rates, $(1-\alpha)W+Q$, by the specific yield, S, which is the water released for every unit decrease in the water table elevation. In the model we propose, the aquifer is one-dimensional and has no cross-sectional area, so R, W, and Q are in units of length/time.

We can examine the system in steady state, where:

$$\frac{dH}{dt} = 0 \tag{2}$$

This provides us with a simple water balance:

$$R = (1 - \alpha)W + Q \tag{3}$$

Based on the linear reservoir assumption, we can write a linear approximation of Q as a function of water table elevation, where β and A are constants (A is defined as the product of two constants, $A=-\beta \cdot H^*$):

$$Q(H) \approx \beta \cdot (H - H^*) = A + \beta \cdot H \tag{4}$$

The water balance (equation 2) can be transformed to write withdrawal as a function of elevation:

$$W(H) = \frac{R - (A + \beta H)}{1 - \alpha} \tag{5}$$

H describes the state of the aquifer, and the current steady state is H_0. The decision water managers must make is to choose H_1, the steady-state elevation to be maintained going forward. If H_1 is different from H_0, there is a transition period where the system is not in steady state; the water table is being raised and additional water stored by reducing the pumping rate, or lowered and additional water mined by increasing the pumping rate.

3.1 Economics of the Model

In an ideal economic management scenario, the choice of steady-state water table elevation is made to maximize economic benefits. We consider a one-time management decision to make an immediate and permanent pumping rule so that pumping will lead to a steady-state water table elevation at $H_{1,}$ as dictated by equation 5. Thus, water extraction is $W=W(H_1)$.

Costs and benefits change through time as a function of prices for the means of extracting and utilizing water and goods and services produced using water. The water provides a benefit at any point in time, t, of B(W,t). The cost of extracting water at rate W from elevation H is given, at any point in time, by C(W, H(t),t). The rate of withdrawal is fixed by the decision to set pumping at the rate necessary to hold the groundwater table at H_1. If the water table is not at elevation H_1 initially, H(t) moves in transition from H_0 to H_1. The flow Q also provides a continuous benefit, U(Q,t), for $H> H^*$, which can be written as $U(A+\beta H(t),t)$ using the linear approximation from equation 4.

We introduce an indicator function, I, such that:

$$I(H(t)) = \begin{cases} 1, H(t) > H^* \\ 0, H(t) \leq H^* \end{cases} \tag{6}$$

Given these functions, the total net economic benefit, including natural outflow benefits from U(Q,t), at any point in time is given as a function only of the elevation of the water table over time, tb(H(t)):

$$tb\big(H(t)\big) = B(W,t) - C\big(W,H(t)\big) + I(H(t)) \cdot U\big(Q(H(t))\big) \tag{7}$$

Integrating equation 7 over time, the discounted (accounting for the time value of money with interest rate r) benefits minus costs provide the total net benefits through time of the decision and gives the total net benefit function, $TB(H_1)$:

$$TB(H_1) = \int_0^\infty \big[B(W,t) - C\big(W,H(t)\big)\big]e^{-rt}dt + \int_0^\infty I(H(t)) \cdot U\big(Q(H(t))\big)e^{-rt}dt \tag{8}$$

The total benefit function has two components, whose integrals have been separated, and to guarantee a solution to the manager's problem, we assume each component is concave with increasing depth to water, S_L-H_1, over the relevant range (see Figure 4 for the general shape of total benefits as a function of S_L-H_1).

3.2 Extension to Multiple Thresholds

Multiple threshold systems with more than one natural outflow, such as systems with groundwater flow to both a river and a spring, are easily simulated using the model (Figure 3). Consider a system with n water table thresholds. For simplicity, number the thresholds from 1 to n such that H_1^* is at the highest elevation, H_2^* the second highest, and so on until H_n^*, which is the threshold at the lowest elevation.

The groundwater outflow rate at any threshold, indexed by i, can be written using the approximation from equation 4 where β_i is a constant corresponding to each threshold H_i^*:

$$Q_i(H) \approx \beta_i \cdot (H - H_i^*) \text{ for } H > H_i^* \tag{9}$$

For a water table elevation above some threshold, k, but below the next threshold, k+1, that is $H_k^* < H < H_{k-1}^*$, the total system outflow is the sum of all the individual outflows that occur below the elevation of the water table:

$$\sum_{i=k}^{n} Q_i(H) = \sum_{i=k}^{n} \beta_i \, (H - H_i^*) = H \cdot \sum_{i=k}^{n} \beta_i - \sum_{i=k}^{n} \beta_i \cdot H_i^* \tag{10}$$

Other than H, all the terms in equation 10 are constants. Between threshold points, the combined outflow changes linearly with elevation. However, the combined outflow function for all H has n discontinuities that occur where:

$$H = H_i^*, i = 1,2, \ldots, n \tag{11}$$

Thus, although for the remainder of the paper we focus on the single threshold case, the results can be easily extended to multiple thresholds.

4. Economic Results

To analyze the decision facing a social planner or resource manager attempting to choose the elevation at which to maintain the water table, H_1, we plot total net economic benefits (equation 8) as a function of depth to the water table, S_L-H_1. Figure 4a represents a scenario where maintaining the threshold-dependent outflow and associated service also maximizes economic value. Figure 4b shows a scenario in which continued depletion of the aquifer, beyond the threshold point, creates more value. The x-axis represents decreasing water table elevation, or alternatively, increasing depth to the water table. In the single threshold case, the total net benefits function has two local maxima. When H_1 is set at elevation H_P (depth S_L–H_P), the total benefit function is at the local maxima representing the productive benefits of pumping, minus the pumping costs. When H_1 is set at (the higher) elevation H_E, the total benefit function is at the local maxima representing the net productive benefits of pumping summed with the benefits of the outflow, Q. The maximum total benefit at H_E can occur where H_E is greater or equal to H^*, depending on the relative curvature of the functions representing the total pumping benefits and ecosystem benefits.

4.1 Comparison to Traditional Model

In the traditional model the pumping rate is at steady state, W_0, if:

$$W_0 = \frac{R}{1 - \alpha} \tag{12}$$

In comparison, the steady-state pumping regime of the new model, when the water table elevation is above the threshold (equation 5) also includes natural outflows. If there is no human groundwater withdrawal, the new model shows that the system is in natural steady state when Q=R. Using the linear approximation from equation 4 for Q, the natural system steady state occurs at a water table elevation of H_{ss}:

$$H_{ss} = \frac{A - R}{\beta} \tag{13}$$

In comparison, the traditional model cannot be in steady state without human pumping, which excludes representation of natural systems in steady state. The new model more accurately represents a natural groundwater system by showing that extraction must always be less than recharge in steady state unless there are no natural outflows.

The new model represents the system in steady state prior to human extraction. Pumping lowers the water table, which in turn reduces the natural outflow rate until the steady-state condition, equation 4, is satisfied. Lowering the water table decreases natural outflow rates, which is balanced by the increased extraction. At steady state in the new model net extraction rates are always less than the recharge rate when the water table exceeds the threshold elevation.

In the traditional model, anytime W satisfies the steady-state pumping regime, where net pumping is equal to R, H is maintained at its current level. In other words, in the traditional model the same extraction rate is maintainable for any water table elevation, which is not consistent with experience in the real world. In contrast, the new model more accurately reflects how, at steady-state, higher rates of extraction are associated with lower water table elevations.

Economists are often interested in what occurs when groundwater users are allowed to pump without restriction, known as open access. When marginal benefits are decreasing with increasing water use, the new model shows a lower resulting steady-state water table elevation than the traditional model because of the additional outflow. That is, in systems that have a natural outflow component, modeling open access extraction without outflow systemically underestimates water table drawdown.

5. Discussion of the Model

When an aquifer is drawn down, some of the extracted water was originally in storage, and it is mined. Economists have long been interested in the tradeoffs of maximizing the value of the flow (renewable) portion and of the stock (stored) portion of an aquifer. Doing so requires balancing future cost of decreased water table elevation with the present use of stored water. We acknowledge this is a very interesting question, but argue the traditional single-cell model fails to provide a realistic representation of tradeoffs in water systems where natural outflows are important. In aquifers with high flow to stock ratios, a decrease in stock, and thus steady-state water table elevation, can significantly increase the portion of the flow that can be captured at the new water table elevation. An alternative way to look at this is that in these aquifers a reduction in stock can cause dramatic changes in outflows to important services.

The model we describe, while a simplification, allows the use of a single-cell model in many cases where the traditional model would not be relevant. Even though groundwater system outflows may occur at different geographical locations from the site where water extraction is occurring, these outflows can still be modeled as linearly dependent on water table elevation at the extraction site. Figure 5 illustrates a hypothetical example of a system with multiple natural outflows at varying threshold elevations. As described in Section 3, groundwater flow rates to a river located at some distance from the extraction site (Figure 5) can be modeled as linearly dependent on the water table elevation at the extraction site based on the linear reservoir concept (Brutsaert, 1994; Brutsaert, 2010) . Likewise, evapotranspiration rates from wetlands can be modeled as linearly dependent on the depth of the water table below the wetland surface, for water table elevations between the wetland surface and a defined extinction depth (Figure 5) (Luo et al., 2009). In this case the threshold elevation (below which the benefit of the wetland environment will be lost) is the extinction depth of wetland evaporation.

Regardless of whether it is considered a valued service, regional groundwater discharge that leaves the modeled system (Figure 5) should be included in any groundwater model unless the system is hydrologically closed. Regional groundwater discharge rates can be modeled as linearly dependent on the elevation of the water table, as would be the case for a simple bathtub model (Moore and Derry, 1995) with the addition of a scaling factor that represents specific aquifer properties (i.e. hydraulic conductivity). This representation of regional groundwater discharge in economic modeling is consistent with the methods of Gisser and Mercado (1973).

While single cell models are useful in visualizing and solving economic questions about aquifer behavior, they also have a number of drawbacks. Pumping in a single-cell model is immediately transmitted to the entire modeled system. In real groundwater systems, temporal and spatial lags exist and are typically too significant to model using a single-cell framework. Additionally, such a single-cell model does not allow for the exploration of geographical effects of varying extraction placements. More complex economic models have been proposed which look at the economics of spatial and temporal effects of pumping (Brozovic et al., 2006, 2010). We argue a single-cell model is best used to describe steady-state systems and, importantly, sustainability goals are themselves often based on an assumption of steady-state. Thus, evaluating the consequences of management decisions on sustainability, defined using steady-state concepts, is precisely where the single-cell model can be useful.

There is evidence worldwide that groundwater resources are often not sustainably managed (or managed at all), an observation consistent with the understanding of groundwater as an open-access resource (Nelson, 2012; Fishman et al., 2011). A counterintuitive economic result, from a paper by Gisser and Sanchez (1980), has emerged when the traditional single-cell model is used to compare open-access and optimal pumping plans. Known as the Gisser-Sanchez Effect, the result of the paper indicates that optimally managing an aquifer does not result in significant economic benefits (see Koundouri (2004) for a summary of this literature). Since the cost of implementing a management regime may be high, the Gisser-Sanchez Effect seems to justify a decision not to manage (Burness and Brill, 2001). We find that this result disappears as the benefits from the use of outflows, and thus benefits of maintaining higher groundwater tables, increase.

In addressing the Gisser-Sanchez Effect, Esteban and Albiac (2011) incorporate an explicit ecological externality of water use to attempt to include the benefits of these services. They define ecosystem damage as a parameter multiplied by the total amount of water withdrawn in excess of recharge. The new model more correctly demonstrates that extraction, even extraction less than recharge, necessarily reduces the water table and thus can cause damage to system outflows and associated services. It also provides for a more realistic representation of these services, demonstrating how these services depend on water table elevation. Specifically, these services are damaged when the water table elevation approaches a threshold and eliminated when the water table elevation falls below that threshold. Even with these differences, the results of the new model are consistent with Esteban and Albiac’s (2011) result that the Gisser-Sanchez Effect disappears in the presence of outflow benefits.

The theoretical steady-state water table elevation that results in the economic maximum is independent of the recipients of the benefits of extracted water and natural outflows. However, who receives these benefits may depend on whether the water table is above or below a threshold. For instance, the public at large may share the benefits of maintaining the water table above a threshold while the benefits of groundwater extraction fall to a small group. Unequal distribution of benefits among users is also an important factor limiting successful collective management of common pool resources (Libecap, 1994). In the next section we apply our model to a case where these issues are present.

6. Case study: Ojos de San Pedro, northern Chile

The Ojos de San Pedro (OdSP) area in northern Chile’s hyperarid Atacama Desert has experienced significant changes due to human water extraction. OdSP is located near the Bolivian border along the San Pedro River (~21.98° N; 68.31° W), a tributary of the Loa River, at an elevation of ~3800 m (Figure 6). This area supported a lake and wetlands system until increased water extraction, primarily for use in copper mining, lowered the water table elevation causing the successive desiccation of the lake and then wetlands systems and the loss of groundwater flow to the San Pedro River. The OdSP village was abandoned in the early 1970s as a result of the loss of its surface water resource (Molina and Montecino, 2006). Here we apply our model to the OdSP area, designating the groundwater flow to the San Pedro River, the wetlands and lake environments, and the surface water resource provided to the village as threshold dependent natural outflow services.

6.1 Hydrologic Setting

In this hyperarid region, precipitation is highly correlated with elevation, with higher elevations receiving more precipitation (Houston and Hartley, 2003). Below 2000 meters, precipitation is nearly non-existent, with annual average precipitation rates as low as 2 mm, which occur as individual rainfall events of ~10 mm every few years (Romero and Kampf, 2003). The OdSP region is in the upper reaches of the Loa Basin and as such is comparatively rich in water resources compared with lower elevations where population centers and mining activities are located. The rivers of the Loa hydrologic system, including the San Pedro River, are exclusively groundwater fed except during rare precipitation events (Houston, 2006a). Potential evapotranspiration rates are high due to the extreme aridity of the region and range from 2190 to 41,998 mm/yr when measured using pan evaporation techniques (Chauffaut, 1998; DGA, 2003).

The OdSP aquifer is located within an east-west valley bounded by volcanic peaks (Figure 6) and is composed of gravels and sands with some interbedded lava flows (CORFO, 1977). The aquifer is reported to extend approximately 150 m below the surface where it is thickest based on borehole data (CORFO, 1977). The OdSP aquifer system has been described as a water resource system in which recharge and discharge rates are high in comparison to the stored water volume of the aquifer (CORFO, 1977). Currently, the San Pedro River is dry where it reaches the Loa River. However, stream flow data from a temporary set of gauging stations operated in 2001 along the Loa River (Alex Covarrubias, personal communication, September 27, 2012) provide evidence that groundwater discharge from the San Pedro Basin provides approximately 400 l/s of water to the Loa River.

6.2 Case History

Information about granted water rights is available for this region and presented here, however, information about actual historical water extraction rates is not available. In 1909 the first allocation of water rights in the San Pedro Basin was made; a railroad company was granted surface water rights amounting to 80 l/s upstream of the OdSP region. Prior to 1958 a lake existed in the OdSP region and the village was located near its shore (Molina and Montecino, 2006) (Figure 6). In 1958 rights to divert 31.5 l/s of surface water upstream of OdSP were granted to a mining company (DGA, 2005; Yanez and Molinas, 2008). By 1961 the lake had experienced a ~85 % reduction in size and the newly desiccated area had become wetlands (Instituto Geográfico Militar, 1971). Beginning in 1968, groundwater resources were extracted from the OdSP region, first through drainage dredging, and then later using pumping wells. By 1972 the wetlands and lake systems no longer existed (Klohn, 1972) and the village was abandoned soon after (Molina and Montecino, 2006). Rights to the groundwater resources in OdSP, accessed both through dredging and pumping, were formally allocated retroactively to the mining industry in early 1990s and were restricted to a combined total of 1,200 l/s (DGA, 2012). The modern San Pedro River bed is dry in the study area due to the continued groundwater extraction that has occurred.

6.3 Hydrologic Analysis

In this case study we assume the hydrologic system to be in steady state during the three distinct time periods we focus on: before human water use when the lake was at its fullest extent, in 1961 when the lake had dried significantly but surface water was still available, and modern conditions in which no surface water exists and the village has been abandoned. We make this assumption based on the high hydraulic conductivities of the aquifer materials; however, as with any complex system, in reality it is most likely in flux. In applying our model, we consider changes in human water usage to be the primary factor that perturbs the steady-state nature of the hydrologic system. However, natural fluctuations in the climate on a yearly and decadal scale (Houston, 2006b) have also likely affected the water table elevation through time.

Based on modern remote sensing imagery and an historical air photo, at its largest extent the OdSP lake covered an area of ~6.4 km^2 and the elevation of the lake surface and the water table elevation was ~ 3805 m.a.s.l (Instituto Geográfico Militar, 1971). The average San Pedro River flow rate, prior to human groundwater extraction, was approximately 700 l/s (CORFO, 1977). By 1961 the area covered by standing water had been reduced to ~0.8 km^2; ~5.6 km^2 was wetlands (Instituto Geográfico Militar, 1971) and the water table elevation was ~3801 m.a.s.l. Based on monitoring well data, the average present (2010 to 2011) water table elevation in the OdSP, excluding cones of depression near pumping wells, region is ~3797 m.a.s.l., approximately one meter lower than the river bed elevation of ~3798 m.a.s.l. (Unpublished data, DGA, 2012). The modern water table does not crop out at the surface. In the modern system, the San Pedro River is currently dry downstream of the study area except where pumped groundwater is transferred to the river bed for transport downstream. In applying our model to this system, we designate 3798 m.a.s.l. to be the threshold elevation. When the water table elevation is beneath this threshold natural groundwater outflows from the aquifer to the San Pedro River, the lake and the wetlands, cease.

As the water table elevation fell, river outflow rates and evapotranspiration rates were reduced and eventually ceased. River outflow was reduced from 700 l/s when the water table elevation is 3805 m.a.s.l. to zero l/s when the water table fell below the threshold elevation of 3798 m.a.s.l. We interpolate the rate of outflow to decrease linearly with the lowering of the water table elevation. Reductions in the evapotranspiration rate are estimated as a series of linear trends and thresholds based on the changing surface area of the lakes and wetlands as water table elevation decreased. The average evaporation rate in the San Pedro basin from 1968 to 1976 was recorded as 4198 mm/yr (Chauffaut, 1998). This is the value we used to estimate evapotranspiration from the lake surface. A good estimate of the evapotranspiration rate in wetlands in the Atacama Desert is 2190 mm/yr (CORFO, 1977). This is the value we used to estimate evapotranspiration from the wetlands. Table 1 shows the estimated reductions in groundwater flow to the San Pedro River and evapotranspiration from the system due to successive water table lowering for the time spans in question. These reductions represent successive reductions in natural outflows from the modeled system; this allowed for the accompanying increase in extraction rate at each steady state.

Additionally, we estimate the volume of stored water that was depleted before 1961 and that has been depleted since 1961 due to the decreases in water table elevation. This depleted 'stock' consisted of both stored lake water and stored aquifer water. We consider the OdSP aquifer to be ~20 km^2 based on surficial geologic and topographic characteristics (Figure 6) and assume an average specific yield of 0.15 for the aquifer as a whole (CORFO, 1977). For the purposes of these estimates we assume a simplified aquifer shape of a triangular prism based on the mapped surficial footprint of the aquifer and the calculated average topographic slope of contact of the porous rocks with the less porous volcanic rocks that surround and underlie the aquifer. Additionally, for the purposes of these estimates we assume the geometry of the OdSP lake to be conical. Table 1 shows the estimated loss of stored water volume that occurred as a result of progressing from each steady-state water table elevation to the next (before human use, 1961 and present).

As well as examining the effects of what has already occurred in the OdSP aquifer system, we estimate the theoretical reductions in stored water volumes that would occur if water table elevations were lowered beyond the present elevation of 3797 m.a.s.l. down to the base of the aquifer. Figure 7 displays the economic interpretation of the case study and is based on these estimates.

6.4 Economic Interpretation

This case study illuminates the economic consequences of incorporating threshold-dependent outflows in a cost-benefit analysis of a system in which the water table elevation has been lowered by human extraction. We use water price averages between 2000 and 2009 in the area near OdSP from Catastro Público de Aguas, (see Edwards et al. (2013) and Cristi et al. (2012) for additional information on this price data). The current weighted average water price for water transfers near OdSP is $326,178 per l/s with around 900 l/s total traded .We use the present price of water, rather than historical prices, to simulate the water extraction benefits, because the data is readily available and it is easier to compare these modern prices to the perceived modern values placed on the ecosystem and village, which were not measured in this study.

Prior to 1961, we estimate that the water table elevation decreased by 4 m, which led to the elimination of much of the standing surface water at OdSP, decreasing the evapotranspiration rate by an estimated 356 l/s and reducing groundwater flow to the San Pedro River by ~400 l/s.

These reductions in natural outflow rates were associated with an estimated increase of 756 l/s in extractable groundwater at the new steady-state elevation of 3801m. Because this increase in extractable water was accompanied by a 400 l/s decrease in flow to the San Pedro River—surface water available for economic use—the net increase in available water is 356 l/s. At average prices this net increase is worth around $116 million. Using a 7% discount rate, we expect the stored water that was depleted to be worth only about 13.0% of the value of the captured evapotranspiration.

Between 1961 and present, the continued lowering of the water table that resulted in the elimination of surface water, the desiccation of the wetland ecosystem at OdSP, and the loss of groundwater flow to the San Pedro River is estimated to have made an additional 795 l/s of groundwater available for extraction. This corresponds to a net increase in available water of 495 l/s, an amount of water worth around $161 million at current prices. The stored water that was depleted during this stage is only around 4.4% of the value of the increase in steady-state water availability at the new elevation of 3797 m.

These value estimates represent only the monetary value of extracted waters and do not take into account the value of lost outflow services provided by river, lake, and wetlands resources. The value of the net increase in extractable water may be partially or wholly offset by the loss of valuable riparian, lake and wetland flows and by the decrease in available surface water for the inhabitants of the OdSP village. The abandonment of the OdSP village in the early 1970s is an additional cost associated with these decreases in water table elevation and also acts to offset the value of net increases in extractable water.

One important implication of these estimates of extracted water values is that the value of water from the increase in steady-state extraction rate that occurred due to passing the 3798 m.a.s.l. threshold is around an order of magnitude greater than the value of the "mined" water or stock. This indicates that, even without taking into account the value of outflow services, the threshold dependent outflow behavior is economically more important in this type of aquifer than “groundwater mining”, at least for shallow water table depths.

At OdSP increasing water extraction rates and the associated drop in the water table elevation caused the system to pass an important threshold that resulted in loss of ecosystems and the only surface water resource used by a village. All of the economic, social and ecological benefits provided by the natural outflows were lost when this threshold was crossed. However, the increase in water extraction associated with this drop in water table elevation has monetary value and is important to consider. Figure 7 plots the tradeoff between pumping-only benefits and the benefits provided by maintaining a water table elevation that preserves the wetland ecosystem and village.

Estimating the value of the village and ecosystems using economic techniques would require data and analysis far beyond the scope of this study. Therefore, we do not attempt to place a value on these outflow services. Instead, we plot a function that indicates what the current value of all future benefits from the ecosystems and village would need to exceed to justify a decision to maintain a particular water table elevation using benefit-cost analysis. The light grey shaded area in Figure 7 indicates the possible values that the outflow services (river flow, riparian, lake and wetlands ecosystems, the existence of the OdSP village) could have for which the overall economic optimum would be achieved by maintaining these outflows. In other words, if the value provided by natural outflow falls within this region, then the water table elevation that would maximize the total value of the water resource system would be above the outflow threshold. In this scenario, maintaining the natural groundwater outflows would be the economically advantageous decision. What elevation to maintain the water table at – and thus what natural outflow rate to maintain – would depend on where within the light grey area the value provided by the natural outflow falls. The dark grey area indicates the possible values for the village and ecosystems for which the overall economic optimum would occur at a water table elevation below the threshold elevation. If the value provided by the outflow is within this area, then the overall economic optimum scenario would not maintain natural outflows, rather it would draw down the water table elevation to 3715 m.a.s.l., well below the threshold elevation.

Figure 7 suggests that maintaining a water table elevation near its initial, pre-development, level must provide high benefits to be justified using cost-benefit analysis. Lowering the water table some, while still maintaining outflow services at lower outflow rates, may decrease the value of these services. Still, it is likely that such a decision would increase the likelihood of a sustainable solution also conforming with the results of a cost-benefit analysis. This is because even a minimal lowering of the water table elevation increases the rate of steady state groundwater extraction. That increase, in turn, increases the value of pumped groundwater, meaning that the outflow services do not need to be as valuable in order to justify their protection.

If the benefits of outflows are not large enough to justify maintaining high water table levels, the decision reverts to one that maximizes the value of the pumped water only. As is the case in OdSP, this economically optimal water table elevation may be far below the 3798 m.a.s.l. threshold elevation. In OdSP, this maximum economic value occurs at a 90 m reduction in water table elevation, or at a water table elevation of 3715 m.a.s.l. This is far below the modern water table elevation of 3797 m.a.s.l. Three potential reasons may explain why the water table has not been lowered to its apparent economically optimal depth through pumping and more research is needed: (1) There are institutional limits on the amount of water that may be withdrawn--e.g. the property right to extract groundwater is limited. (2) The stored water is being captured over time, the system is not in steady-state and the drawdown has not yet reached the new lower limit. (3) One or more of our assumptions about aquifer water availability and geometry, the value of water, or the cost of extraction is incorrect.

In the case of the OdSP system, lowering the water table elevation beyond the threshold resulted in an important social effect: a shift in which groups used the water resource. Surface water use by villagers at OdSP was replaced by groundwater use by the mining industry. This is an important distributional result of the management decision that may have political and social implications not expressly addressed by the model.

7. Conclusion

As demonstrated in the prior section, the economic value of extracted water can be quite high. When extraction decreases the water table elevation below certain threshold points, valuable ecosystems and other services may be lost. The traditional economic model of an aquifer as a single cell without outflow characterizes the value of pumped water but fails to incorporate the value of natural outflows. This underestimates the benefits of maintaining higher water table elevations. Managing aquifers without accounting for the value of outflows may lead to social welfare and environmental losses.

The traditional economic model also gives the false impression that sustainable, steady-state groundwater development is possible if groundwater extraction rates are equal to recharge rates for a basin. This is not true because groundwater systems have natural outflows that cannot be completely captured by pumping. The new model illustrates how in steady state systems with natural outflows, extraction rates are always less than recharge rates. This is an important point for water resource managers to note. Too often, management decisions are still based on the false premise that sustainable development can be achieved by limiting extraction rates to recharge rates.

Another important insight from the new model is that as the water table decreases, steady-state pumping rates can increase because natural outflow rates decrease. This point is demonstrated in the case study, where a decreasing water table elevation reduced evapotranspiration and groundwater flow to the river and associated services, while simultaneously increasing the steady-state extraction rate. The model introduced in this paper better represents the behavior of systems, like OdSP, that have high flow to stock ratios. Sustainable management solutions, where high water table elevations protect valuable outflows to ecosystems and other services, are more likely to correspond to economically optimal solutions in these settings.

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Table 1: Summary of estimated hydrologic magnitudes and calculated economic values

	Before human use	Before human use to 1961	1961	1961 to present	Present
Size of lake (km^2)	6.4		0.8		0
Size of wetland (km^2)	0		5.6		0
Water table elevation (m.a.s.l.)	3805		3801		3797
Decrease in evapotranspiration (l/s)		356		495	
Decrease in surface water outflow (l/s)		400		300	
Net value of ‘captured’ outflows		$116 million		$162 million	
Depletion of stored water (liters)		2.08×10^{10}		9.61×10^{9}	
Value of depleted stored water		$15 million		$7 million	

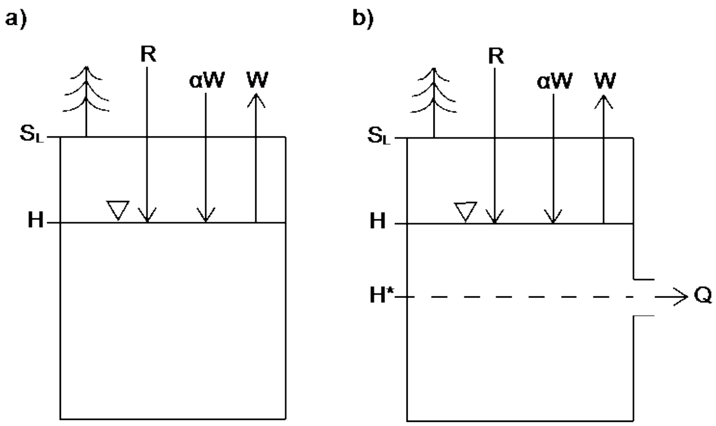

Figure 1: a) the traditional single-cell model of an aquifer system, b) the new model which includes a threshold elevation and outflow occurring at that threshold elevation. Notation: R-recharge rate (m/yr), H-water table elevation (m), S_L-ground surface elevation (m), W-groundwater extraction rate (m/yr), H^*-threshold elevation (m), Q-outflow rate (function of H) (m/yr)

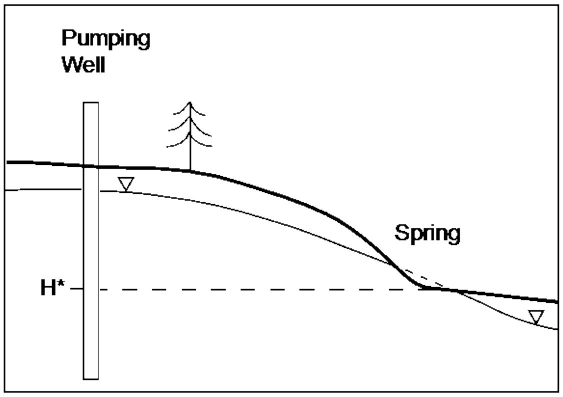

Figure 2: An illustrative case of a groundwater pumping well near a spring. Extracting water at the pump site lowers the water table, reducing the hydraulic gradient between the pump site and the spring, which reduces the groundwater flow to the spring. If pumping lowers the water table below a threshold elevation (H*), groundwater flow to the spring ceases.

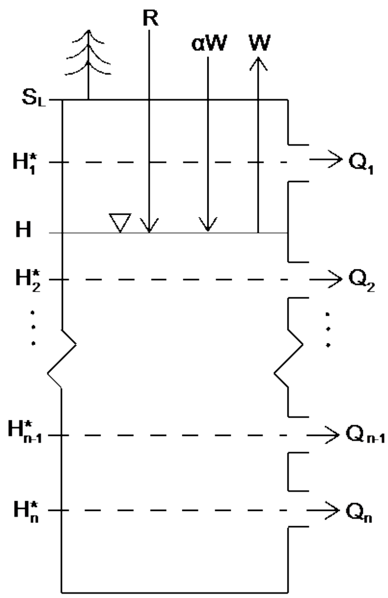

Figure 3: New economic aquifer model extrapolated to multiple threshold elevations and multiple corresponding outflows. Notation: R-recharge rate (m/yr), H-water table elevation (m), S_L-ground surface elevation (m), W-groundwater extraction rate (m/yr), H_i^*-elevation of threshold i (m), Q_i-outflow rate corresponding to threshold i (function of H) (m/yr)

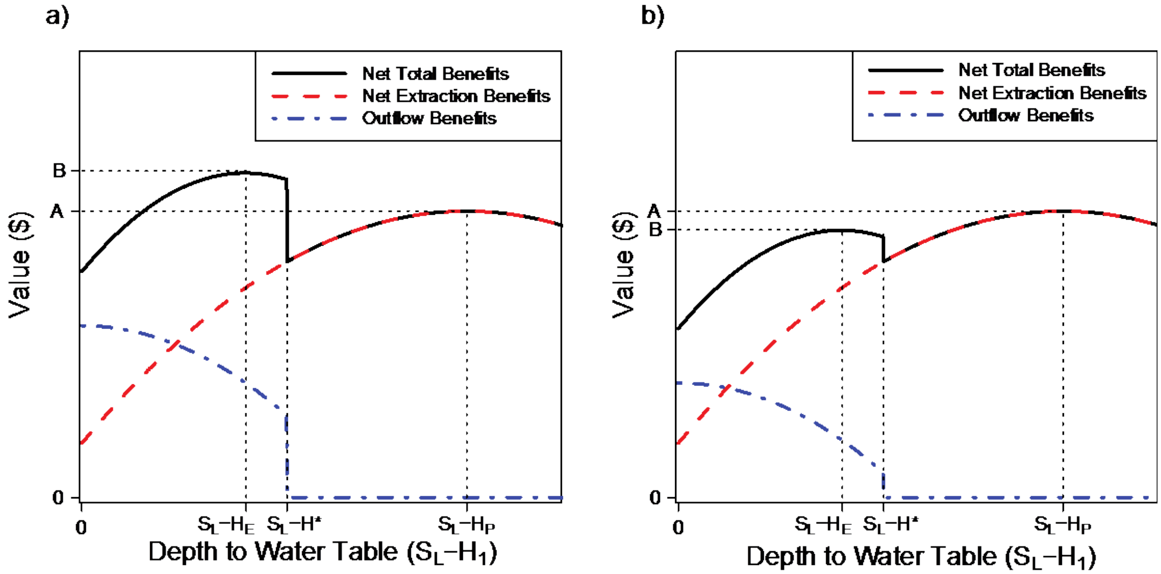

Figure 4: Value of water resource system shown as a function of increasing depth to the water table. At the threshold elevation, H^*, a discontinuity exists in the outflow benefit curve and the net total benefit curve. a) shows the benefits for cases where the maximum economic value occurs when the natural outflow is maintained; b) shows the benefits for cases were the maximum economic value occurs when the water table is lowered below the threshold elevation and natural outflows are sacrificed.

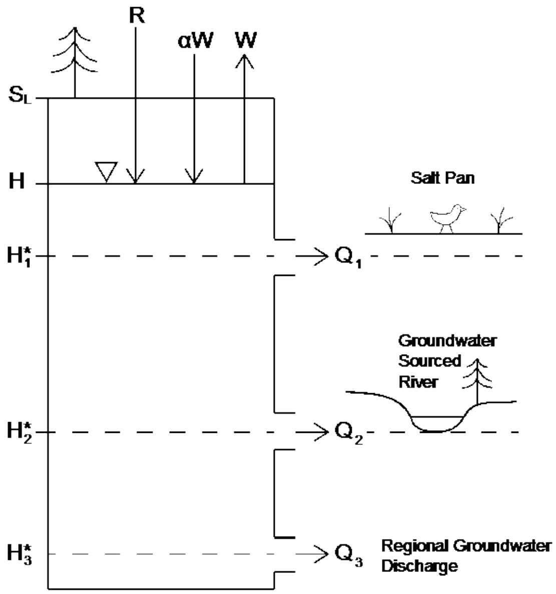

Figure 5: Example of the model applied to a system with an evaporative salt pan, a groundwater sourced river, and regional groundwater discharge to a down gradient groundwater system.

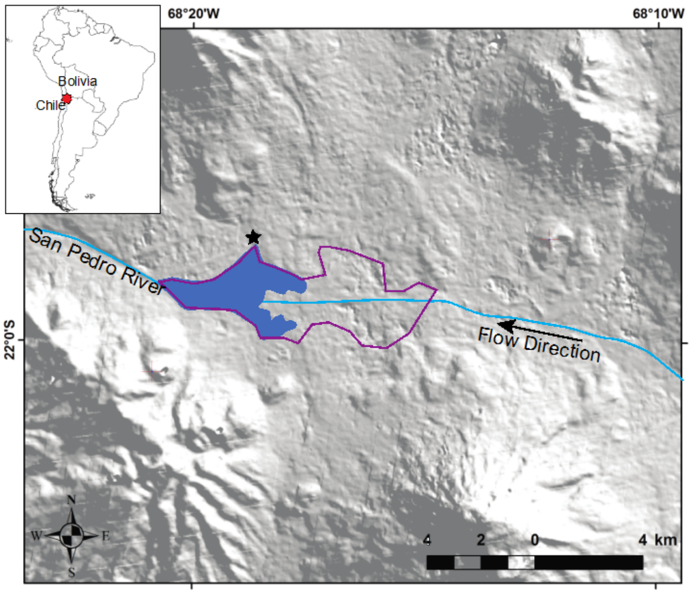

Figure 6: Ojos de San Pedro area in the San Pedro River Basin. The maximum extent of the Ojos de San Pedro Lake is shown in blue. The designated aquifer footprint is indicated by the purple polygon. The black star shows the location of abandoned Ojos de San Pedro Village.

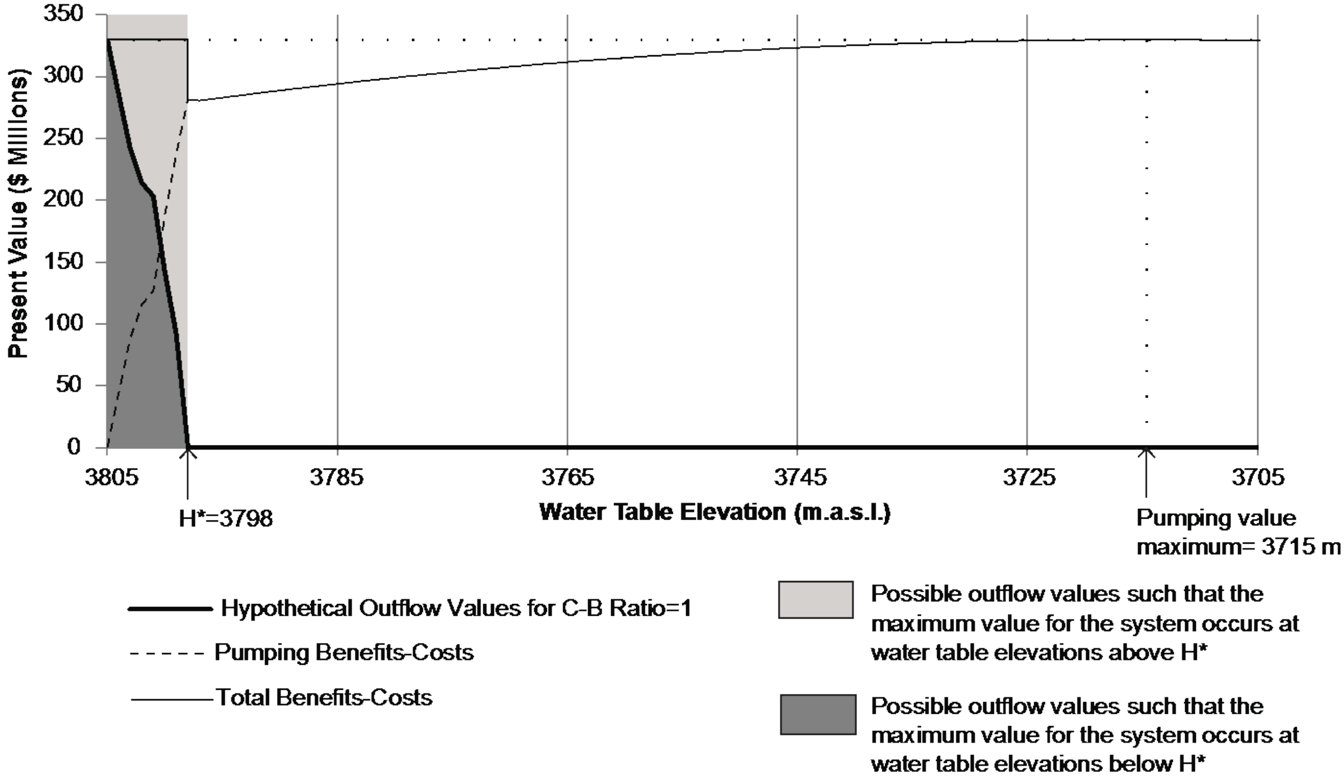

Figure 7: Economic simulation of OdSP aquifer values at different water table depths with a hypothetical outflow benefits function indicating the value of outflow services required to justify maintaining this water table depth using benefit-cost analysis.

CHAPTER 4

GROUP DEVELOPMENT AND INTEGRATION IN A CROSS-DISCIPLINARY AND INTERCULTURAL RESAERCH TEAM

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Abstract

Cross-disciplinary research is necessary to solve the many complex problems that affect society today; including problems involving linked social and environmental systems. Examples include natural resource management or scarcity problems, problematic effects of climate change, and environmental pollution issues. Intercultural research teams are needed to address many complex environmental matters as they often cross geographic and political boundaries and involve people of different countries and cultures. It follows that disciplinarily and culturally diverse research teams are organizing to investigate and address environmental issues. This case study investigates a team composed of both monolingual and bilingual Chilean and North American university researchers who are geologists, hydrologists, engineers and economists. The objective of this research team was to study both the natural and human parts of a hydrologic system in a hyper-arid region in northern Chile. Interviews (n=8) addressed research questions focusing on the interaction of cross-disciplinary diversity and cultural diversity during group integration and development within the team. The case study revealed that the group did not

progress linearly through the expected stages of team development, rather they returned repeatedly to the conflict or storming stage after arriving at a 'false norming' stage of group development. Results showed that language translation served as a facilitator to cross-disciplinary integration of the research team. Cross-disciplinary barriers were found to be more difficult to overcome than intercultural barriers during research team development.

1. Introduction

Cross-disciplinary research, defined here as research that involves teams of scientists from different disciplines or specialties (Aagaard-Hansen and Svedin, 2009), is widely considered necessary to address complex problems that involve coupled social systems and earth systems, such as resource management, water scarcity, and climate change (Bakker, 2012; Carew and Wickson, 2010; Jakobsen et al., 2004; Klein, 2004; Metzger and Zare, 1999; Mobjork, 2010; Robinson, 2008; Tress et al., 2007). Because coupled human-environmental systems interactions are so complex and interdependent, no one discipline has the tools and outlook necessary to effectively address them. Only through cross-disciplinary interactions can the most important environmental and natural resource research questions be determined and addressed (Klein, 2004). For example, in order to address the challenges that climate change and rising sea levels pose for low-lying communities, social scientists, engineers and climate scientists often must work together across disciplines. Following common convention (e.g. (Aagaard-Hansen and Svedin, 2009; Rosenfield, 1992; Wickson et al., 2006), we use the term “cross-disciplinary” to refer to any research involving team members of varying specialties (disciplines). Multi-disciplinary, inter-disciplinary, and transdisciplinary refer to subsets of cross-disciplinary research that range on a continuum from least to most disciplinarily integrated (see p. 4 for definitions).

Despite the importance of cross-disciplinary research to our present environmental problems, such projects face greater barriers to success than mono-discipline research projects. This is because disciplinarily-based communication and cultural barriers exist between academic disciplines and extra time, skills, and commitment are necessary to breach those barriers (Jakobsen et al., 2004; Tress et al., 2007). Additionally, the evaluation and reward structures of research universities and funding agencies have evolved specifically for mono-discipline projects (Carew and Wickson, 2010). Funding institutions have begun to recognize that cross-disciplinary research is also important. For example, the National Science Foundation (NSF) has developed grant programs for coupled human-natural systems and for science, engineering and sustainability education and many universities are implementing cross-disciplinary research initiatives. However, there is still much progress to be made in developing standards to adequately assess cross-disciplinary projects and the researchers involved in them (Aagaard-Hansen and Svedin, 2009; Carew and Wickson, 2010; Klein, 2004; Metzger and Zare, 1999).

Complex environmental problems, such as water resource management problems, often cross political and geographic boundaries and affect people of different nationalities and cultures. Just as cross-discipline collaboration is necessary to address complex, coupled societal-environmental problems, international and cross-cultural collaboration is vital in tackling these problems as well (Metzger and Zare, 1999). For example, effective groundwater management of aquifers that cross international boundaries requires well-functioning international teams. International cross-disciplinary research teams face additional challenges compared single nationality teams due to the differing culturally-based assumptions, values, and norms represented within the group (Bachmann, 2006).

In a cross-disciplinary research group that includes team members from different cultures and countries, two social and logistical challenges must be confronted in order to achieve project success: 1) *effective intercultural communication is necessary* (e.g. Bartel-Radic, 2006; Earley and Mosakowski, 2000; Ochieng and Price, 2010; Oetzel, 2009; Zander and Butler, 2010), often across language barriers, and 2) *cross-disciplinary integration must be achieved* (e.g. Aagaard-Hansen and Svedin, 2009; Eigenbrode et al., 2007; Graybill et al., 2006; Jakobsen et al., 2004; Tress et al., 2007; Wickson et al., 2006).

Here we investigate how disciplinarily and culturally diverse working teams develop, deal with conflict, and become productive as a research team by examining a case study. This case study focuses on an international, cross-disciplinary research team composed of Chilean and North American economists, engineers, hydrologists, and geologists studying the linked physical and social-economic components of a hydrologic system in northern Chile.

The paper begins with literature reviews on the topics of group development theory, intercultural communication and cross-disciplinary integration. We use this literature review as a basis in formulating the questions that focus our research. We then discuss our qualitative data gathering and analysis methods and present the results of our research. The paper concludes with a discussion of the implications of our results, a brief evaluation of the interview method, and conclusions and recommendations for intercultural, cross-disciplinary working teams.

2. Literature Review

2.0 Group Process

Groups of people working together on a common project, such as research teams, have long been understood to progress through a set of development stages. These stages of group development were originally described by Tuckman (1965) and included: ‘forming’ when the group first comes together and politeness and commonality prevail; ‘storming’ when conflicts arise and disagreements occur; ‘norming’ when rules for how the group will function and a shared understanding of the task are established; and ‘performing’ when tasks are carried out and progress toward the completion of the groups goals occurs. Later, a final development stage of ‘adjourning’ was added (Tuckman and Jensen, 1977).

Since Tuckman’s original theory was developed, researchers have challenged and refined this framework of group development. Gersick (1988) described a form of punctuated equilibrium wherein group development progresses in short, distinct time periods rather than gradually throughout the life of the group. McGrew and others (1999) found that development often proceeds both forward and backward in long-term working groups, and added declining stages such as ‘de-storming’ and de-norming’ to the model. Marks and others (2001) defined reoccurring, cyclical development stages devoted to task work, planning and evaluation. Rickards and Monger (2000) examined the importance of the behavior of team leaders and found that group development and functioning are facilitated by creative and open leadership. Other researchers have focused on the role of conflict within working groups and found that project related and interpersonal conflicts increase through time in effective working groups, peaking during project deadlines (Jehn and Mannix, 2001). Still others prefer process-based models of team development, rather than progressive stage-based models, such as Tuckman’s model (Kuipers and Stoker, 2009). Kupers and Stoker (2009) outline a model of team development involving three ongoing process types: intra-team relations, managing tasks, and external relations and evaluation.

Tuckman's "forming, storming, norming, performing and adjourning" model has remained an important organizing theory of group development even as it has undergone adaptation and as other process-based models have been proposed (Miller, 2003). We examine our case study through the lens of Tuckman's model, while also focusing on elements of the process of integration and development as a research team. Whether and how the unique attributes of cross-disciplinary, intercultural groups affect the progression through group development stages is an important question that we examine in this work.

2.1 Intercultural Communication and Development of a Team Culture

Culturally diverse teams, defined by Stahl et al. (2010) as "those whose members come from a variety of different cultural backgrounds, reflecting both surface-level (e.g., country-of-origin, ethnicity and race) and deep-level (e.g., values and attitudes) dissimilarity", exhibit higher levels of problem solving creativity and adaptability compared with mono-cultural teams (Ochieng and Price, 2010; Stahl et al., 2010). A diverse team can generate and challenge ideas for longer durations than can mono-cultural teams because they don't succumb to groupthink as easily (Stahl et al., 2010). Moreover, diverse teams are more likely than mono-cultural teams to make ethical decisions in a wide variety of circumstances because of this decreased tendency towards groupthink. However, communication within a culturally diverse work group can be challenging. Table 1 summarizes characteristics of effective and ineffective intercultural communication based on an analysis of the literature.

Intercultural work teams have been shown to be most effective when they are able to develop their own cohesive team culture, a task that is more easily accomplished within either extremely culturally homogenous or extremely culturally heterogeneous groups (Earley and Mosakowski, 2000). Homogenous groups can immediately draw on their shared culture to form a team culture quickly. Extremely culturally diverse teams take more time to form a team culture, but are usually very successful in doing so because mono-cultural subgroups do not develop within the team. Teams composed of moderately culturally heterogeneous members often encounter more difficulties in forming a team culture. This is because, in a moderately diverse team, numbers of team members who share a culture can form factions within the group (Earley and Mosakowski, 2000) and competing mono-cultural leadership and communication structures sometimes develop (Li et al., 1999), hindering the emergence of a team culture. This tendency to form factions within the group can be exacerbated if subgroups share many cultural or demographic characteristics with one another. The boundaries that exist between group members have been described as "faultlines" with the strength of a faultline dependent on how many characteristics are shared within each subgroup (Lau and Murnighan, 1998; Zander and Butler, 2010). For example, if a group is composed of several European economists and several North American engineers, that group may experience greater challenges in forming a team culture than a group in which there are economists and engineers of both nationalities.

2.2 Cross-Disciplinary Integration

The degree of integration achieved by the research group is one of the major factors that affect the outcome of a cross-disciplinary research project. The greater the level of integration among disciplines, the more positively researchers describe their experience and the productivity of their research project (Tress et al., 2005). In a cross-disciplinary research project, the level of integration among different disciplines can be described as a continuum with three points: multidisciplinary on one end, interdisciplinary in the middle, and transdisciplinary on other end

(Aagaard-Hansen and Svedin, 2009; Rosenfield, 1992; Wickson et al., 2006). Table 2 summarizes the characteristics of each of these levels of cross-disciplinary integration.

Multidisciplinary projects (Aagaard-Hansen and Svedin, 2009) involve researchers from different fields working alongside one another or in sequence, but within their own disciplines, to solve a common problem. Interdisciplinary projects require researchers from different fields to work together using agreed upon methodologies that incorporate their disciplinary approaches (Aagaard-Hansen and Svedin, 2009). However, the individual members of interdisciplinary teams do not abandon their own disciplinary values and understandings of science and knowledge. Transdisciplinary projects achieve the highest level of integration. Transdisciplinary research requires disciplinary scientists to set aside their own conceptual frameworks and discipline-based epistemologies to form a new methodology unique to the problem focus (Aagaard-Hansen and Svedin, 2009). Each researcher incorporates ideas and values from their teammates' disciplines into their thinking and jointly develops a novel approach to research methods and problem formation. Wickson and others (2006) describe interdisciplinary collaboration as a mixing of disciplines and transdisciplinary work as a fusion of disciplines in which disciplinary methodologies and epistemologies no longer exist. Some scholars have described transdisciplinary research as necessarily incorporating stakeholder input (Tress et al., 2005). In the face of many barriers to integration, such as the pressure to produce disciplinary results, a cross-disciplinary research team may revert to working multidisciplinarily even if they originally strived for a greater level of integration (Pohl, 2005).

Integration across disciplines can occur in many ways; however, well-integrated groups have many similar characteristics. For example, a well-integrated cross-discipline research group develops a common language and shared terminology (Tress et al., 2007).

Misunderstandings and challenges resulting from communication across disciplines are recognized and overcome in such groups. A well-integrated group develops a shared idea of what types of data and methodologies are valuable and what should be discarded (Tress et al., 2007). Members of such a group work toward the same, agreed upon, collaboratively established research goal. In a highly integrated group, disciplinary members change their own disciplinary assumptions or values as a result of their participation in cross-disciplinary research (Carew and Wickson, 2010). A cross-disciplinary research group that is able to acknowledge and learn from the paradoxes that emerge during the study due to their differing disciplinary epistemologies is highly integrated (Wickson et al., 2006). Well integrated cross-disciplinary research groups also share a common understanding of the level of integration the group is striving to accomplish and the terminology of cross-disciplinary studies (e.g. interdisciplinary vs. transdisciplinary) (Tress et al., 2005). Finally, if the project produces new understanding and learning that results in joint publications with authors from different disciplines, this is a concrete indication that a high level of integration has been achieved.

3. Methods

3.1 Case Description

The case study presented here focuses on a cross-disciplinary, intercultural research group studying a linked physical and social-economic water resource system in northern Chile. This research team offers a unique opportunity to investigate how a cross-disciplinary, intercultural team develops and how cohesion and integration develop (or do not develop) across disciplines, cultures, locations, and languages during the collaborative process. The research team under study is composed of four economists, four geoscientists and an engineer. Seven members of the group are professors and two are graduate students. The research team includes three females, all geoscientists from the United States, and six males, economists, geoscientists and an engineer from both Chile and the United States. Team members are of two main nationalities: three team members are Chilean and six team members are from the United States, one of whom is British. In addition to the difference in nationalities within the research team, they also have varying fluency in two languages, Spanish and English. Of the nine team members, three are fluent in their non-native language, four have moderate fluency, and two speak only their native language. Figure one illustrates the linguistic, cultural, and disciplinary heterogeneity of the study group.

The goal of this group is to develop a hydro-economic model and use that model to help assess varying water resource management options. The research group carried out a planning trip in Chile in March, 2011. A major goal of this trip was to develop a common and detailed understanding of what the research team hoped to accomplish. During the trip, the research group met with governmental agencies, stakeholder groups, and others scientists who have an interest in the hydrology and water resource management of northern Chile. The research group also engaged in a series of internal meetings during which they shared their own perspectives, motivations and disciplinary expertise. After the planning trip, the team worked together over two years to write and submit two cross-disciplinary research grant proposals.

3.2 Research Questions

The following research questions motivated this study: (1) How did the intercultural, cross-disciplinary research team progress through the stages of team formation (forming, storming, norming, performing)? Was the research team's progression sequential, non-sequential, or cyclical? (2) Did intercultural communication facilitate interdisciplinary integration and team cohesion? (3) What was perceived as the greater barrier to team formation and integration, cultural differences or disciplinary differences? (4) What challenges to integration did the intercultural, cross-disciplinary research group encounter and how did the group deal with these challenges?

Answering these questions will require not only examining the process of the team's development but also intercultural communication within the team and the level of cross-disciplinary integration achieved by the team. Metrics for effective intercultural communication and cross-disciplinary integration have been compiled based on the literature review and are shown in Tables 1 and 2. These metrics were used as a basis for the coding frame that was developed during qualitative analysis.

3.3 Participant Observation

One of the authors, Kirk-Lawlor, is a member of the research team under study. Therefore this case study is based, in part, on participant observation methodology, which has a long history as a qualitative data collection method (Patton, 1990; Strauss and Corbin, 1998). Kirk-Lawlor participated in and observed the group's face-to-face meetings, including structured meetings, field trips and social events, as well as internet-based voice conferences. Attention was paid to the group's team development and research processes. Studies using participant observation methods range over a large spectrum in how involved the researcher is in the setting or group being studied. This range extends from full participant to complete observer (Patton, 1990). In this case, Kirk-Lawlor is a fully participating member of the research group, not just an outside observer. This presents both possible benefits and limitations. The researcher must work to self-consciously acknowledge their own reactions, memories, feelings, and thoughts and distinguish them from the respondents' experiences. This effort is aided by the input and perspective of Allred, coauthor of this study, who is not a member of the case study research team and, as such, offers an outsider's perspective. As Strauss and Corbin (1998) describe, it may be helpful for the researcher to draw on their own experience and feelings during data analysis in order to be more sensitive to possible meanings, categories and dimensions contained in the data, however, they must remain consciously aware of how they use their own experiences.

3.4 Online Interviews

An online interview is a qualitative interview that is conducted online, as opposed to over the phone or in-person (Salmons, 2010). For this study, online interviews were sent to eight respondents (all research members except Kirk-Lawlor) using the online service Survey Monkey. The interview requests were sent approximately six months after the research team completed their field trip and face-to-face meetings and immediately following the first collaborative grant writing process. Reminders were sent out after four weeks. All eight respondents completed the online interviews. Most did so within six weeks of receiving the online interview request. Both Spanish and English versions of the online interview questions can be found in Appendix A.

The online interview, though a relatively new method for qualitative data collection, has been used effectively under a variety of conditions (Bampton and Cowton, 2002; Salmons, 2010). Communication methods can be categorized as either synchronous or asynchronous in both time and place and as either text or voice based (Mann and Stewart, 2000; Salmons, 2010). Voice based communication includes face-to-face interviews, which are synchronous in both time and space, and telephone interviews, which are synchronous in time but not place. Interviews conducted through online instant messaging or through text messaging with mobile phones are both examples of text-based communication that is synchronous in time but not place. Online interviews, like the one in this study, in which the respondents receive questions by email or a web-based interface and can respond to those questions when they choose to, are asynchronous in both time and place. This method has some significant advantages over face-to-face or telephone interviews (Bampton and Cowton, 2002; Salmons, 2010) including: giving respondents time to consider their answers before responding and the ability to come back to their responses over time, responding anonymously, reducing the need for travel, eliminating scheduling challenges (including time-zone challenges), and eliminating the need for transcription.

Of course, there are also drawbacks to choosing a text-based, asynchronous interview method. Some richness in the data is sacrificed because verbal and non-verbal information such as tone of voice, eye contact, pace of speech and facial expressions are not available to the researcher (Salmons, 2010). Also, the asynchronous nature of online interviews limits the spontaneity of responses (Mann and Stewart, 2000).

3.5 Qualitative Data Analysis

Analysis of the online interview responses was done using a hybrid grounded theory and thematic coding process (Strauss and Corbin 1998). This process included a coding framework based on a literature review (see Tables 1 and 2) but also followed grounded theory practices, which allowed thematic codes to emerge that did not necessarily fit within the pre-established framework. Grounded theory is a way of analyzing qualitative data based on inductive rather than deductive reasoning (Patton, 1990). Often, implicit within a hypothesis are assumptions about important variables and their relationships to one another within pre-defined theoretical framework. By consciously avoiding a hypothesis before analysis, grounded theory methodology allows categories and connections and eventually theoretical interpretations to emerge unhindered from data (Patton, 1990; Strauss and Corbin, 1998). Analysis and coding of the online surveys was done using the software program, AtlasTI. Coding is an iterative process of extracting meaning, categories (grouping ideas), and dimensions (ranking the severity along a continuum) from complex responses by analyzing words and phrases, asking questions, and making comparisons (Strauss and Corbin, 1998).

4.0 Results

Below we present the results of this qualitative study organized by research question. Major themes that emerged in relation to this research question during the analysis of responses and the codes associated with them are shown in Table 3. We address three broad themes: team formation stages, cultural and disciplinary dimensions, and challenges and strategies.

4.1 *Team formation stages*

Research question #1: *How did this intercultural, cross-disciplinary research team progress through the stages of team formation?*

Instead of progressing in a linear way through the team formation stages defined by Tuckman (1965), the cross-disciplinary, intercultural team cycled back repeatedly from the norming stage to the storming stage ("repeated return to storming stage" theme, Table 3). Participants found repeatedly that, although they thought they had established a common understanding of disciplinary concepts and project goals, they were still working under a significantly different set of understandings and assumptions from one another. Persistent disciplinary differences and misunderstandings, at first unrecognized, led to conflict and a return to the storming stage of group formation. During these repeated storming stages, group members challenged one another's disciplinary assumptions, asked for clarification on unfamiliar concepts, and worked to understand foreign discipline's epistemologies. For example, the physical scientists came to understand the idea of 'value' differently through discussions with the economists. Similarly, the economists came to understand the interconnection between the surface water and ground water resources through discussions with the physical scientists.

One key finding was that of disciplinary cross-talk, where what members of one discipline communicated was different from what members of another discipline understood. Thus, the team was operating in a 'false norming' stage (false norming stage theme, Table 3), in which team members thought they understood one another and were 'on the same page' while they were actually not communicating effectively. During this 'false norming' stage team members felt more comfortable with one another and with the project because they believed they understood one another well. This comfort was based on both project-based discussions and on strengthened interpersonal relationships that developed among group members through their social and academic interactions.

Some group members found it surprising that cross-disciplinary communication difficulties remained even after establishing strong relationships and respect among group members. Indeed, after the team became comfortable with one another, it was more challenging for them to recognize misunderstandings because they weren't as attuned to watching out for them. This allowed the group to enter a 'false norming' stage. Realizing that this cross-talk was occurring (that the team was operating in a 'false norming' stage) was both important and sometimes frustrating because team members had to return to already discussed topics and this repeated backtracking was not familiar for team members who had previously participated in only disciplinary collaborations.

As respondent four described:

Later, when preparing our proposal, it was truly surprising to discover that we were not communicating clearly about what each discipline assumed were the conditions needed to achieve a sustainable state for the system of interest. I say it was surprising because we had all become such good friends, learned to talk with one another very freely, and discovered curiosity about one another's discipline. But we were having these discussions about the project design that went in circles and were causing increasing tensions, until we discovered that we had different assumptions. But we hadn't spotted the clues that we held different assumptions in what one another said or wrote.

Achieving this cyclical return to the storming stage of group formation involved a balance of deference and assertiveness in conversations among the group members. Listening and conversational deference (accepting other members explanations and ideas without challenging them) fostered respect among group members, while interruptions and challenges in conversation helped to clarify underlying differences in understanding. Often formal interactions (such as meetings) were characterized by more deferential conversational styles, while informal interactions (conversations over meals, during breaks, and travel etc.) were when challenges, questions and requests for clarification happened ("communication in formal vs. informal settings" theme, Table 3) . Disciplinary tensions developed during formal meetings where members were more deferential, then were healed during informal discussions when clarifications and justifications for viewpoints were asked for and received. As respondent five described:

There was a tremendous amount of listening and patience of colleagues across disciplines in explaining their discipline when the process began. I question how helpful this really was, as there was almost too much explanation and not enough questioning and clarifying which may have sped up the process. .. Although this could have been a intra-team source of problems, there were ample opportunities for offline [informal] questions and clarification which defused these tensions.

In addition to the setting (formal vs. informal), the level of comfort among group members and the pre-existing relationships that existed between some team members affected the balance between deferential and assertive communication. Team members felt more comfortable interrupting and challenging other team members when they had a well-developed, strong relationship with them. This meant that researchers who had previously worked together on disciplinary projects were more conversationally assertive with one another than with less familiar colleagues. As cross-disciplinary relationships within the team as a whole developed, group members became more comfortable asserting themselves with their colleagues of other disciplines. Respondent three described:

> The personal familiarity of other physical scientists tend to make them more 'argumentative' which means butting in or being cut short when you haven't finished the economists do this too once they are more familiar with us or the material. But this more indicating a healthy evolution of working relationships to argue something out than go away and simply dismiss something.

In the end, this cyclical group formation behavior, with repeated returns to the storming stage of group development, was necessary in integrating the group sufficiently to produce a strong cross-disciplinary research proposal together. However cross-disciplinary communication challenges remain. Respondent five writes:

> We've tried to talk a lot. I think the [communication] strategies are effective, but I think we'll need to develop more precise, almost methodological strategies for identifying what we know about what the other discipline is thinking, as well as doing, why, and be systematic in making sure that we understand each other.

Even though the research team has reached the performing stage of group formation, producing a collaborative grant proposal, it may be necessary for them to return to the storming phase as misunderstandings and disagreements emerge.

4.2 *Cultural and Disciplinary Dimensions*

Research question #2: *What was perceived as the greater barrier to team formation and integration, cultural differences or disciplinary differences?*

For this research group cross-disciplinary challenges were more difficult barriers to group integration than were intercultural challenges (“cross-disciplinary vs. intercultural challenges” theme). When questioned about the intercultural and cross-disciplinary challenges the team faced, respondents uniformly focused on disciplinary based challenges. Respondent seven stated:

No he detectado problemas culturas les que afecten a la comunicación entre los miembros del equipo. *Translation: I didn't notice any cultural problems that affected the communication between team members.*

Respondent six described their experience similarly:

Nunca tuve que cambiar mis comportamientos o forma de hablar, y realmente no sentí verdaderas diferencias culturales, salvo el idioma. *Translation: I never had to change my behavior or way of speaking, and I really wasn't aware of any cultural differences, except for the language.*

Respondent three acknowledged the language barrier between team members as a challenge but identified cross-disciplinary differences as most challenging:

My very limited knowledge of Spanish is awkward, but was foreseeable and can be rectified. I think the biggest challenge is not making assumptions about knowledge of our cross-discipline colleagues.

Respondent four, a U.S. geoscientist, stated that communication with the economists (across disciplinary boundaries) was harder than with Chileans (across cultural boundaries). Respondent seven stated that while communication itself has proceeded easily, reconciling disciplinary differences has been challenging:

El equipo está compuesto por personas extraordinarias y con las cuales la comunicación ha sido muy fácil y amena. No obstante aquello, hemos necesitado trabajar bastante para compatibilizar las distintas visiones académicas y puntos de vista que son propias de cada disciplina. *Translation: The team is composed of extraordinary people with whom communication has been very easy and pleasant. Nevertheless, we have had to work hard in order to reconcile different academic outlooks and points of view that belong to each discipline.*

When describing intercultural challenges, respondents focused on the language barriers within the group and on the translation process ("translation" theme, Table 3). The language barrier was acknowledged as a challenging part of working in an intercultural team, however, it was always perceived to be a surmountable challenge. Respondents describe many of the indicators of successful intercultural communication occurring within the team, including high levels of respect, time made for everyone to contribute to conversations, frequent communication and translation, and standardization and simplification when speaking. Respondent three describes an example of intercultural accommodation in the face of the language barrier:

With our Chilean colleagues, I either tried to speak slower and or more clearly, and also used simpler language, especially using words that are almost identical.

Respondent seven describes the receptiveness of the team to differing ideas:

Estimo que todos y cada uno de los miembros del equipo ha sido escuchado y las opiniones de cada uno son muy bien valoradas. Ello refleja que el equipo es abierto y receptivo a distintos puntos de vista. *Translation: I feel that each and every member of the team has been listened to and each of their opinions are very valuable. This is reflective of how the team is open and receptive to different points of view.*

Respondent six acknowledged that the language barrier was a challenge but gave credit to the rest of the team for making an effort to communicate completely in spite of this barrier:

Respecto al idioma, si bien mi ingles no es muy fluido, no represento un problema, gracias a que investigadores estado unidenses hablan muy bien el español. Con el resto del equipo siempre hubo la disposición a entenderse aun si se me hacia dificultoso expresarme o comprender lo que me decían. *Translation: With respect to language, it's true that my English is not very fluent, this didn't represent a problem, thanks to US researchers who speak Spanish well. With the rest of the team, there was always a willingness to [try to] understand me although I had difficulty expressing myself and understanding what they were saying to me.*

One reason that this team may not have struggled with intercultural communication is that the team members share a common culture of academia. While there are differences in the funding structures between Chilean and U.S. academic systems, the overarching academic culture and goals of research scientists from the two countries are very similar. Respondent four describes that shared culture as a basis for building a connection between team members:

We have in common some general work activities (teaching, mentoring students, research, a history of attending grad school somewhere previously), and this is a foundation from which I ask questions.

For this team, cross-disciplinary barriers were experienced as more significant and difficult to overcome compared with intercultural barriers (including language barriers). Cross-disciplinary challenges included lack of group members' knowledge of one another's fields and important philosophic differences between group members of different disciplines. Respondent two focuses on the challenges that arose due to the different ways research is carried out across disciplines and states that this was especially difficult for more experienced researchers who had not worked in cross-disciplinary projects before:

> The key challenges are acquiring a willingness to respect and understand the very different approaches, methodologies, terminology, and protocols that exist across disciplines. This challenge is especially difficult for senior researchers who have learned and succeeded in their discipline's structure.

Philosophic differences between group members of different disciplines emerged through discussions of how to interpret and define the concept of sustainability. Respondent five described this conflict as one that was clearly delineated by discipline:

> In preparation for a second grant, there were signs of discomfort, particularly among the geoscientists, who I believe felt the economists were too intent on seeking short term material improvement as opposed to long run resource sustainability. This difference is clearly disciplinary, as similar positions have been taken by economists on one side and geoscientists on the other, regardless of nationality.

Challenges and conflicts relating to the cross-disciplinary nature of the research team emerged frequently throughout the team's time together and were addressed by repeatedly returning to the storming stage of group process.

Research question #3: *Did intercultural communication facilitate interdisciplinary integration and team cohesion?*

The translation process emerged as the most important component of intercultural communication for this team ("translation" theme, Table 3). Translation itself acted both as a facilitator and a barrier to the team's progress.

The research team was composed of both Spanish and English speaking monolingual members as well as members who were bilingual whose native languages were either English or Spanish. The presence of these bilingual team members was extremely important to the functioning of the group in both cross-language and cross-disciplinary dimensions. Respondent eight described the importance of the bilingual group members:

Una gran ayuda para superar aquellos problemas de comunicación ha sido la participación en el equipo de al menos 4 investigadores bilingües, con los cuales se ha resuelto cualquier problema de poca o nula comprensión de lo tratado en alguna reunión, conversación o documento. *Translation: The participation of at least four bilingual researchers in the team was greatly helpful in overcoming these communication problems, with them whatever problem of little or no understanding was resolved in a meeting, conversation or [written] document.*

The translation process slowed down group conversations, which was expressed as both helpful and sometimes frustrating to team members. The slow pace of translation helped prevent cross-disciplinary confusions from persisting, thus preventing potential false norming stages from emerging. While the added time that translation required meant that fewer subjects could be covered in meetings and that monolingual team members were not engaged in the dialog for periods of time, it also allowed bilingual team members a second chance to hear and understand new ideas and viewpoints. This facilitated cross-disciplinary understanding. Additionally, translation provided a means for group members to show that they had been paying careful attention to one another or to stakeholders. This demonstrated respect among team members and facilitated further interdisciplinary integration. Respondent four describes in detail how translation aided cross-disciplinary communication:

The cross-language communication was extremely helpful in reducing the cross-disciplinary confusion. Our communications were greatly slowed down, providing more processing time in which the cross-disciplinary uncertainties could be recognized. And our communications required translation, during which the bilingual team members had a chance to hear one another's explanation of a technical phrase and recognize errors in comprehension (i.e., an economist said something in English which was misunderstood by the English-speaking geologists, one of whom passed the error into Spanish, but the bilingual economists found the error, and explained to the geologists in all languages the correct meaning of the phrase). It was messy but effective.

Not only was translation helpful in preventing cross-disciplinary misunderstandings, it was also a useful tool for managing meetings when disciplinary-based differences in communication styles were causing friction. Respondent four describes how translation was used as a management tool when trying to provide time for everyone to add their voices to the discussion:

It [translation] actually seemed to have a beneficial role in managing the meetings. I found that it seemed less rude to interrupt a person who was either dominating the questioning or was answering a question in a rambling long-winded fashion to ask for a pause for translation, than to try to cut them off and redirect the discussion for any other excuse.

Of course the translation process was not without its problems. Mistranslation did result in misunderstandings that were sometimes not noticed and corrected promptly. For example, it took the group weeks to discover that they had different ideas of how the term 'sustainable' was defined and understood. Also the language barrier between some team members made it more difficult for them to connect socially with one another without the presence of a bilingual team member. Respondent one noted one problem with how translation worked within the research team:

Unfortunately, there was a lot of speaking to the translator, not the other person.

Language barriers can cause communication to be strained; thus translation was an important tool to bridge that communication gap between group members. However, translation itself did not completely eliminate the barrier. Translation acted as a facilitator to interdisciplinary integration because it helped team members to recognize disciplinary cross-talk. However, it also slowed down group discussions, which was frustrating for some group members.

4.3 *Challenges and Strategies*

Research question #4: *What challenges to integration did the intercultural, cross-disciplinary research group encounter and what strategies did the group use to deal with these challenges?*

The research team encountered many challenges inherent to intercultural, cross-disciplinary research, many of which have been mentioned in the previous sections. Here we catalog these challenges and delve into coping strategies used by the research group to confront them. Table 4 summarizes the challenges faced and strategies used by the research group.

4.3.1 Challenges

Cross-disciplinary research involves a large time commitment and balancing this with other work responsibilities was challenging for the team. The language barrier and the time necessary for translation also intensified this challenge. Respondent seven describes:

> En resumen las estrategias [de communicación] han sido eficientes, pero han requerido de importantes cantidades de tiempo. *Translation: In summary, the [communication] strategies have been effective, put they have required significant amounts of time.*

Respondent five also described the considerable time commitment needed for effective cross-disciplinary communication within the team and noted the need to develop methods for understanding cross-disciplinary colleagues and communicating effectively with them:

> I think the [communication] strategies are effective, but I think we'll need to develop more precise, almost methodological strategies for identifying what we know about what the other discipline is thinking, as well as doing, why, and be systematic in making sure that we understand each other. That process is time consuming and that is hard for academics who are very busy. Such understanding is not leading directly to publications, but is groundwork for making sure that we work well together.

As the above response demonstrates, the time invested in this type of project does not result in publications at the same rate as disciplinary projects. This presents a challenge for researchers because the process by which they are evaluated by universities and other institutions is often heavily based on the number of publications in primarily disciplinary journals.

As reported in section 4.2, disciplinary differences in terminology, communication style and philosophical worldviews proved challenging to the group as work progressed. Misunderstandings and conflicts arose from these disciplinary differences and these required time and patience to overcome. Respondent one writes about the difficulty of explaining one's own discipline to teammates:

> However, one of the largest challenges at the beginning was communicating the essence of one's discipline to the other colleagues, and particularly here I'm thinking of the economists to natural scientists and vice versa.

Communication challenges sometimes revolved around simple things such as common words that were understood differently across disciplines. Respondent four described:

> If we hear words that seemed very uncommon in everyday usage, then we have a clue that they are a specialized "term" and know enough to ask for a definition or synonym. The challenges arise in the discovery that some words in everyday usage mean different things within a discipline than we expected them to.

One example of this kind of word was 'aquifer'. During group conversations it became clear that the team members understood the word aquifer to mean different things. Specifically, to the geologists 'aquifer' referred to a body of rock or loose debris that contained water; they understood an aquifer as fundamentally three-dimensional. The economists were much more interested in how far below the surface the water was and referred to an aquifer moving up or down; their conceptual model of an aquifer was simpler and revolved mainly around the depth to the water.

In other situations cross-disciplinary barriers were philosophically based rather than vocabulary based. Respondent one described disciplinary philosophical differences as a significant challenge:

> I think there were considerable philosophic hurdles to overcome because the economists asked many difficult, probing questions at many of the meetings, which seemed nearly offensive to the natural scientists.

Some cross-disciplinary challenges were centered on deciding how completely to integrate the research project across disciplines. Setting goals for how integration should work in the team was a challenge. Respondent one described:

> Disciplinarily one of the biggest challenges was overcoming the idea that each discipline could do their own thing, like satellites around a cross-disciplinary project. What became clear was that many of the things each side wanted to do didn't rely on strengths of the other side (here side are natural scientists and economists).

The research team also faced externally imposed challenges such as the differing funding options available to researchers from different countries. Many grants and funding sources do not allow for funding of colleagues from different nations. This necessitated dual grant writing efforts that were divided by nationality and operated on differing timelines, challenging intercultural team integration. The result of this difference in possible funding sources is that North American members of the research team were more focused on some aspects of the project and Chilean members were focused on others. The type of research proposal that is likely to receive funding differed between Chile and the U.S. This is because funding agencies in each country have different focuses. Specifically, the National Science Foundation in the U.S. is often interested in new foundational science and the applicability of a particular research project broadly to many situations. Chilean governmental funding agencies are more interested in solving regional problems within Chile.

Additionally, U.S. researchers were able to apply for grants specifically designed for cross-disciplinary projects, while Chilean funding agencies did not support cross-disciplinary research specifically at the time of this project. Respondent six, a Chilean team member, felt that cross-disciplinary research was not well supported in Chile and that the inclusion of U.S. researchers made that type of research possible:

> Creo honestamente que esa capacidad de coordinar investigadores desde distintas miradas, aun no la poseemos en mi pais… A pesar de que en Chile pueden existir los investigadores apropiados para generar este tipo de propuesta, dudo que las estructuras científicas [nacionales] permitan hoy día generar este tipo de sinergía solo con investigadores nacionales. *Translation: I honestly believe that we do not yet have the ability to coordinate researchers who come from different perspectives in my country…Although there might be researchers that could generate this type of proposal in Chile l, I doubt that the scientific structures [within the country] would permit this type of synergy with only Chilean researchers.*

Several respondents noted that the research team could have benefited from more clearly defined leadership. Perhaps due to the diverse nature of the research group, dual lines of leadership developed split along disciplinary lines. Likely, due to their limited knowledge of each other's fields, researchers did not feel comfortable stepping into the role of leader of their cross-disciplinary colleagues. Respondent one writes:

> Although many group members provided the services of a group leader at various times, there was no person who was really in control and this allowed too much uncertainty and created a lot of stress.

Respondent seven suggested that a team member or administrator serve as a team coordinator:

> Ello [problema de organización] podría solucionarse en parte, con alguien con mayor dedicación a la formulación del proyecto mismo y que pueda coordinar y hacer seguimiento de los distintos requerimientos a cada uno de los miembros del equipo. *Translation: This [organizational problem] could be solved in part by having someone who was more dedicated to the development of the project itself that could coordinate and monitor the various requirements of each team member.*

The geographic distance between team members posed a challenge for the team because it reduced the frequency of face-to-face meetings and made scheduling online conferencing more difficult due to different time zones. In addition, written communication often passed back and forth very rapidly by email, especially as grant application deadlines approached. Respondent six described how challenging it was to keep abreast of all of these modes of communication when conversations were progressing rapidly:

Como lo mencioné anteriormente, se produjo una sinergía muy grande, en que la comunicación fue muy expedita, y apoyada en medios tecnológicos: discusión de textos por email, y videoconferencias. Para mí fue difícil seguir ese nivel tan rapido de comunicación, fundamentalmente porque este año hemos tenido problemas de demandas estudiantiles a nivel nacional, que a los académicos nos han consumido mucho tiempo. *Translation: As I mentioned earlier, there was a great synergy, in that communication was very open and supported by technological means: discussion of documents by email and videoconferencing. For me it was hard to keep up with that fast pace of communication, mainly because this year we had nationwide problems with student demands that have taken up much of our time as academics.*

4.3.2 Strategies

The challenges the team encountered were overcome with willingness on the part of the team to work together and to consider changing their own viewpoints or conception of the project. Respondent four describes how her understanding of the project changed as a result of team discussions:

I am thinking much more critically about the potential importance of heterogeneous water recharge, and heterogeneous pumping capacity, as a result of the interdisciplinary discussions than I was beforehand.

Field trips and face-to-face group activities, including social activities such as meals, served an important role in overcoming the challenges posed by this type of research project and promoting cross-disciplinary integration and team development. The research team traveled together during an approximately ten-day field trip of the study region. This extended time together was extremely useful for the team in coming to a common understanding of the research problem and developing the working relationships between team members. All of the respondents agreed that the field trip was very valuable. Respondent three wrote, "The planning meeting was invaluable; if we had not met face to face the team would not have gelled." Similarly, respondent five wrote, "The field trip was absolutely essential."

During the field trip group members significantly augmented and revised their understandings of the interconnected hydrologic and social system and of the research project goals. Respondent three (a physical scientist) described a benefit of the field trip to their understanding of the social system, "The complexity of the social science side of the proposed study is much more apparent [due to the field trip]."

Not only did the field trip offer opportunities to hear from stakeholders and to learn about the natural hydrologic system and regulatory structures, it offered unstructured time to get to know other team members, an important strategy for overcoming disciplinary divides. Respondent seven described the importance of the field trip:

> La visita a terreno fue altamente provechosa, y mirada en forma retrospectiva la considero indispensable... En terreno pudimos compartir y aprender de los mismos usurarios agrícolas, indígenas, municipalidades y minería, como también de la autoridad encargada del manejo del agua (DGA regional). El viaje a terreno también permitió conocer en persona al resto del equipo, y ello unido a la convivencia de esos días, ha facilitado el trabajo posterior.
> *Translation: The field trip was extremely helpful and in retrospect I consider it to have been essential...In the field we could share and learn from agricultural, indigenous, municipal and mining users, as well as the responsible water management authority (the regional DGA). The field trip also allowed us to meet in person with the rest of the team and this along with being together for those days has facilitated our later work.*

Learning together as a whole team during the field trip also gave the team a shared body of knowledge and vocabulary to draw on in order to describe disciplinary concepts using concrete examples. Communicating based on these specific examples proved a valuable strategy in bridging differing disciplinary epistemologies and knowledge. Respondent one described this well:

> Next, it [the field trip] provided a body of shared knowledge for the group, which facilitated conversation. Although we didn't share the same disciplinary body of knowledge, the breadth of meetings provided a sort of localized knowledge that has allowed for sophisticated discussions by example rather than theory. For instance, we talk about the indigenous wells going dry because we had shared the experience of hearing about them.

Team members also found that the field trip experience gave them a greater appreciation for, and understanding of, the importance of the other disciplines within the team. Respondent three, a geoscientist, writes that after the field trip, “The complexity of the social science side of the proposed study is much more apparent.”

The geographical distance among group members was dealt with through regular voice conferencing using Skype and frequent email communication. Electronic communication included sending draft documents back and forth between team members. Online file sharing services could have also been helpful; however, the group relied on email.

Bilingual team members overcame the language barrier among team members with careful translation. This took considerable time and meetings had to be planned with this in mind. Also, group members tried to speak slowly in a standardized language in order for colleagues to understand what they were saying better. At least two group members, one Spanish speaker and one English speaker, took formal foreign language courses during the time the group was active in order to improve their language skills and help understand their fellow group members.

5 Discussion

This study offers a new contribution because of its focus on the combined effects of both cross-disciplinary and intercultural diversity within a working research team. Most previous research on the subject of diversity within working groups has been done either on culturally diverse teams or on cross-disciplinary teams—but not examining these aspects together. This study revealed that the process of translation within an intercultural, bilingual team can serve as a facilitator to the team’s integration across disciplines. In particular, translation of disciplinary-based (e.g. geoscience) statements by a team member of another discipline (e.g. an economist) provides an opportunity for other bilingual team members to notice and correct cross-disciplinary misunderstandings as they occur.

Results of this study confirm effective strategies for intercultural communication delineated in Table 1, including slow paced communication, frequent translation and respectful communication. Assertive, though not aggressive, conversational styles (see Table 1) were also instrumental in helping the group to uncover hidden miss-understandings (reveal false-norming stages). Like previous studies mentioned in the literature review, we also found that this cross-disciplinary team struggled to overcome methodological and epistemological differences (e.g. defining ‘sustainability’) and to develop workable cross-disciplinary communication methods.

This case study revealed that this intercultural, cross-disciplinary research team did not progress sequentially through Tuckman’s team formation stages. Rather the team proceeded cyclically through the formation stages, repeatedly returning to the storming stage of group development. The diversity of the team, both cultural and disciplinary, presented unique challenges to achieving true understanding and agreement within the group, requiring these repeated periods of “storming” before cycling through the “performing” stage. However, cross-disciplinary team integration greatly benefited from this repeated return to the storming stage of group development. Indeed, team integration suffered when false-norming stages were allowed to persist because disciplinary misunderstandings interfered with the progress on the cross-disciplinary goals of the project.

The results of the study showed a difference between formal and informal communication settings for this intercultural, cross-disciplinary team. Formal settings fostered more deferential communication, while informal settings allowed for group members to challenge each other and ask for clarification on points where disagreement existed. In this sense, formal meetings moved the group towards the norming (or false-norming) stage of group development and allowed the group members to show respect for one another, while informal settings provided important opportunities for the group to return to the storming stage of group development. We suspect that a reason for this difference can be found in group size. Formal meetings involved the entire group and it could have been seen as more confrontational to question or challenge a group member in front of everyone else. Informal settings allowed for one on one or small group conversations, which were more likely to lead to discussions of disciplinary misunderstandings.

In this research team, cross-disciplinary challenges overshadowed intercultural challenges as the team was working to become cohesive. This may be because intercultural communication within the research team was facilitated by a shared academic culture and by the fact that two of the North American team members have extensive experience working in Chile and carrying out collaborative research with Chilean colleagues.

5.1 Discussion of online interview method

The online interview is a valuable method for this type of study largely because it eliminates many language barrier problems. In this case, a respondent who was less comfortable speaking English or Spanish did not have to participate in a spoken interview but could instead take time to read questions and provide written responses. Using written interview methods also eliminates the potential complication of employing multiple interviewers, based on fluency in each language. Conducting online interviews eliminates the need for transcription, which for a bilingual study poses an additional challenge because of the need for a bilingual transcriber. This method allows respondents to take their time and carefully consider their answers, which may result in richer responses. The online interview method can also be more comfortable for respondents in situations in which the researcher is a member of the group they are studying. This methods allows the respondent to communicate anonymously through writing about sensitive issues rather than discuss them directly with a member of their group.

The online interview method, however, did have some drawbacks. This format does not allow the researcher to easily ask for clarification if the answers given to a question are unclear. Also, respondents took varying amounts of time to complete their interviews, resulting in responses that were spaced out over time and from different temporal perspectives. Some respondents were considering experiences which had just taken place, while others were looking back in hindsight after a few months. This added another element of heterogeneity to the results.

6. **Conclusions and Recommendations**

Intercultural, cross-disciplinary research teams should expect to devote more time to communication, negotiation and team management than monocultural, disciplinary teams, especially in the early stages of project formation. This additional time and effort is devoted to overcoming language barriers through translation, working to bridge cultural differences, and to discovering and overcoming disciplinary divides. Cross-disciplinary research is slower to produce results, however, these results have the potential to be important over a broad range of disciplines and more readily applied to complex real-world problems. For example, while disciplinary hydrology research in northern Chile could help elucidate the structure of aquifers and volumes of water moving through them, such research would not be able to adequately address the economic and social effects of changing water availability or the hydrologic effects of human water exploitation. Cross-disciplinary, intercultural research teams would be well advised to facilitate storming stages of group development by expecting and embracing disagreements and conflicts that repeatedly arise among group members. This is a necessary part of developing into a cohesive intercultural, cross-disciplinary team. Researchers may become frustrated by the slow progress towards the performing stage of group development, but this negotiation of terminology, scientific meaning, and method is important. One way to facilitate these kinds of discussions is to provide plenty of informal and face-to-face interactions among group members. This allows teams to break into smaller, more intimate groups to bring up issues they don't understand or points of disagreement. Field trips as well as meals and other informal social events can be useful in this regard.

In mixed-language groups, translation itself offers an opportunity to clarify disciplinary misunderstandings. Groups that explicitly recognize this additional benefit of translation, beyond simply communicating across language barriers, may find the slow pace of communication less frustrating for group members. Thus, allowing time for translation can benefit overall understanding among the disciplines.

The benefits of the translation process to cross-disciplinary integration can be extended to monolingual or mono-cultural cross-disciplinary groups. Such groups can use cross-disciplinary 'translation' as a useful tool to better understand one another. Even when translation between languages is not necessary, group members can practice cross-disciplinary 'translation' by restating the ideas of members of another discipline to the group as a whole. For example, using this strategy, a cross-disciplinary research team could split into pairs of one social scientist and one physical scientist to discuss an issue or work on a problem. Then, when the whole group reconvenes, the physical scientist could explain the social scientist's ideas to the group and vice versa. This strategy may help bring subtle cross-disciplinary misunderstandings to light and further the goal of cross-disciplinary integration.

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Table 1: Intercultural communication metric[a]

Ineffective	Effective
Communication occurs primarily in writing or by phone	Face to face communication is common
Communication is infrequent, avoided, or insubstantial	Communication is frequent and substantive
Infrequent/poor translation	Frequent/accurate translation
Native speakers speak in accented, idiomatic, fast passed language	Native speakers speak in standard, simplified, non-colloquial language
Conversations are dominated by one sub group	Pauses in conversation provide a time for other group members to enter the conversation
Problems are not spoken about publicly by the group	Conscious effort is made to hear from members of each sub groups (solicit and encourage participation)
Dual chains of command develop within sub groups	Trust increases over time within the group
Sub groups feel they are not heard or do not have time allotted for their participation	Social/cultural reciprocity happens
Participants accentuate different verbal and non-verbal behavioral patterns (divergence)	Respect among group members is high and communicated to each other
Participants maintain their own verbal and non-verbal behaviors without deference to other culture's norms (neutral)	Cultural and communication differences are discussed openly
Negative or hostile attitudes and emotions are expressed towards other group members/cultures	Helping takes place across sub groups
	Status indicators are equal across sub-groups
	Participants are active and open-minded listeners: -creation of new conceptual categories -openness to new information -awareness of more than one perspective
	Participants adopt similar verbal and non-verbal behaviors (convergence)
	Shared participation -all participants do their fair share of work -information shared among group members
	Participants are assertive without being aggressive when necessary

[a] Table 1. This metric is based on a literature review (Bachmann, 2006; Bartel-Radic, 2006; Earley and Mosakowski, 2000; Li et al., 1999; Ochieng and Price, 2010; Oetzel, 2009; Stahl et al., 2010; Stirling and Tully, 2004; Zander and Butler, 2010).

Table 2: Cross-discipline integration metric[a]

Multidisciplinary • Disciplinary researchers work alongside one another on distinct, disciplinary parts of a larger, multi-part project. • Minimal information exchange occurs between disciplines. • Disciplinary methodologies are maintained.
Interdisciplinary • Transfer of information occurs across disciplinary boundaries, however, transfer of philosophies and epistemologies does not occur. • Incorporation of foreign disciplinary bodies of knowledge into disciplinary work. • Researchers learn to understand the languages of the other disciplines; however, they do not incorporate foreign discipline language into their own work. • Disciplinary methodologies are maintained. • Contributions from each discipline are necessary to attack the chosen problems, but the results can be divided into disciplinary fields.
Transdisciplinary • Researchers set aside their disciplinary epistemologies in favor of a newly created cross-disciplinary epistemology, which is iterative and evolving. • Understanding of research philosophies occurs across disciplines and new, integrative philosophies are developed. • Common cross-discipline language is created and incorporated into each researcher's work. • The results of research pertaining to the problem questions will not fit within any single discipline. • Iterative and evolving methodologies. • Deconstruction of disciplinary bodies of knowledge through exposure to one another.

[a] This metric is based on a literature review (Aagaard-Hansen and Svedin, 2009; Eigenbrode et al., 2007; Graybill et al., 2006; Heemskerk et al., 2003; Jakobsen et al., 2004; McAlpine et al., 2010; Metzger and Zare, 1999; Tress et al., 2005; Tress et al., 2007; Wickson et al., 2006).

Table 3: Themes and codes related to research questions

Themes	Codes
Repeated return to storming stage	• communication challenges - recognizing disciplinary cross-talk • communication facilitator- cyclical discussion • overcoming disciplinary thinking
False norming stage	• assumptions • communication challenges - cross disciplinary • unsuccessful cross disciplinary communication
Communication in formal vs. informal settings	• communication challenges - reluctance • formal meeting • field trip • informal setting
Conversational deference vs. assertiveness communication styles	• communication – assertiveness • communication - assertiveness (lack of) • communication - unequal voice • communication -equal voice • respect – for teammates
Developing shared experiences; Relationship development	• communication facilitator - preexisting relationships • communication facilitator - strengthening relationship • integration facilitator - shared local knowledge/geography • relationship strengthening
Translation	• translation as a communication facilitator • translation as an aid to cross-disciplinary communication • benefits to bilingual group members • translation demonstrates respect • speaking to the translator instead of speaking to other group member
Cross-disciplinary vs. intercultural challenges	• disciplinary vocabulary • disciplinary epistemologies • different disciplinary meanings for same words • translation challenges* • national differences in funding sources

*The ‘translation challenges’ code overlaps both the ‘cross-disciplinary vs. intercultural challenges’ theme and the ‘translation’ theme.

Table 4. Challenges experienced by team and strategies employed

Challenges	Strategies
Large time commitment necessary	Plan for the additional time necessary to foster group integration
Geographic distance between team members	Use videoconferencing, telephone conferencing and frequent written communication
Language barrier	• Carefully (and patiently) translate everything so group members are not left out of conversations • Consciously use translation as a tool to promote better communication across disciplines. • Encourage team members to improve their language skills
Disciplinary gaps in knowledge, disciplinary philosophical differences and disciplinary differences in communication style	• Be alert to hidden misunderstandings • Plan as many face to face meeting time as possible • Plan activities or fieldtrips for the whole team to do together • Create time for informal interactions and conversations to take place • Decide as a group how disciplinarily integrated the project will be and work together towards that goal
Academic reward structure not always accommodating to this type of research	Team members should work with their institutions and deliberately plan how this kind of work will be evaluated
Differing funding structures in different countries	
Lack of a single leader	Consider assigning a clear team leader and/or hiring a team administrative coordinator

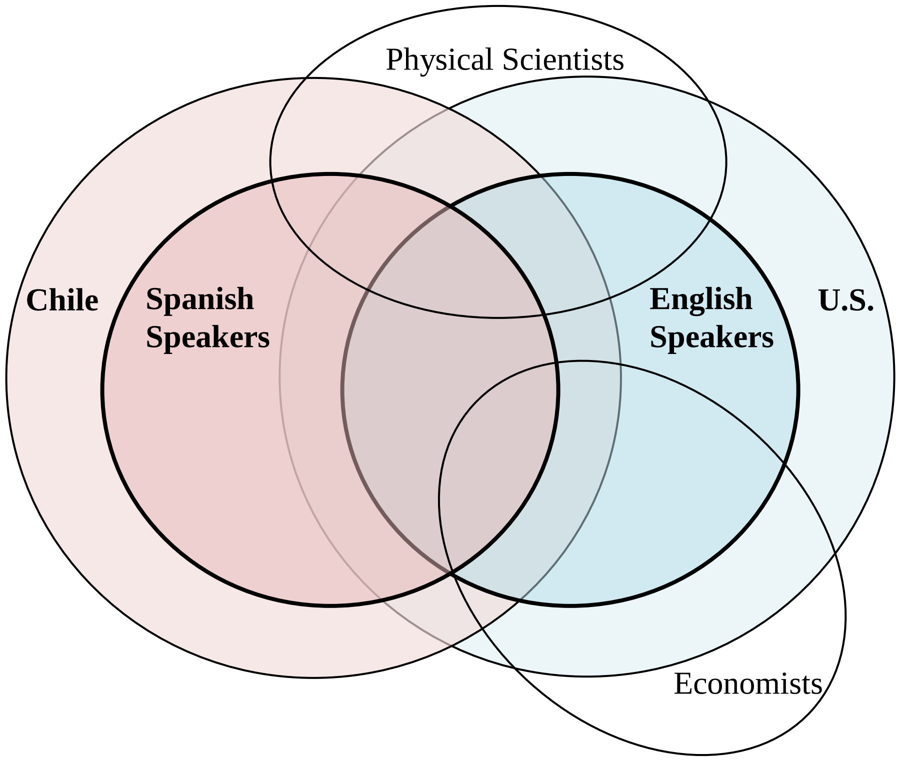

Figure 1 Caption:

This figure shows the distribution of characteristics among research team members in the case study group including, nationality, language fluency, and discipline.

CHAPTER 5

WATER RESOURCES AND HUMAN USE IN THE LOA RIVER SYSTEM OF NORTHERN CHILE: A NUMERICAL GROUNDWATER MODEL FOR USE IN MANAGEMENT

Abstract

The Loa Rive hydrologic system of the hyperarid Atacama Desert of northern Chile presents numerous water resource management challenges. Human water use for industrial mining operations, irrigation, and municipal uses is limited by the scarcity of freshwater resources in the region. Rainfall events that create runoff are very rare. The result is that surface water, as well as groundwater, resources are replenished through groundwater recharge at less arid, high elevations. This attribute of the hydrologic system makes it suited for a groundwater modeling study such as the one presented here. A steady-state numerical groundwater model was developed and calibrated using USGS MODFLOW-2005 based on known subsurface geological and hydrological information, stream gauging data, consumptive water usage data, and scarce groundwater recharge data. This model encompassed the Loa River topographic basin and part of the Altiplano Plateau east of the Loa River. Two aquifers separated by an aquitard are modeled within the Calama Valley, whereas elsewhere a single aquifer is modeled. The simulated groundwater fluxes within the system were studied and three hypothetical groundwater extraction scenarios were imposed on the lower aquifer within the Calama Valley. Resulting changes in groundwater flux into the rivers, out of the lower aquifer, and to the southwest from the Calama Valley were analyzed. Reductions in the water table elevation and the heads within the lower aquifer that resulted from hypothetical extraction scenarios were also analyzed. Model results indicate that ~23% of the groundwater discharged within the Loa River topographic basin originates as recharge east of the topographic basin. Groundwater fluxes out of the lower aquifer

to the west were found to be ~28 l/s and fluxes to the southwest from the Calama Valley were found to be ~97 l/s. Hypothetical lower aquifer pumping scenarios produced reductions in simulated groundwater flow to the rivers, especially within river reaches nearest to the imposed pumping. Lower aquifer pumping scenarios also produced depressions in the simulated water table elevations and reductions in the simulated lower aquifer heads within the Calama Valley. These effects increased in magnitude with higher rates of modeled extraction. For the intermediate scenario of 525.5 l/s total imposed extraction, groundwater flux to rivers was reduced by ~1,249 l/s in total, the water table elevation was depressed by a maximum of ~79 m, and the lower aquifer heads decreased by a maximum of ~96 m.

1 Introduction

The Loa River of northern Chile lies within the hyperarid Atacama Desert (Figure 1). Average rainfall amounts in the Loa catchment range from 2 mm/yr in the driest areas to ~170 mm/yr in the Andes Mountains (Houston and Hartley, 2003). Despite its extreme aridity the region is home to a population of more than 500,000 residents, living primarily in the cities of Anofagasta and Calama but also residing in small rural communities, and to many large copper mining operations. The mining, municipal, and agricultural users compete for the very limited surface water and groundwater resources of the Loa hydrologic system. Surface water resources are diverted from the Loa River and its tributaries using aqueducts and channels. Groundwater resources are extracted primarily from the unconfined regional aquifer for use in mining; however, in the past decade regulatory agencies have begun to consider groundwater extraction from a lower aquifer. In addition to human water users, the limited water in the region supports the flora and fauna that live in and depend upon small-scale wetlands and salars.

In Chile water resources are regulated and allocated by the national agency, Dirección General de Aguas (DGA). The management regime in the region is based on the hydrologic balance (Ministerio de Justicia, 1981; Ministerio de Obras Publicas, 2005). Total water rights allocations are legally limited to the recharge rate for the basin. Groundwater rights are allocated on the condition that their use does not impact the availability of surface water and groundwater for other water rights holders. Since legal revisions were passed in 2005, minimum ecological water flows must also be maintained to protect ecosystems (Ministerio de Obras Publicas, 2005). To this end, water rights allocation decisions are based on a conceptual model of the regional hydrologic system that includes aquifer structures and porosities, groundwater-surface water flow interactions, groundwater recharge rates and sustainable ecological water uses. Therefore, any errors in the hydrologic balance or the conceptual aquifer model used by the DGA have the potential to lead to unintended effects on both the environment and human users.

The Loa River catchment abuts the Chile-Bolivia international border and the two countries have had ongoing conflicts over surface water resources, specifically in the Siloli River, a tributary of the Loa (Mulligan and Eckstein, 2011; Zambrano, 2013). The possibility of cross-border groundwater flow between Bolivia and Chile is a contentious and politically sensitive issue. The DGA does not identify any cross-border groundwater flow to be occurring and their water balance reflects this (DGA, 2003b).

This study presents a steady state three-dimensional numerical groundwater model that addresses several of the limitations of both the present hydrologic balance and conceptual aquifer model on which the DGA bases regulatory decisions (DGA, 2003b). Specifically, the boundaries of this model are many kilometers outside of the topographic catchment boundaries, which allows the model to demonstrate the extent of water flux across the surface catchment boundaries based on geology, topography, and recharge rates. Secondly, the model's lower aquifer rock units intersect the river canyon, allowing them to potentially discharge groundwater to the surface. The model presented here also integrates stream gauging data along the Loa River and its tributaries with modeled groundwater flows. However, this study does not directly model surface water flows in the Loa system. Geographically smaller three-dimensional numerical groundwater models have been done for portions of the Loa River hydrologic system in the past (e.g DGA, 2003b; Fuentes Carrasco, 2009; Matraz Consultores Asociados S.A. and Universidad Politécnica de Cataluña, 2012) but they did not include the system's entire recharge and discharge areas.

We use the model presented here to address two major questions: (1) How much (if any) groundwater is discharged from the lower aquifer into lower elevation (down hydraulic gradient) parts of the system? (2) How might increased groundwater extraction from the lower aquifer in varying locations affect the future availability of water resources? The answers to these questions are important because increased exploitation of the lower aquifer is currently under consideration and, due to the likely surface discharge from the lower aquifer, such exploitation may pose a larger risk to surface water flows than is currently appreciated.

2 Setting

The study area ranges in elevation from sea level in the west to 4,000 to 6,000 m elevation of the Altiplano Plateau and Andes Mountains in the east (Figure 1). From the west to the east the study region is composed of 1) a coastal mountain range, termed the Coastal Cordillera, 800 to 2,000 m in elevation, 2) a forearc basin ~1,000 m in elevation, here termed the Central Depression, 3) a Precordillera mountain range reaching 4,000 m at its peaks, 4) the Calama Valley, the central part of which is ~2,500 m in elevation, and the Upper Loa Valley, 5) the volcanic peaks that make up the Andean volcanic arc and rise to ~ 6,000 m. These peaks constitute the topographic and surface water divide between the Pacific to the west and the closed basins to the east and are partly coincident with the international border with Bolivia (Figure1), 6) east of the volcanic arc lies the Altiplano, an internally drained plateau of >4,000 m scattered with volcanic peaks reaching up to 6,000 m in elevation. The topography of the Alitplano plateau just east of the topographic divide varies from north to south within the study area. In the southern part, volcanic centers dominate the Altiplano and the elevation is consistently over 4300 m, while in the north a topographic lowland below 3800 m in elevation is present. The hyper arid climate of northern Chile is due to several factors, including the rain shadow effect of the Andes Mountains on moist air coming from the east, the cold Humbolt Pacific current along the coast and its associated thermal inversion, and the Southeast Pacific Ocean atmospheric high pressure system (Vuille and Ammann, 1997; Rech et al., 2002; Houston and Hartley, 2003; Vernekar et al., 2003). Precipitation rates in this region are highly correlated with elevation with higher elevations receiving more precipitation (DGA, 2003b; Houston and Hartley, 2003). Groundwater recharge rates also increase with increasing elevation. No significant recharge occurs below 4000 m elevation(DGA, 2003b).

The Upper Loa River flows south from its headwaters and is joined by the San Pedro River and Salado River tributaries whose headwaters are near the volcanic peaks that comprise the topographic basin divide (Figure 1). Within the Calama Valley the Loa River turns to the west and flows parallel to its San Salvador tributary as it exits the Calama Valley through a gap in the Precordillera mountain range and flows into the Central Depression. Within the Central Depression the Loa River curves and flows north for ~100 km until it passes west through the Costal Cordillera and empties into the Pacific Ocean.

On a regional scale, the Loa River and its three major tributaries are primarily groundwater fed except during rare precipitation events (Houston, 2006). However, at a local scale, there is known to be groundwater-surface water exchange in the Loa River. For example, in the Calama Hill region, the river appears to lose water, only to gain it again further downstream (Matraz Consultores Asociados S.A. and Universidad Politécnica de Cataluña, 2012). While geometries and interconnections between water bearing geologic units are not fully understood, a semi-confined or confined lower aquifer and an unconfined upper aquifer exist beneath much of the Calama Valley (Houston, 2004; Knight Piésold S. A., 2005; Montgomery and Associates Consultores Limitada, 2010).

On a long wavelength scale, the topography of the study region is high in the east and lower in the west. On a shorter wavelength scale, individual volcanoes within the Andes volcanic range define the east-west topographic divide within the study region. The groundwater flow systems that develop in situations where shorter wavelength topography is imposed on a longer wavelength topographic trend have been demonstrated (Tóth, 1963). In such situations we can expect local, intermediate, and regional groundwater flow systems to develop. These systems are nested and dependent on variations in topography at increasing scales. Local groundwater flow systems can flow in opposite directions from regional flow systems and regional flow systems can cross local topographic divides (Tóth, 1963). Therefore, it is possible that Loa River surface drainage boundaries do not coincide with the boundaries of the groundwater system. It has been reasoned that recharge is occurring on the Altiplano Plateau, within easternmost Chile and western Bolivia, and flowing to the west (Houston, 2004), crossing the topographic divide through regional groundwater flow paths beneath the volcanoes (Pourrut and Covarrubias, 1995; Montgomery et al., 2003). Sedimentary deposits and fractured ignimbrites exist beneath the volcanoes and are likely to serve as permeable units for regional groundwater flow (Montgomery et al., 2003), connecting the closed basins of the Altiplano with the Loa groundwater system (Houston, 2004). However, this regional flow scenario is controversial and not accepted by everyone. In light of the political implications of possible trans-boundary flow between Bolivia and Chile, it is important to explore hydrogeological scenarios that provide insight into the likelihood and extent of such flow.

2.1 Major sedimentary units and hydrogeologic interpretation

The sedimentary units within the Loa hydrologic system can be divided into three major sedimentary basins: 1) the forearc sedimentary basin in the Central Depression to the west, within which the Loa River flows north, 2) the Calama sedimentary basin east of the Precordillera bedrock pinch point, 3) the sediments of theAltiplano Plateau. While the model presented in this study encompasses all of these geographic regions, it is most refined within the Calama sedimentary basin, which is roughly coincident with the modern Calama Valley. Within the Calama sedimentary basin we describe both an upper and a lower aquifer with an aquitard separating them; elsewhere, we model a single phreatic aquifer. The major hydrological units of each sedimentary basin are described below.

2.1.1 Forearc sedimentary basin

In the forearc basin, the Upper Oligocene to Miocene Altos de Pica Formation overlies a deformed basement consisting of intrusive igneous rocks and deformed sediments (Victor et al., 2004). The Altos de Pica Formation consists of partially lithified non-marine alluvial conglomerate, sandstone and ignimbrite (Victor et al., 2004; Nester, 2008; Jordan et al., 2010). The hydraulic conductivity of the Altos de Pica Formation is expected to range from high in less consolidated conglomerate beds, to low within more welded ignimbrite beds. The Altos de Pica

Formation is unconformably overlain by Upper Miocene to Pliocene alluvial fan and aeolian deposits in the eastern part of the forarc basin (Kiefer et al., 1997; Nester, 2008; Jordan et al., 2010) that interfinger with Upper Miocene to Pliocene lacustrine deposits and evaporites in the western part of the forearc basin (Saez et al., 1999; Nester, 2008).

Since focus is placed on the Calama Valley in this model, less detail is given to the complex hydrogeology of the forearc sedimentary basin. Therefore, the sedimentary rocks of the forearc sedimentary basin are modeled as a single aquifer without significant confining units and are grouped together as one hydrogeologic layer.

2.1.2 Calama sedimentary basin

Several stratigraphic studies of the Calama sedimentary basin describe the regional sedimentary units of hydrologic interest (e.g. CORFO et al., 1977; May, 1997; May et al., 2005; Jordan et al., 2006; Blanco, 2008; Blanco and Tomlinson, 2009; Tomlinson et al., 2010). We group the sedimentary units together in our interpretation as two distinct aquifer packages and a aquitard which separates them. Table 1 shows available experimental hydraulic conductivity values for Calama sedimentary basin units. Figure 2 provides a representative cross-section view of the hydrogeology of the Calama sedimentary basin, adapted from Jordan and others (submitted). The hydrogeological basement rocks in the Calama Valley are composed of Paleozoic and Mesozoic deeply buried and consolidated sedimentary rocks, plutonic rocks and metamorphic rocks (Blanco and Tomlinson, 2009; Tomlinson et al., 2010).

The Eocene aged Calama Formation (Naranjo and Paskoff, 1985; Blanco et al., 2003; May et al., 2005; Blanco, 2008) consists predominantly of conglomerate with clasts ranging in size from pebble to cobble (May et al., 2005). The base of the Calama Formation contains the Topater Member consisting of interbedded volcaniclastic and andesite beds (Blanco, 2008). The

Calama Formation crops out in the southern quarter of the Calama Valley (Blanco and Tomlinson, 2009; Tomlinson et al., 2010); its subsurface continuity to the north and west are uncertain.

Along the eastern margin of the Calama sedimentary basin, the Oligocene to Lower Miocene Yalqui Formation (May, 1997; Blanco, 2008) overlies the deformed Mesozoic and Paleozoic sedimentary and volcanic rocks (Blanco, 2008). The Yalqui Formation consists of sedimentary breccias, gravel conglomerates, volcanic breccias and some sandstone beds (Blanco, 2008). Jordan and others (2006) interpret that the Yalqui Formation thickens westward in the subsurface, and is a widespread unit below the north-central Calama sedimentary basin. The Lower Miocene Yeso Formation rests unconformably atop the Yalqui Formation and consists of sandstones and gypsum deposits (Blanco, 2008).

The Miocene Jalquinche Formation (May, 1997) unconformably overlies the Yeso Formation (Blanco, 2008). The Jalquinche Formation consists of mudstones, fine grained sandstones, which are red in color, and evaporites (May et al., 2005). In the western part of the basin the Jalquinche Formation contains more mud rich layers (Blanco and Tomlinson, 2009). In the central part of the basin the Jalquinche Formation interfingers with the Middle Miocene Lasana Formation composed of conglomerate channel fill deposits, coarse sandstones and mudstone beds (May et al., 2005; Blanco, 2008).

We interpret the modeled lower aquifer layer to consist of the Calama, Yalqui, Yeso, and Lasana Formations, where it underlies the aquitard, and the eastern Jalquinche Formation east of UTM coordinate 533,000 m east. Reported hydraulic conductivities within the lower aquifer range from 0.02 to 100 m/d (Table 1) (Houston, 2004; Matraz Consultores Asociados S.A. and Universidad Politécnica de Cataluña, 2012).

A modeled aquitard consists of the Sifon Ignimbrite and the western portion of the Jalquinche Formation. Where the aquitard is not present, a single phreatic aquifer is mapped. The Late Miocene Sifon Ignimbrite can be found across much of the central and eastern Calama Basin (de Silva, 1989; Houston, 2004; Blanco, 2008; Tomlinson et al., 2010). This ignimbrite is up to 80 m thick where it ponded in previous topographic lows (Houston, 2004). The degree of welding within the ignimbrite decreases to the west within the study area (de Silva, 1989). At the confluence between the Loa River and the Salado River the Sifon Ignimbrite is 8 to 10 m thick and unwelded (de Silva, 1989). It continues to thin to the west and is no longer mapped by UTM coordinate 528,000 m east (Blanco and Tomlinson, 2009). The hydraulic conductivity of the Sifon Ignimbrite is reported as 1×10^{-6} m/d (Matraz Consultores Asociados S.A. and Universidad Politécnica de Cataluña, 2012). The hydraulic conductivity in fractures within the welded Sifon Ignimbrite has been calculated as 3×10^{-5} m/d (Table 1) (Houston, 2004).

Three units comprise the upper aquifer of the hydrogeologic model above the aquitard. The Upper Miocene to Pliocene Chiquinaputo Formation (Blanco, 2008) consists of fluvial conglomerates and sandstones, deposited along the eastern and northeastern margins of the basin (May et al., 2005; Rech et al., 2010). To the west the Chiquinaputo Formation interfingers with the Upper Miocene to Pliocene Opache Formation (May et al., 2005; Blanco, 2008; Rech et al., 2010). The Opache Formation is composed of limestone, calcite-cemented sandstone and conglomerate, and some diatomites (May et al., 2005). Its hydraulic conductivity has been measured to range from 1 to 2 m/day within the matrix rock and up to 120 m/d in fissures and karstic preferential flow paths (Table 1) (Houston, 2004). In the higher elevations on the eastern side of the Calama Basin the Upper Miocene Toconce Formation interfingers with the Opache Formation (Houston, 2004). The Toconce Formation is composed of tuffs, reworked tuffs, sandstones and conglomerates (Houston, 2004). The Toconce Formation has a measured hydraulic conductivity of 1 to 30 m/d (Table 1) (Houston, 2004).

The Upper Pliocene to Pleistocene Chiu-Chiu Formation unconformably overlies the Opache and Chiquinaputo Formations in the low areas near the rivers in the central and northeastern parts of the Calama Basin (Blanco, 2008). The Chiu-Chiu Formation consists of mudstones, sandstones, diatomites and interbedded conglomerate channel fill deposits (May et al., 2005; Blanco, 2008).

The modeled upper aquifer, above the aquitard, is interpreted to consist of the Chiquinaputo, Opache, and Chiu-Chiu Formations, and the Lasana Formation where it overlies the aquitard. Hydraulic conductivity measurements within the upper aquifer range from 0.0015 to 300 m/d (Matraz Consultores Asociados S.A. and Universidad Politécnica de Cataluña, 2012).

2.1.3 Altiplano Plateau sediments

The surficial geology of the Altiplano Plateau has been mapped by the Chilean, Bolivian, and U.S. governments (Pareja et al., 1978; Rramírez and Huete, 1981; N. and Lahsen, 1984; Marsh et al., 1992; Minería, 2002). The sediments of the Altiplano Plateau overlie a basement of Ordovician to Devonian clastic sediments and late Paleozoic and Mesozoic sedimentary and igneous rocks (Elger et al., 2005). The thickness of the sediments in the Altiplano sedimentary basin range from ~ 400 m to over 6 km (Welsink et al., 1995; Elger et al., 2005). These sediments consist of late Pliocene to Paleocene clastic sediments, including the Santa Lucia, Potoco, and San Vicente Formations, and late Miocene to recent volcano-sedimentary deposits (Elger et al., 2005). The Cenozoic units are grouped together into a single phreatic aquifer unit.

3 Groundwater Model

The purpose of this model is to investigate the large-scale, whole system water fluxes and the possible impact of increased groundwater extraction from the lower aquifer. In particular, we are interested in groundwater fluxes from the lower aquifer flowing west out of the Calama Valley, through the San Salvador-Loa Valley, and in groundwater movement southwest out of the Calama Valley into the Central Depression (Figure 1). Previous studies provided little information about the westward groundwater flux beyond the regions of well fields west of Calama city, and they did not explore the possibility of a southwestward groundwater flux out of the Calama Valley that diverges from the direction of river flow. Consequently, these fluxes have not been considered within the management framework. We will use the model to investigate the possibility that these groundwater fluxes exist and the possible impact of increased groundwater extraction from the lower aquifer on lower and upper aquifer heads and on groundwater fluxes.

3.1 Model Structure and Boundary Conditions

The steady-state groundwater flow model presented here was developed using USGS MODFLOW-2005 and the USGS ModelMuse graphical user interface. MODFLOW-2005 is a three-dimensional finite difference groundwater flow model that operates based on Darcy's Law of flow through porous material in combination with a mass balance equation (Harbaugh, 2005).

The model is vast, approximately 300 km from east to west and 250 km from north to south. It spans over 5,500 m in elevation from sea level at the western model border to the highest volcanic peaks within the model boundaries. The data available to constrain the model are sparse. Only seventeen river gauging stations are currently maintained in the study region. Other gauging stations have been active in the past but are abandoned. Head observation wells are located only within and near the Calama Valley and subsurface geologic data are also concentrated in this region. Because of the scarcity and geographic concentration of hydraulic head measurements, we rely on large-scale observations of water table elevation as a vital component for calibration. For example, the locations of salars and wetlands and the absence of ponded water at locations throughout the model inform the model's calibration.

The grid size for the model ranges from 2 km x 2 km in the Calama Valley to 4 km x 4 km in the outer reaches of the model, including the Altiplano (Figure 3). The model topography was downsampled from the ASTER Global DEM version 2 (NASA and METI, 2011). The western boundary of the modeled system is the Pacific Ocean, which is modeled as a constant head boundary at sea level (Figure 4). The northern and southern boundaries coincide with the boundaries of the Loa topographic watershed basin. The northern boundary and most of the southern boundary are interpreted as groundwater no-flow boundaries. However, adjacent to the southern model boundary in the Sierra Gorda region there is a constant head boundary, which simulates groundwater flow leaving the topographic watershed to the south (Figure 4). The eastern boundary of the modeled system is within the surface water catchment of the Altiplano Plateau and roughly bisects the highlands (Figure 1). This eastern boundary is modeled as a no flow boundary except in the northeastern corner of the model. In its northeastern corner the model includes a part of the Salar de Uyuni salt pan. In order to simulate the high evaporation rates on the salar, this area is modeled as a constant head boundary which acts as a sink, not a source due to the modeled hydraulic gradients in the Altiplano (Figure 4).

Recharge from precipitation accounts for all water inflows to the model. Water outflows from the model are divided between the following: 1) discharge to the constant head boundary representing the Pacific Ocean, 2) discharge to the drain boundaries (Figures 3 and 4) that represent the region's rivers, 3) discharge to the constant head boundary representing evaporative loss in the Salar de Uyuni, 4) discharge to the Sierra Gorda constant head boundary representing southerly groundwater flow out of the model, 5) discharge to the evapotranspiration boundary in the Salar Llalqui region (Figure 4) and 6) modeled groundwater extraction wells that represent human groundwater consumption (Figure 5).

The system was modeled as eleven layers of varying thicknesses and hydraulic conductivities with a minimum layer thickness of 5 m. The top six layers represent the region's sedimentary rocks. Taken together, these six sedimentary rock and pyroclastic volcanic layers are thickest within the centers of the sedimentary Calama and Pampa de Tamarugal Basins and within the Altiplano. The sedimentary rocks overlie a very low hydraulic conductivity basement. The basement rocks extend all the way to the model top within the Coastal Cordillera mountain range and the Precordillera mountain range. The thicknesses of the layers and their hydraulic conductivities across a representative cross section of Calama Valley are shown in Figure 7.

Hydraulic conductivity anisotropy, K_h/K_z, where K_h is horizontal hydraulic conductivity and K_z is vertical hydraulic conductivity, was set at 10 x uniformly for the model. This choice was made because sedimentary rocks, which act as the region's aquifers, are often layered, creating the possibility of preferential lateral flow and barriers to vertical flow (Anderson and Woessner, 1991). Reported hydraulic conductivity anisotropy in sediments and sedimentary rocks range from 2 x to 100 x (Todd, 1980; Domenico and Schwartz, 1990).

A single aquifer is modeled across much of the basin including the Central Depression, the Altiplano (Figure 6), the Upper Loa Basin and the San Pedro Basin. Two aquifers are modeled within the Calama Valley and the Salado River drainage basin. In this region an aquitard of lower hydraulic conductivity modeled in layers 3 and 4 separates the two higher hydraulic conductivity aquifer layers (Figure 7).

The uppermost layer of the groundwater model corresponds to unconsolidated sedimentary debris. Beneath the debris layer the Opache, Chiquinaputo and Toconce Formations, as well as the Pampa del Tamarugal sedimentary units, are grouped together to form the upper aquifer model layer. The Opache Formation has karstic characteristics, however, it is modeled as though it were a porous medium with a higher average hydraulic conductivity. This is a recognized groundwater modeling method for karstic units (Scanlon et al., 2003). Where the Sifon ignimbrite or the mud-rich facies of the Jalquinche Formation serve as an aquitard, they are modeled as a low hydraulic conductivity layer between the lower and upper aquifer layers. Beneath the modeled aquitard, the lower aquifer layer represents the Yeso, Yalqui, Calama and Lasana Formations as well as Jalquinche Formation east of UTM coordinate 533,000 east. The thicknesses of modeled aquifer and aquitard layers as well as the varying elevation of the bedrock surface west of the Andean topographic divide are based upon published field data (outcrop and stratigraphic section descriptions) (May et al., 1999; Houston, 2004; May et al., 2005; Blanco, 2008; Blanco and Tomlinson, 2009), unpublished field data of T. Jordan (Teresa Jordan personal communication, 2014), seismic reflection profiles of the Calama area (Jordan et al., 2006; Blanco, 2008), borehole logs (CORFO et al., 1977; Tomlinson et al., 2010; Matraz Consultores Asociados S.A. and Universidad Politécnica de Cataluña, 2012; Jordan et al., submitted), published aquifer interpretations (Houston, 2004), and remote sensing image interpretation using Google Earth.

The area east of the topographic divide, the Altiplano Plateau, was modeled as a phreatic aquifer unit that decreases in hydraulic conductivity with depth. The top four model layers in the Altiplano Plateau are treated as one hydrogeologic aquifer unit, which was assigned laterally varying hydraulic conductivities during the calibration process. The base of the aquifer unit is at

3400 m above sea level and the thickness varies due to topography, ranging from ~300 m to ~ 1900 m. In the Altiplano region, model layers five and six are of uniform thickness of 500 m (ranging from 2900 m to 3400 m above sea level) and were assigned a uniform hydraulic conductivity lower than the conductivities of the overlying aquifer during the calibration process. Beneath 2900 m above sea level the hydraulic bedrock is modeled in the region. Cross sections of the groundwater model showing the Altiplano region are shown in Figure 6.

The Loa River and its tributaries are modeled as drain boundaries in MODFLOW (Figures 3 and 4). This allows groundwater to leave the ground and enter the rivers, but does not allow the rivers to be a source for the groundwater. This is appropriate because, at the regional scale, the rivers in this area are supplied by groundwater baseflow and are not sourced by runoff, and as such they do not provide new inflow to the groundwater system (Houston, 2006). This model does not simulate groundwater-surface water exchanges that occur on small geographic scales.

The region's salars are modeled in three ways. In the Altiplano, Salar de Uyuni abuts the northeastern edge of the model (Figure 8). Salar de Uyuni is the largest salt pan in the world, with reported evaporation rates of 1500 mm/yr (Rouchy et al., 1996). Since groundwater from the modeled region leaves the geographical boundary of the model as evaporation from Salar de Uyuni, the salar is modeled as a constant head boundary at 3640 m elevation. Smaller salars on the Altiplano (Figure 8), such as Salar Ascotan, are completely within the model. These salars are not assigned special properties, such as MODFLOW evapotransiration boundaries, because they are located within the recharge area and may be fed by surface water imputs. Within the Calama Basin, a wet area known as Salar Llalqui (Figure 8) is modeled using the MODFLOW evapotranspiration (EVT) package. This choice was made because, at ~2480 m elevation, Salar

Llalqui is effectively outside of the recharge area and is supplied by groundwater. Therefore, evapotranspiration in Salar Llalqui is a direct loss from the groundwater system.

Recharge rates in this region are positively correlated with elevation (Chauffaut, 1998; Houston and Hartley, 2003; Houston, 2009). Recharge is effectively confined to eastern areas of the model with elevations of greater than 3500 m. Modeled recharge rates were varied during calibration of the model and the calibrated recharge rates are shown in Figure 9. As a starting point for calibration a published empirical exponential function relating recharge to elevation was used:

Recharge (mm/yr)= $0.0001 \times e^{0.0029A}$ (Houston, 2009) **(1)**

where A is elevation (m)

Human groundwater extraction is modeled using MODFLOW extraction wells placed at specific permitted extraction locations (Figure 5). For the years of hydraulic head data used during calibration 2003-2006, modeled groundwater extraction was restricted to the upper aquifer. Therefore, modeled extraction wells were placed within the phreatic aquifer. Within the Loa River watershed mining companies are collectively extracting groundwater at a rate of approximately fifty percent of their total allocated groundwater extraction rights (Proust Consultores, 2008). All groundwater rights in this region are held by mining corporations. Therefore, the modeled groundwater extraction rates are set at fifty percent of the allocated rights (DGA, 2003a, 2008). The combined modeled extraction from wells totals 1,051 l/s. This includes all groundwater rights for which the locations are documented in governmental reports (DGA, 2003b, 2008). Consumptive surface water usage rates and locations are based on allocated rights to non-irrigation surface water usage (DGA, 2005), and adjusted estimates of consumptive irrigation usage for different locations (DGA, 2005). Modeled consumptive surface water use was included in the model as part of the drain flux calibration data set.

4 Calibration of Model

The model was calibrated to both head and flux observations using trial and error methods. During calibration we varied the recharge rates, the hydraulic conductivity of model areas, the conductance of the drain boundaries, and the evapotranspiration rate in Salar Llalqui using trial and error methods. The goal of this calibration was to achieve the best possible agreement between the model and what is known about the elevation of the water table, the head measurements within the lower aquifer and the groundwater discharge to rivers along measured stretches.

4.1 Observation Data Sets

Averaged piezometric head measurements taken between 2003 and 2006 from 94 observation wells within the upper and lower aquifers within the Calama Basin were used in calibration (Figure 10) (Knight Piésold S. A., 2005; Montgomery and Associates Consultores Limitada, 2010; DGA, 2012).

The drain flux along eight reaches of the Loa River System (Figure 11) is calculated as the difference between the upstream and downstream gauging measurements, adjusted for evaporation and consumptive use. Estimates of groundwater flux to the rivers along specific stretches (Table 2) were made using averaged annual river flow measurements from 2003 and 2009 (Knight Piésold S. A., 2005; DGA, 2012). The differences between upstream and downstream flow measurements were combined with stream evaporation estimates and human consumptive surface water usage rates within specific stream reaches (DGA, 2005, 2008; Proust Consultores, 2008) in order to produce the drain flux estimates (Table 2). Stream evaporation estimates (Table 2) were calculated by multiplying the stream surface area by the regional pan evaporation rate and adjusted by a scaling factor of 0.7 to account for higher pan evaporation rate compared with natural evaporation rate (Dingman, 2002). Stream lengths and widths were calculated using GoogleEarth imagery.

Consumptive surface water use can be separated into three categories: mining industry use, municipal use and irrigation. The mining industry's actual consumptive use of surface water is approximately fifty percent of their allocated rights (Proust Consultores, 2008). Therefore, in calculating drain flux, surface water usage rates for mining were assumed to be fifty percent of their allocated rights (DGA, 2005). Consumptive irrigation surface water usage rates have been estimated based on the area of irrigated land and the crop type for the Loa River Basin (DGA, 2003b, 2005). Because irrigation is seasonal and only occurs during the growing season, in this model irrigation was assumed to be occurring for only one quarter of the calendar year. Therefore, estimated consumptive irrigation usage was reduced by seventy five percent from DGA estimates (DGA, 2003b, 2005).

The general equation used to calculate drain flux estimates is as follows:

$$F\ (l/s) = Q_u - Q_d - E - SW - I \qquad \textbf{(2)}$$

where F (l/s) is the groundwater flux into the stream reach (a negative number), Q_u (l/s) is upstream average flow, Q_d(l/s) is downstream average flow, E (l/s) is calculated evaporation along the stream reach, SW (l/s) is consumptive surface water use, and I (l/s) is consumptive irrigation use. In reach C spring flow is also included in the drain flux observation calculation as an additional groundwater flux to the stream. For reach C:

$$F\ (l/s) = Q_u - Q_d - E - SW - I - S_{oo} - S_{ss} \qquad \textbf{(3)}$$

where S_{oo} is spring flow at Ojos Opache (Figure 11, number 4) and S_{ss} is spring flow at the San Salvador River headwaters (Figure 11, number 5). Because groundwater flux into the river is a negative number and spring flows represent an additional groundwater input to the stream, S_{oo} and S_{ss} are subtracted from the upstream flow measurement.

A range of drain flux measurements for each reach was calculated (Table 2). This range was determined by varying the reported pan evaporation rates, which range from 0.06 m/d to 0.115 m/d (Chauffaut, 1998; DGA, 2003b) and by varying the stream widths, which were estimated to between four and eight meters based on field observations.

4.1.1 Limitations of observation and model data sets

The model topography is down-sampled from the ASTER Global DEM (NASA and METI, 2011). It should be noted that studies (e.g Bhakar et al., 2010; Czubski et al., 2013) have shown the ASTER GDEM to be less accurate for hydrological uses than the SRTM DEM (USGS, 2004). Czubski and others (2013) report differing elevation root mean squared errors of ~12 m for the SRTM DEM and ~17 m for the ASTER GDEM. However, the ASTER GDEM was originally chosen for use as model topography during the beginning stages of this modeling project and was retained throughout.

The observation well heads used for calibration are located primarily within the Calama Valley, not in the other parts of the model (Figure 10). The four easternmost wells, of the 96 total observation wells, are located just east of the Calama Valley in the Salado River drainage basin (Figure 10). The lack of groundwater monitoring within the rest of the Loa groundwater system is a challenge for calibration. However, since our research questions focus on the Calama Valley, it is less problematic that the observation data are concentrated there. In calibrating the rest of the model outside Calama Valley we relied on our knowledge of where the groundwater reaches the surface and where it is buried. For example, several lakes exist in the Altiplano, here we know the groundwater reaches the surface. Conversely, there are no ponds or lakes within the Central Depression so we know the water table is below the surface there.

Uncertainty in the reported well head elevation and location is a limitation of the observation data sets. For example, the locations of the wells were reported only to the nearest degree and minute of latitude and longitude for one data set (DGA, 2012). Also, conflicting information exists on the elevations of well heads for some observation wells. Different sources disagree on the elevation of well heads by up to 73 meters (Salazar M. et al., 2010b, a; DGA, 2012). For consistency the elevations listed on the DGA monitoring site map were used for that data set (Salazar M. et al., 2010b, a). Another limitation is that map projections used in the available data sets are often not reported, adding to possible location error.

River flow measurements and observation well heads were not continuously reported and measurements were taken with differing frequency. We have attempted to use reported data from overlapping periods between 2001 and 2009. Available groundwater monitoring well heads from the DGA data set were averaged for the years 2003 through 2006 (DGA, 2012). This was done in part to conform to the timeframe of piezometric head data available for a private data set (Knight Piésold S. A., 2005). The head measurements reported in this private data set were taken non-continuously between 2003 and 2005 and all available measurements were averaged for use in calibration (Knight Piésold S. A., 2005). Mean of annual average flow gauging measurements from 2003 through 2009 where used when at least seven months of measurements from the year were reported (Montgomery and Associates Consultores Limitada, 2010; DGA, 2012).

4.2 Calibration Results

4.2.1 Calibration to Head Observations

The simulated water table elevation from the calibrated model is shown in Figure 12. The difference between observed and simulated heads (residuals) for the calibrated model is shown both in map view (Figure 13) and graphically (Figure 14) for 94 observation wells. The average absolute value of head residuals rounded to the nearest meter is ~18 m and the root mean square of head residuals is ~25 meters. Head residual absolute values range from <1 m to ~100 m. These residual values may seem large to modelers used to working with consistent observation datasets and groundwater models that encompass smaller geographic areas. However, the topographic elevation within the bounds of this model ranges from 0 to 5500 m. Because of the extreme topographic relief over which calibration must occur, and the known uncertainty in the head observations, we are satisfied with this head calibration.

The simulated water table elevation exceeds the modeled topography in three cells and along the coastline (Figure 15). Along the coastline this is due to a combination of the imposed Constant Head Boundary (CHB) of 0 m representing the Pacific Ocean and DEM elevations lower than sea level. The difference between the CHB and the topography is ~1 m or less at the coast. Two cells in the western Altiplano indicate ponding: one cell simulates ponding of ~1 m within the northern part of Salar Ascotan and one cell simulates ponding of ~2 m within the southern part of Salar Ascotan. Since, based on Google Earth remote sensing imagery (Landsat), the water table is above the land surface in some places in Salar Ascotan at some time, this simulated result is reasonable. In the far northeastern part of the model one cell simulates ponding of ~1 m. This is in the area near the border of Salar Uyuni. There is standing water in the Salar Uyuni seasonally (Hönninger et al., 2004). Therefore, this is ponding is not a concern.

During the calibration process a constant head boundary was added to the model near the southern border in the Sierra Gorda region (Figure 4). This constant head boundary removes water from the model and represents groundwater moving out of the southern border of the model. This addition was made because simulated water table elevations in the uncalibrated model were almost 300 m higher than topography at this location. The elevation of the constant head boundary is 1615 m based on several head measurements in observation wells (Christian Herrera personal communication, 2014).

4.2.2 Calibration to Drain Flux Observations

The calibrated model simulates a total flux, rounded to the nearest 10 l/s, of 4,380 l/s (Table 2) exiting the model through measured drain reaches. Estimates for actual total groundwater flux to measured river reaches range from 3,390 l/s to 6,640 l/s (Table 2); the simulated total flux falls within this range. Reaches used in calibration are shown in Figure 11. Table 2 lists both the range of estimated actual drain fluxes and the calibrated model's simulated fluxes to each measured reach. The simulated drain flux to each measured reach is within the range of estimated river fluxes. During calibration recharge rates were reduced over most of the model except for a portion of the Upper Loa headwaters. Final, calibrated recharge rates are shown in Figure 9. Hydraulic conductivities were also reduced across the whole model in order to lower the total flux rates to the drains to within the estimated range. Once that was accomplished, the model was calibrated to flux rates to individual reaches. This was accomplished by adjusting the hydraulic conductivity of areas near particular stream reaches to raise (increases flux) or lower (decreases flux) the water table.

4.2.3 Calibrated Drain Conductance

Drain conductance is a factor that quantifies the resistance encountered by groundwater flowing into the river system using Darcy's Law. Conductance relates the groundwater flow into the drain to the difference between the drain elevation and the piezometric head in the drain cell.

$C\ (length^2/time)=(L*K_{rb}*W)/T_{rb}$ **(4)**

where C is drain conductance with units of length squared per time, L is river length including all meanders, K_{rb} is hydraulic conductivity of the river bed sediments, W is the width of the river and T_{rb} is the thickness of the river bed sediments.

ModelMuse allows the drain length, L, to be calculated and automatically incorporated into the conductance term, a capability which was employed. However, the drain boundary is less sinuous than the actual river it represents. Therefore, a relative sinuosity term, S_r, is included in the conductance equation. Relative sinuosity is the additional sinuosity of the actual river in comparison to the modeled drain. Conductance per unit drain length (C_l) was specified for the model such that:

$C_l\ (length/time) =(S_r*K_{rb}*W)/T_{rb}$ **(5)**

Since we do not have reliable information on the actual conductance from field studies, we varied the drain conductance during calibration of the model. In the calibrated model, drain conductance per meter drain length is 100 m/d for all drains.

4.2.4 Calibrated Recharge Rates

Calibrated recharge rates are shown in Figure 9. As a starting point for calibration, recharge rates were defined based on an empirical equation **(1)** relating recharge rate to elevation for the study region (Houston, 2009). Using this empirical equation for recharge rates, hydraulic conductivities were adjusted and the model was calibrated to head measurements. A good fit to the head observations was achieved in this manner. However, fluxes into the drains along measured reaches were too high. Therefore, in order to reduce groundwater flux through the model, recharge rates were reduced across much of the model and hydraulic conductivity values were adjusted. The recharge rate was reduced by fifty-seven percent for most of the model area, resulting in the following function for recharge rates:

$$R = 0.43(0.0001 \text{ x } e^{0.0029A}) \quad \textbf{(6)}$$

Here R is the recharge rate in mm/yr and A is the elevation in meters.

A 57% reduction in recharge rate from starting assumptions is not unreasonable in this case. Recharge in this area is very poorly constrained and other regional recharge estimates based on sparse precipitation data (DGA, 2003b) are also less than the recharge from equation 1.

A constant equation for recharge across the entire model resulted in a simulated water table elevation in the headwaters of the Upper Loa River that was low and consequently the groundwater flux to the drains in reach F (Figure 11) was too low as well. Therefore, within an area of approximately 1,600 square kilometers (shown as a polygon in Figure 9) in the headwaters of the Upper Loa watershed, recharge was increased by 38 percent resulting in the following function for recharge within that area:

$$R = 1.38(0.00001 \text{ x } e^{0.0029A}) \quad \textbf{(7)}$$

This area with higher assigned recharge rates includes the high recharge areas of the high elevation volcanoes that form the topographic divide between the Upper Loa catchment and the Altiplano. The area extends to the south covering areas where the simulated water table elevation was too low. This higher recharge area was necessary in order to calibrate the model to stream discharge measurements in the Upper Loa River. However, systematically higher precipitation rates in the northern portion of the Upper Loa catchment compared with the highlands to the south, have not been reported based on meterological gauging station data (Matraz Consultores Asociados, 2014). To our knowledge, no meterological gauging data exists within the area that is assigned higher modeled recharge rates (Matraz Consultores Asociados, 2014).

4.2.5 Calibrated Hydraulic Conductivities

The calibrated hydraulic conductivities of model layers are shown in Figure 16. In most places within the model, hydraulic conductivities were reduced during calibration from starting assumptions. This was done, in combination with a reduction in recharge rates, to reduce the groundwater flow through the model and calibrate to drain flux measurements. Other changes in hydraulic conductivity were made to calibrate heads to head measurements in the Calama Valley and to reduce ponding in areas without surface water. In two notable areas hydraulic conductivity was increased from starting assumptions in order to reduce flow into drains in the northern Coastal Cordillera, and to reduce simulated ponding near the Salar de Uyuni in the northeast portion of the model.

Bedrock was assigned a hydraulic conductivity of 0.0035 m/d except in the northern Coastal Cordillera, where it is 0.07 m/d to 0.11 m/d. The larger hydraulic conductivity values in the northern portion of the Coastal Cordillera bedrock that were assigned during calibration in order to reduce the water table elevation near the Loa River, are consistent with known areas of faulting across this part of the Coastal Cordillera (Allmendinger et al., 2005).

Hydraulic conductivities assigned to sedimentary rock units range from 0.01 m/d to 350 m/d with the highest values in the northeast near the Salar de Uyuni. The aquitard that separates the upper and lower aquifers within the Calama Valley and the Salado River drainage basin is assigned a hydraulic conductivity of 0.035 m/d. This value is higher than the highest reported hydraulic conductivity measurement of 0.005 m/d for the aquitard (Table 1). In the Calama Valley and the Salado River drainage basin the upper and lower aquifer units are assigned hydraulic conductivities ranging from 0.125 to 1.05 m/d. In the San Pedro River drainage basin the aquifer units are assigned a hydraulic conductivity of 0.1 m/d. In the Upper Loa Valley the assigned hydraulic conductivity of sedimentary units ranges from 0.1 to 10 m/d. These values are within the range of reported values for the hydraulic conductivity of the upper and lower aquifers (Table 1). The units representing the volcanic arc that serves as the eastern border of the Loa River watershed are assigned a hydraulic conductivity of 0.0175 m/d in most places. On the Altiplano Plateau sedimentary units (top four model layers) are assigned hydraulic conductivity values ranging from 0.0175 to 350 m/d, shown in blues, green, yellow and red in Figure 16 A, B, C and D. Model layers 5 and 6 are assigned a hydraulic conductivity of 0.035 m/d and layers 7 and below are bedrock. The highest hydraulic conductivities in the Altiplano, which are represented by red in Figure 16, were assigned to low lying areas closest to the Salar Uyuni.

4.2.6 Evapotranspiration Rate

In the Salar Llalqui region an evapotranspiration rate was defined in 17 model cells (Figure 4) because several meters of simulated ponding occurred in the uncalibrated model. The reported evaporation rate in Salar Uyuni, 1500 mm/year, was used as a starting point for calibration. However, this produced too great of an effect on the model fluxes. The evapotranspiration rate was reduced by a factor of ten to 150 mm/year. This eliminated ponding in the region while maintaining appropriate heads and drain flux rates in the rest of the model.

5 Results

5.1 Model Fluxes

The best calibrated version of the model has a total recharge of ~15,900 l/s rounded to the nearest 10 l/s, which represents the only inflow to the model. Extraction wells that represent human groundwater use account for modeled outflows of ~1,050 l/s. Drain boundaries representing the rivers account for ~4,520 l/s of the model outflows. On the Aliplano Plateau a modeled outflow of ~9,620 l/s occurs at the constant head boundary that represents evaporation from the Salar de Uyuni. At the western model boundary, a modeled outflow of ~520 l/s occurs at the constant head boundary that represents groundwater flow from the Coastal Cordillera bedrock into the Pacific Ocean. An additional outflow of ~40 l/s occurs at the constant head boundary at Sierra Gorda and represents flow exiting the model to the south. Finally, an outflow of 150 l/s occurs at the evapotranspiration boundary that represents the Salar Llalqui site.

Modeled groundwater fluxes through boundaries of interest were measured using the zone budget capability of MODFLOW (Figure 17) and are rounded to the nearest 1 l/s. The westward groundwater flux leaving the lower aquifer within the San Salvador-Loa Valley is simulated to be ~28 l/s. The simulated groundwater flux leaving the Calama Valley towards the south within the modeled sedimentary rocks is ~69 l/s. If this flux is measured through the entire model, including the bedrock, it comes to ~97 l/s. Of the groundwater flux leaving the Calama Valley towards the south, ~40 l/s exits the model at the Sierra Gorda constant head boundary, while the remainder flows to the west beneath the Central Depression and the Coastal Cordillera and exits the model at the Pacific Ocean.

5.2 Comparison between model and DGA hydrologic balance

In a 2003 water balance study the DGA (DGA, 2003b) recognized recharge occurring in the Loa system above 4000 m and only within the topographic watershed. The 2003 study, of the Loa River catchment only, calculated a total recharge of 6,410 l/s using precipitation measurements (dependent on elevation) and calculated evapotranspiration rates. In comparison, the total modeled recharge rate for this study’s much larger area, rounded to the nearest 10 l/s, is ~15,900 l/s, ~248% more than that presented in the 2003 study. However, the recharge area in the model presented here is much more extensive; it covers some ~20,000 km^2 more area than the 2003 study. It extends beyond the topographic divide of the Andes volcanic range, shown in Figure 1, and into the Altiplano Plateau. Therefore, it would make sense to compare the total modeled recharge that occurs west of the topographic divide in this model to the recharge rates presented in the 2003 study. West of the topographic divide the total modeled recharge rate is ~4,850 l/s, ~24% less than the rate presented in the 2003 study.

5.3 Groundwater flow across topographic and international boundaries

The modeled net groundwater fluxes described in this section are all less than ~15% of the model's total water budget. These fluxes are small compared with the model's uncertainty. The hydraulic conductivity values for the model have uncertainties of orders of magnitude associated with them. The hydrogeology of the model, meaning the thicknesses and dimensions of units with varying hydraulic conductivity characteristics, is also highly uncertain and contributes even more significantly to the uncertainty associated with the model results. Therefore, these modeled fluxes should not be interpreted as accurate, even in their direction of flux, because they are within the bounds of uncertainty of the model. However, examining these fluxes gives information about how the model works and how the modeled groundwater moves across different boundaries of interest. The results presented in this section also demonstrate that a cross basin and international net groundwater fluxes emerge from a model with boundaries far from both the topographic divide and the international border. Therefore, it is not a possibility that should be discounted out of hand. This justifies investment in improved hydrological and hydrogeological data sets.

Since the model presented here includes a portion of the Altiplano Plateau, we can examine whether the model simulates groundwater flow across the topographic divide that defines the eastern border of the Loa River catchment (dashed white line, Figure 1). In order to do this, we compare the total recharge rates and the total model outflows that occur west and east of the topographic divide. If, west of the topographic divide, higher total groundwater discharge rates occur than total groundwater recharge rates, then the model is simulating cross basin groundwater flow from the east to the west. Modeled groundwater discharge west of the topographic divide occurs at groundwater extraction wells, drain boundaries representing rivers, the Pacific Ocean constant head boundary, the Sierra Gorda constant head boundary, and the Salar Llalqui evapotranspiration boundary. Rounded to the nearest 10 l/s these discharges total ~6,280 l/s. In comparison the total modeled recharge west of the topographic divide is ~4,850 l/s. Therefore, in this model, there is a westerly net flux of ~1,430 across the topographic divide. This represents ~9% of the total water budget.

The regional topographic divide of the Andes volcanic range is not coincident with the Chile-Bolivia border everywhere in the model (Figure 1). A portion of the Altiplano is Chilean territory (between white and yellow dashed lines, Figure 1). Therefore, we also present a comparison of the total modeled recharge and discharge rates in the two countries. Of the total, whole-system modeled recharge (~15,900 l/s), ~8,810 l/s occurs in Bolivia and ~7,090 occurs in Chile. Of the total whole-system modeled discharge, ~9,620 l/s occurs in Bolivia and ~6,280 l/s occurs in Chile. This means that there is a modeled easterly net flux of ~810 l/s of groundwater moving from Chile to Bolivia (9,620-8,810=810). This represents ~5% of the model's total water budget.

In the groundwater model near the Chile-Bolivia border (Figure 1), modeled net groundwater flow moves in different directions across the topographic divide (westerly) and across the international border (easterly). Therefore, we more carefully investigate the modeled groundwater flows between the topographic divide and the international border (Figure 1), an area which we term the Ascotan Region. To do this we first separate the model into three zones using the MODFLOW Zone Budget package. These zones extend through the entire thickness of the model and include: the model west of the topographic divide, the model east of the international border, and area between the topographic divide and the international border (Figure 18, A). In this region of the groundwater model the cell sizes are 16 km^2.

Based on this zone budget analysis, ~970 l/s of groundwater, or ~6% of the total water budget, flows directly from Bolivia to Chile across the southern portion of the international border, where the border is coincident with the topographic divide. No groundwater is modeled to flow directly from Chile to Bolivia along this segment of the international border. The groundwater fluxes between the Ascotan Region and the modeled areas to the east and west of it are more complex. The zone budget analysis shows that ~1,610 l/s of groundwater flows from the Ascotan Region to the west, while ~1100 l/s flows from the west to the Ascotan Region. This results in a net groundwater flow of ~510 l/s, or ~3% of the total water budget, from the Ascotan Region to the west across the topographic divide. On the eastern side, ~3,040 l/s of modeled groundwater flows from the Ascotan Region to the east, while ~1,260 l/s flows from the east into the Ascotan Region. This results in a net groundwater flow of ~1780 l/s, or ~11% of the total water budget, from the Ascotan Region into Bolivia. Therefore, in the calibrated model, recharge that originates in the Ascotan Region flows both to the west and to the east. However, if we examine the net flows, we see that the modeled groundwater flow from the Ascotan Region to the east is more than three times greater in magnitude than the flow to the west.

Because the zone budget analysis indicates that modeled groundwater is flowing in both directions across both the western and eastern boundaries of the Ascotan Region, it makes sense to investigate whether there are any interesting flow differences with depth across the region. Is groundwater flowing in different directions or at different magnitudes dependent on depth? Therefore, we further separate the Ascotan Region into three different zones based on hydraulic conductivity and model layers (Figure 18, B and C). The upper zone (green in Figure 18) consists of the top four layers of the model, a single hydrogeologic unit that extends down to approximately 3400 m in elevation. These top four layers represent have higher hydraulic conductivity values, ranging from 0.0175 m/d to 350 m/d, and represent the modeled aquifer material in the Altiplano. The top for layers also have vertically matching hydraulic conductivity regions within the Ascotan Region and within the Altiplano in general. The middle zone (yellow in Figure 18) consists of layers 5 and 6 of the model within the Ascotan Region. These layers have a lower hydraulic conductivity, which is uniformly assigned to be 0.035 m/d. The lower zone (red in Figure 18) consists of model layers 6 through 11 within the Ascotan Region, which are bedrock layers with a uniform hydraulic conductivity of 0.0035 m/d.

The depth-dependent zone budget analysis shows that groundwater is flowing both into and out of the Ascotan Region to both the east and the west for all three depth zones analyzed. However, there are significant differences in the magnitudes of flow and the net directions of groundwater flux within the different depth zones. The net groundwater fluxes between zones are shown in Figure 18 image C. As hydraulic conductivities decrease downward, the magnitudes of groundwater flux also decrease, especially when the thicknesses of the zones are accounted for. The zone budget analysis shows that in the middle and lower depth zones there is a westerly net groundwater flow from Bolivia into the Ascotan Region and from the Ascotan Region to the west beneath the topographic divide. The pattern is different in the upper zone, which represents the aquifer material. Here there is net groundwater flow in both an easterly and a westerly direction from the Ascotan Region.   The net groundwater flow to the east (Bolivia) from the upper Ascotan zone is ~1,970 l/s, or ~12% of the total water budget, while the net groundwater flow to the west (across the topographic divide) is an order of magnitude less at ~210 l/s.

The depth-dependent patterns of groundwater flux shown in Figure 18 are consistent with nested groundwater flow systems, which contain local, intermediate, and regional scale flow paths as demonstrated by Tóth (Tóth, 1963). A regional flow system is active at depth and consists of westerly regional groundwater flow from the Altiplano highlands to the western lowlands. Both westerly and easterly local groundwater flow systems are active in the upper zone between the Ascotan Region and modeled areas to the west and east.

5.4 "Pre-human" scenario In order to examine what the Loa hydrologic system may have been like before humans began extracting groundwater, we eliminated the modeled groundwater extraction wells from the model. Turning off the extraction wells increased the hydraulic heads across the model compared with the calibrated model that includes human groundwater extraction. Increases in water table elevations ranged from centimeters to ~320 m (Figure 19). The effects of eliminating modeled human groundwater extraction on the water table elevation are greatest in the area around the pumping wells in the San Pedro River Basin (Figure 19). Here the water table is up to ~320 m higher when the pumping wells are not activated. This demonstrates the significant simulated water table depression that is caused by groundwater extraction in this region. This result is qualitatively consistent with the trend in historical reductions in the water table that have occurred in the Ojos de San Pedro region since groundwater extraction began (Molina Otarola and Montecino, 2006).

When human groundwater extraction is eliminated from the model, groundwater flux to measured stream reaches increases for all reaches except reach B, which has no modeled groundwater flux to the river in either scenario (Table 3). The increase in groundwater flux ranges from 3% in reach F to 30% in reach C. The total increase in drain flux to all measured reaches is ~800 l/s. If we compare the total modeled groundwater flux to rivers in the "pre-human" scenario (~5180 l/s, Table 3) and the calibrated scenario (~4390 l/s, Table 3), we see that the model predicts that the groundwater flux to rivers has been reduced by ~15% due to human groundwater extraction activities within the measured reaches.

5.5 Lower aquifer extraction scenario

In order to test the possible results of groundwater extraction from the lower aquifer in the Calama Valley, five pumping wells were added to the model near the Loa and Salado Rivers in the Central Calama Valley (Figure 20). These pumping wells were screened within the lower aquifer. Three pumping scenarios were tested. The total imposed rates of extraction within the lower aquifer were the following: equal to the total modeled upper aquifer pumping rate (50% of the permitted upper aquifer water extraction rate) (1,051 l/s), 50% of the total modeled upper aquifer pumping rate (525.5 l/s), and 10% of the total modeled upper aquifer pumping rate (105.1 l/s). Extraction was distributed equally across five wells.

5.5.1 Head drawdown results

Extraction from the lower aquifer caused drawdown in both the phreatic water table elevation and the head measurements in the lower aquifer (Table 4). These effects were concentrated within the Calama Valley and were especially severe near the westernmost imposed extraction well. Figure 21 shows the head drawdown within the lower aquifer (model layer 5) for the 525.5 l/s total extraction scenario. Qualitatively, the pattern of drawdown was similar among all three pumping scenarios. As was expected, the magnitude of drawdown (both in water table elevations and lower aquifer heads) was greater with higher extraction rates. The simulated water table elevation drawdown and the head drawdown in the lower aquifer both extend farther to the south than to the north (Figures 17 and 19). This means that groundwater heads south of the pumping area (the central basin) are more affected by the pumping than those to the north, in the Upper Loa region.

In all three pumping scenarios, the reduction in simulated lower aquifer heads (e.g. Figure 21) is qualitatively similar to the simulated depression of the water table (e.g. Figure 22). However, the head differences in the lower aquifer layer are higher in magnitude than the reductions seen in the water table elevation (Table 4). This is expected because the modeled extraction wells were located within the lower aquifer.

5.5.2 Reductions in groundwater flux to drain boundaries

Reductions in groundwater flux that occurred as a result of imposed lower aquifer extraction are shown in Table 4. These reductions in flux to the model's drains were the result of head drawdown caused by the imposed extractions. Lowering the heads near the drains reduced the nearby hydraulic gradient and resulted in lower rates of groundwater flow into the drain boundaries.

Imposing extraction from the lower aquifer reduced groundwater flux to the model's drain boundaries. Significant reductions (of more than 10 l/s) in groundwater flux to the rivers in reaches C, D, and S (Figure 11) occurred for the three pumping regimes. The highest imposed extraction scenario also resulted in a reduction of groundwater flux to reach E. Total reductions in groundwater flux to the model's drains within measured reaches vary from ~240 l/s reduction in the ~105 l/s total pumping rate scenario to ~2,410 l/s reduction in the ~1050 l/s total pumping rate scenario.

5.5.3 Changes in groundwater fluxes out of the Calama Valley

When the pumping regimes were applied to the lower aquifer, the simulated flux from the lower aquifer to the west (Figure 17) was reduced for all three pumping scenarios (Table 4). This reduction ranged from very small (-<1 l/s or <1%) to extremely significant (~-23 l/s or ~80%). This result is expected because the heads up gradient of this location were reduced due to lower aquifer pumping. This caused the hydraulic gradient across the measurement boundary (Figure 17) to be reduced, reducing the simulated flux.

Imposing pumping in the lower aquifer also resulted in changes in the groundwater flux to the southwest from the Calama Valley (Figure 17, Table 4). However, there were significant differences between the three pumping scenarios. The lowest rate pumping scenario resulted in very small reductions in groundwater flux to the southwest of -<1 l/s or <1%, both within the modeled aquifers and within the complete geological cross section of the model. At the other end of the spectrum, the highest rate pumping scenario resulted in greater reductions in the groundwater flux to the southwest, both within the modeled aquifers (~-6 l/s or ~10%) and within the whole geological profile (~-11 l/s or ~10%). However, when the intermediate pumping regime was applied, the simulated groundwater flux to the south from the Calama Valley actually increased slightly both within the modeled aquifers (<1 l/s or <1%) and within the whole model (-1 l/s or ~1%). This is somewhat counterintuitive because the simulated heads decreased throughout the model due to the pumping. However, in this scenario, up hydraulic gradient (to the northeast) from the "wall" used to measure flux to the south the simulated water table decreased by a smaller amount than it did down gradient to the southwest (Figure 17). This means that, while the regional groundwater table decreased, the hydraulic gradient across the measured zone actually increased very slightly, causing a slight increase in groundwater flux to the southwest.

6.0 Sensitivity Analysis

The following parameters were varied during a sensitivity analysis of the groundwater model: recharge rates, hydraulic conductivities of the model as a whole, drain conductance, vertical hydraulic conductivity anisotropy, and the hydraulic conductivity of the aquitard. The resulting changes in simulated heads, groundwater discharge to drains, and drawdown due to simulated lower aquifer pumping are presented both quantitatively (Table 5) and qualitatively (Table 6).

The goal of the sensitivity analysis is to help determine how confident we can be in the results of the model. Since many of the parameters used in the numerical model are not well constrained, we use sensitivity analysis to demonstrate the effects of varying these parameters within a reasonable range. A robust model will produce similar results as parameters are varied within a range that maintains a reasonable calibration (Anderson and Woessner, 1991). For this model the results include westward groundwater flux out of the lower aquifer, southwestward groundwater flux from Calama Valley, and the head drawdown effects of imposed lower aquifer pumping. The variations of these results during sensitivity analysis are reported in Table 5. Because the model is calibrated, varying a parameter too extremely may cause the model to become un-calibrated. In this model, loss of calibration due to changing a parameter means that the simulated heads would deviate from the observed heads (either causing ponding or increasing the observation head residuals), or the drain fluxes would deviate from the estimated range. Both changes in model calibration and changes in model results are shown in Table 5. A qualitative sensitivity analysis that includes the geographic areas most affected by varying each model parameter is shown in Table 6. Please refer to Tables 4 and 5 throughout the following discussion of the sensitivity analysis.

6.1 Sensitivity to Recharge Rates

Recharge rates were varied by +/- 10% across the whole model. These changes disrupted the drain flux calibration such that the resulting drain fluxes are not acceptable. Additionally, increasing the recharge by +10% produced ponded areas and caused the model to diverge from calibration. Both model flux results and head drawdown results were found to be insensitive to changes in recharge rates of +/- 10%. Consequently, we can be confident that small changes in recharge rates that do not affect the calibration of the model, would not produce large changes in our results.

6.2 Sensitivity to Drain Conductance

The drain conductance per unit length for all drains in the calibrated model is 100 m/d. Drain conductance per unit length was varied by orders of 1 m/d to 1,000 m/d in all drains. Decreasing the drain conductance disrupted the drain flux calibration such that the resulting drain fluxes are not acceptable and increased simulated ponding leading to a failure of the model to calibrate. However, decreases in drain conductance had little effect on model results. Increasing the drain conductance by a factor of 10 had little effect on either model calibration or results. Consequently, we can be confident that changes in assigned drain conductance would not produce large changes in our results.

6.3 Sensitivity to Hydraulic Conductivities

The hydraulic conductivities of all model units were varied uniformly +/- 10% during sensitivity analysis. These changes disrupted the drain flux calibration such that the resulting drain fluxes are not acceptable. Additionally, decreasing the hydraulic conductivities by -10% produced ponded areas and caused the model to diverge from calibration. The change in groundwater flux from the lower aquifer was less than +/- ~10%. The change in groundwater flux to the southwest was +/- ~10% within the modeled aquifer and less than +/- ~20% across the whole model thickness. As expected, head drawdown from imposed lower aquifer extraction is correlated with the hydraulic conductivity of the modeled units. The greatest water table elevation drawdown ranged from -67 m when hydraulic conductivity was increased +10% to -95 m when hydraulic conductivity was decreased -10%. In comparison, the calibrated model produced a maximum of -80 m of water table elevation drawdown due to imposed pumping.

6.4 Sensitivity to Hydraulic Conductivity Anisotropy

The hydraulic conductivity anisotropy in the calibrated model is 10x uniformly. This means that vertical hydraulic conductivity is equal to one tenth of horizontal hydraulic conductivity. During sensitivity analysis anisotropy was varied between 6x and 18x. Assigning anisotropy of 6x disrupted the drain flux calibration such that the resulting drain fluxes are not acceptable. On the other end of the scale, assigning anisotropy values of 14x and 18x produced ponded areas greater than 5 meters in depth, a result unacceptable for calibration. Varying the anisotropy between 8x and 12x produced drain flux rates within the bounds of calibration and ponding that was less than ~3 m (in the 12x case). The 8x and 12x anisotropy scenarios produced only small changes in model flux results and modeled drawdown results. Consequently, we can be confident that small (up to +/- 20%) changes in anisotropy that do not significantly affect the calibration of the model, would not produce large changes in our results.

6.5 Sensitivity to Hydraulic Conductivity of Aquitard

The hydraulic conductivity of the aquitard is 0.035 m/d in the calibrated model. In comparison, the hydraulic conductivities of the upper and lower aquifer units range from 1.05 m/d in the central Calama Valley to 0.125 m/d in the Salado River Basin. The hydraulic conductivity of the aquitard was varied by +/- 50% during the sensitivity analysis. These changes had little effect on model calibration and produced only small changes in model results.

7.0 Discussion

7.1 Modeling Goals

The groundwater model presented here was developed with the goal of simulating the region's natural groundwater fluxes. The borders of the model were placed far from the area of most interest (the Calama Valley) in order to reduce border effects and let the region's natural topography, geology and modeled recharge characteristics determine the simulated fluxes. This model was not created to reproduce a pre-held belief of the direction and quantity of certain subsurface flows. Rather, it was an attempt to allow a model of the region's groundwater to emerge from a geographically large model with boundaries spatially removed from the Callama Valley.

7.2 Calibration methods and model uniqueness

There are two basic methods for groundwater model calibration, trial and error and automated determination of parameter values. This model was calibrated using trial and error methods by making successive changes to parameters including hydraulic conductivities, recharge rates and model boundaries. Trial and error calibration of groundwater models is preferred by most practitioners (Kresic, 1997; Zheng and Bennett, 2002) and considered an acceptable method by peer reviewed journals (e.g. Scibek et al., 2007). Trial and error calibration methods are easy to understand conceptually and do not require additional computational methods beyond running the model multiple times (Zheng and Bennett, 2002). Trial and error calibration also helps the modeler gain an intuitive sense of how their model works (Kresic, 1997), a very valuable benefit. For this reason it is suggested that even when automated calibration methods will be used some trial and error calibration runs be carried out first (Zheng and Bennett, 2002). A potential drawback of trial and error calibration methods is that they are subjective and influenced by the modeler's personal understanding of the hydrologic system (Zheng and Bennett, 2002). In order to be successful, a modeler must draw on their own understanding of the system they are trying to model and the degree of subjectivity can be greater with trial and error methods than with automated methods.

The benefits of automated calibration methods include: faster determination of the best parameter values, quantitative sensitivity analyses of model parameters, quantitative representation of the 'goodness of fit' of the calibration, and the emergence of problems with the conceptual model (Poeter and Hill, 1997). Automated calibration methods can produce unique parameter values, but only for modeled systems that have been sufficiently simplified. Achieving a unique parameterization of a groundwater model through automated calibration sometimes means that the modeler must extensively reduce the complexity and heterogeneity of their model (Moore and Doherty, 2006). Moore and Doherty (2006) argue that this is sometimes a drawback to automated calibration methods.

The model presented here has too many parameters to be calibrated to a unique solution, regardless of the calibration method used. However, this does not mean that the model is not useful. A non-unique model that represents a complex system to the best of our knowledge can be a very useful tool. In the future, this model could be calibrated using automated methods to achieve a range of possible, non-unique, calibrated parameter values, or it could be significantly simplified and calibrated with automated methods to achieve a unique set of parameter values. While the calibrated parameter values (i.e. hydraulic conductivity values, recharge values etc.) of the model presented here are not unique, we are more confident in the model because it was calibrated to both head and flux observations. Calibrating to both head and flux observations, rather than just head observations, prevents the potential problem of achieving realistic simulated heads but unrealistic simulated fluxes of groundwater through the model. This can occur when modeled recharge rates and modeled hydraulic conductivities are either both too high or both too low and when only head observations are available to use in calibration.

7.3 Model Limitations

This model's strength is in its regional scale. It can be used effectively to analyze the system on the scale of tributary basins and the whole Loa hydrologic system. The model uses a large grid size ranging from 4 km^2 to 16 km^2 and is calibrated to stream reaches that range from ~49 to ~87 km in length. The large scale of the model presents both limitations and advantages for the applicability of the model to different types of questions. For smaller scale, local water management questions, the model presents two limitations. The first is the scale of the model grid. The smallest modeled cell sizes are 4 km^2. This means that the model's grid density is insufficient to answer small scale, local water management questions, such as, for example, "What are the differing available water resources at locations a few kilometers apart from one another around the city of Calama?" The second potential weakness of the model for local questions is the magnitude of error associated with well head observation calibrations. The average absolute value of the difference between the modeled heads and the observed heads for observation wells is over 18 m. This means that, for local questions based on the elevation of the water table, this model will not produce head results the closely mimic available observations.

However, for questions that pertain to potential <u>changes</u> in the simulated heads and drain fluxes, the model can be expected to produce more reliable results. This is because, if the errors associated with modeled heads are systematic and consistent, then the difference between heads with and without imposed pumping regimes will reduce this error.

Another aspect of the model that could potentially limit its applicability is use of MODFLOW drain boundaries to simulate the rivers. In MODFLOW, drain boundaries act as conduits for groundwater to exit the model when the simulated water table elevation is higher than the drain elevation. If the head drops below the drain (river bed) elevation then the drain ceases to function. Drain boundaries cannot simulate losing river reaches where there is flow from the surface water system back into the ground. Drain boundaries are a good choice for modeling the rivers in this system from a regional, whole-model perspective because the rivers are not sourced from runoff and as such they do not provide a new inflow to the groundwater system. However, on a smaller scale, there may be groundwater-surface water exchanges that occur locally between the stream bed and the karstic upper aquifer rocks and the rivers. For example, there is anecdotal evidence that the Loa River loses water to the ground near the city of Calama. Data that would confirm this are sparse. Chemical signatures of the water in the springs west of the city of Calama are similar to the Salado River waters (Klohn, 1972). This could be interpreted to be evidence that Salado River surface waters enters the groundwater system and supplies the springs. Flow measurements of the Loa River taken in 1916 indicate a significant (~2900 l/s) reduction in river flow near and west of the city of Calama (CORFO et al., 1977; Jordan et al., submitted). However, some portion of this reduction may be due to surface water diversions for irrigation near the city, and more recent flow gauging has not shown such significant reductions (CORFO et al., 1977). In any case, the model presented here cannot simulate surface water influx to the groundwater system. However, since the model is calibrated to large-scale river reaches that range from ~49 to ~87 km in length, this issue will only produce errors in the model if an entire calibrated reach has a net loss to the groundwater. The data available indicate that all the river reaches used for calibration have a net flow of groundwater into the river (Table 2), therefore drain boundaries are an appropriate choice to simulate the rivers. For the specific example of river losses around the city of Calama, this area is within modeled reach C, which has a net flow from groundwater to the river.

As mentioned above, this model cannot be used effectively to answer small scale, local river flux questions. However, this limitation originates from the limited available data with which to calibrate the model, not directly from the choice to use drain boundaries for the rivers. The long lengths of calibrated river reaches are due to a lack of gauging stations from which to collect data. Since the river flux is calibrated at this large scale, the model cannot be used to simulate groundwater-surface water interactions at a scale smaller than the density of available river flow data. The available river flow data are too sparse to reasonably model any small scale groundwater-surface water exchanges.

7.4 Loa Basin Water Management and Simulated Groundwater Flows

Currently, the water management policy for the Loa River Basin assumes that all the system's available recharge that is not lost through evapotranspiration is available for human use and to sustain minimum ecological flows (DGA, 2003b; Ministerio de Obras Publicas, 2005). This model demonstrates that simply subtracting the system's total evapotranspiration rate from its total recharge rate will likely produce an overestimate of the water available for human use and ecological flows. The model simulates groundwater flows that leave the Loa system both to the Pacific Ocean (~515 l/s) and to the south (42 l/s at Sierra Gorda). The magnitudes of these outflows are likely different in reality than the simulated magnitudes because a model cannot perfectly replicate the complex hydrologic system. In fact, there is evidence that suggests that the Sierra Gorda flow may be smaller. Unpublished and published reports refer to groundwater extraction now occurring in the Sierra Gorda region (Mayco Consultores, 2013; Christian Herrera personal communication, 2014). Such extraction could reduce the rate of southerly discharge out of the model. However, the likelihood that these outflows do occur, whatever their magnitude, is an important result to consider. As such, inaccessible groundwater outflows both to the Pacific and to the south should be included in the Loa hydrologic system water budget upon which management decisions are based.

The model simulates two particular groundwater flows that are important to the holistic management of the system. First, groundwater that flows to the southwest out of Calama Valley (~97 l/s) is not accessible for human use downstream in Quillagua (number 2, Figure 11) or in the Central Depression. The hydraulic gradients simulated by the model (Figure 12) demonstrate that water leaving the Calama Valley to the southwest (see arrow, Figure 17) exits the model either to the south at the Sierra Gorda constant head boundary or to the west at the Pacific Ocean constant head boundary.

Second, the model simulates a small but significant, ~28 l/s, flux of groundwater exiting the lower aquifer to the west at the termination of the aquitard in the San Salvador/Loa Valley (Figure 17). This water is part of the total water resources available for human use west of the termination of the aquitard (blue area, Figure 17). The flux that exits the lower aquifer may continue to move through the system as groundwater, or some or all of it may end up flowing into the rivers. Both the upper and lower aquifers outcrop in the canyon walls of the San Salvador and Loa Valleys and the termination of the Jalquinche Formation (aquitard) is visible as well. Therefore, both of the aquifers are potential sources for the rivers. This model demonstrates how potential groundwater extraction from the lower aquifer, especially high rates of extraction, could reduce the down-gradient contribution of lower aquifer waters (Table 4). This should be considered when the potential effects of lower aquifer extraction are predicted.

The groundwater flux at Salar de Uyuni is less important from a management perspective, however it represents a very significant component of the model's water balance. The model simulates a groundwater flux of 9,622 l/s exiting the model through the constant head boundary that represents the Salar de Uyuni along the northeastern edge of the model (Figure 4). This flow represents ~61% of the total model outflows. This flux is large, but reasonable considering both the potential for recharge over a wide sector of the model adjacent to the Salar de Uyuni as well as the known high evaporation rates from the surface of Salar de Uyuni. The estimated evaporation rates within the modeled portion of the Salar de Uyuni and the modeled constant head boundary outflow rates there are comparable. In total, ten model cells that are each 16 km^2 are within the Salar de Uyuni, for a total of 160 km^2 area of modeled salar. Reported evaporation rates at the Salar de Uyuni are 1,500 mm/day (Rouchy et al., 1996). Unit conversion and multiplication lead to an estimate of 10,140 l/s total evaporation from the modeled portion of the salar. The modeled rate of ~9,620 l/s is only ~5% less than this roughly estimated rate.

7.5 Lower Aquifer Extraction Scenarios

This groundwater model predicts that groundwater extraction from the lower aquifer within the Calama Valley would depress the water table, drawdown lower aquifer heads, reduce surface water flows, and reduce down-gradient groundwater flow to the Central Depression. These effects are magnified with increased hypothetical pumping rates. Water table drawdown would affect the accessibility of groundwater resources in the Calama Valley, forcing groundwater users to either pump water from deeper depths or reduce their extraction rates. Surface water users, both in the Calama Valley and downstream in Quillagua, would also be affected because groundwater flow into the Loa River would decrease due to a lower hydraulic gradient near the river. Even at the lowest rates of total lower aquifer extraction tested (105.1 l/s), total groundwater flux into the rivers is predicted to decrease by at least ~245 l/s. The average flow at the mouth of the Loa River used during calibration of this model is 238.5 l/s. This means that, for the most conservative pumping regime tested, the Loa River would be dry by the time it reaches the ocean. This reduction in surface water flow would have a significant impact on ecological flows and surface water users, who in these areas are predominantly using the water as irrigation for agriculture.

7.6 Cross-Basin and Trans-Border Groundwater Flow

Political issues surround groundwater and surface water that may cross either the topographic divide of the Andes volcanic range or the international border between Chile and Bolivia (which are at places coincident, Figure 1). This model did not pre-determine the groundwater basin's eastern margin. Instead the model's border was intended to be far enough away from the uncertain position of the groundwater divide that the natural combination of geology, topography and recharge rates would determine the modeled groundwater divide.

The relationship between Chile and Bolivia is strained and conflicts have centered on water resources that cross (or may cross) their shared international border in the past (e.g. Mulligan and Eckstein, 2011; Zambrano, 2013). Addressing such conflicts is not straight forward; particularly when the actual movement of waters is uncertain, as it is for groundwater flows in this region. International water resource law, though complex and evolving, provides some guidelines on how countries should use shared cross-border water resources. Equitable use of shared water resource can take into account previous customary uses of water by border nations and the varying needs of border nations for water to sustain human life, ecosystems and economies (International Law Association, 1966, 2004). Therefore, the modeled cross-basin and trans-border fluxes presented here should not necessarily be interpreted to ‘belong’ to one country or another in a legal sense. Additionally, as described in the results section, the uncertainty associated with the modeled cross-basin and trans-border fluxes is greater than the fluxes themselves. This large uncertainty should be taken into full account during interpretation.

One question that arises due to the different recharge footprints of this model and the 2003 study (DGA, 2003b) is, “Does groundwater that is recharged in the Altiplano move west beneath the topographic divide to supply the groundwater system within the Loa River watershed?” In this model, a simulated net westerly flux representing ~9% of the model’s total water budget crosses the topographic divide. This means that ~23% of the groundwater discharged west of the topographic divide (in Chile) originates as recharge east of the topographic divide (in Chile and Bolivia). Looking at the system from a different perspective, ~13% of the modeled recharge that occurs on the Altiplano, east of the topographic divide, passes beneath the topographic divide and exits the model west of the topographic divide. The model supports the hypothesis posed by others (e.g. Pourrut and Covarrubias, 1995; Montgomery et al., 2003) that groundwater is passing beneath the Andes volcanic range from the Altiplano in the east to lower elevations in the west. Currently, water management in the Loa hydrologic system is based on a water balance that only considers recharge that occurs within the Loa River topographic basin (DGA, 2003b). This model suggests that Chilean water resource managers should consider expanding the recharge area included in their water balance calculations.

The international border between Chile and Bolivia does not follow the topographic divide everywhere in the model, instead a portion of the Altiplano Plateau is in Chile (Fig. 1). Therefore, we can expect different net fluxes across the international border than across the topographic divide within the model. This model simulates a net easterly groundwater flux of ~5% of the model's total water budget from Chile to Bolivia. This represents ~9% of the total modeled discharge rate within Bolivia and ~11% of the total modeled recharge rate within Chile. Because this is a net result, it should not be taken to signify that there are no modeled fluxes of groundwater that move from Bolivia to Chile. In fact, if we examine the simulated groundwater fluxes across the southern part of the international border, where it is coincident with the topographic divide, we see a net westerly flux from Bolivia to Chile of ~6% of the model's total water budget. However, in the northern portion of the model, where the international border does not coincide with the topographic divide there is a simulated easterly net flux of ~11% of the model's total water budget from Chile to Bolivia.

Conceptually, it is not surprising that there are differences in the simulated net groundwater flux across the northern and southern portions of the international border because different topographic gradients exist in the north and south. In the southern part of the model, where the international border and topographic divide coincide, the Altiplano has a higher average elevation than in the northern part of the model, near the Ascotan Region. So, although the regional topographic gradient slopes down to the west across the whole model, it is steeper in the southern portion. This difference in the topographic gradient affects the slope of the simulated water table and thus the fluxes. Additionally, the water table is elevated just west of the Ascotan region due to the higher rates of recharge imposed on this region during calibration. This effectively decreases the hydraulic gradient between the northern Altiplano and Upper Loa Basin.

The depth dependent zone budget analysis of the Ascotan Region shows that the model simulates local and regional groundwater flow paths (Tóth, 1963). Deep, regional westerly groundwater flow paths simulate water moving from the Altiplano to the west, while shallower, local groundwater flow paths move in both an easterly and a westerly direction from the Ascotan Region. This is consistent with the western sloping long wavelength topographic gradient across the whole model and with the many local topographic gradients of individual volcanoes.

The simulated groundwater fluxes that cross topographic divides and international borders are small in magnitude compared with the groundwater model's uncertainty. Both the magnitude and the direction of simulated groundwater flows across these boundaries of interest are within the model uncertainty. Therefore, the lesson that should be taken from this model is not whether or how much groundwater is flowing across specific boundaries, but instead that international and inter-basin groundwater flux can be simulated with a geographically inclusive model such as this one. It is possible for such fluxes to exist and they should be considered from a water management perspective on local, national and international levels. Regardless of the directions and magnitudes of actual groundwater and surface water flows, if the goal is successful long-term management, Chile and Bolivia should begin working together to address their shared water resource management responsibilities.

7.7 Paleoclimate variability in the study area

The climate of the study area has fluctuated during the late Quaternary, with multiple wetter periods compared with the modern hyperarid climate (Rech et al., 2002; Latorre et al., 2003; Latorre et al., 2006; Gayó et al., 2012a; Gayó et al., 2012b). Late Pleistocene regional paleoclimate periods with higher precipitation and groundwater recharge rates compared with the base hyperarid state have been termed Central Andean Pluvial Events (CAPE). The CAPE intervals and Holocene wetter paleoclimate periods are associated with larger and deeper lakes in the Altiplano Plateau (Sylvestre et al., 1999; Placzek et al., 2006), higher elevation wetlands in the Calama Valley (Rech et al., 2002), increased vegetation and rodent evidence in the Central Depression and the western slope of the Andes (Latorre et al., 2003; Latorre et al., 2006; Gayó et al., 2012a), and evidence for human irrigation in the Central Depression (Gayó et al., 2012b). Varying paleoclimate proxies used in different geographical locations and at different elevations have produced numerous discrepancies in the precise timing of wetter regional climate events. However, several studies using different paleoclimate proxy methods point to increased precipitation from 17.6 Ka—14.2 Ka (Rech et al., 2002; Latorre et al., 2006; Gayó et al., 2012a), 13.8 Ka—9.7 Ka (Rech et al., 2002; Rech et al., 2003; Gayó et al., 2012a), 8 Ka—6.8 Ka (Rech et al., 2002; Latorre et al., 2006), and three more recent wetter climate periods in the last 2,500 years (Gayó et al., 2012b). These studies used paleoclimate proxies including paleowetland deposits (Rech et al., 2002), relict and fossilized vegetation and rodent middens (Latorre et al., 2003; Latorre et al., 2006; Gayó et al., 2012a), and archeological remains (Gayó et al., 2012b). The groundwater in the Calama Valley and the Central Depression has also been dated using ^{14}C dating techniques and found to have a maximum recharge age of 3 to 5.5 Ka (Godfrey et al., 2014).

7.7.1 Paleoclimate and model interpretations

The calibration runs and sensitivity analysis runs preformed on this groundwater model can be applied to paleoclimates with higher recharge rates. Wetter climate periods in the past are thought to have had up to approximately twice the modern rates of precipitation (Latorre et al., 2006). Model calibration began with a total recharge rate of approximately twice the calibrated recharge rate and sensitivity analyses runs were completed for 110% of the calibrated recharge rate. Higher rates of modeled recharge led to increases in the water table elevation in the Altiplano Plateau, producing ponding in internally drained basins. Higher rates of modeled recharge also produce ponding in the low areas of the Calama Valley and Central Depression. These ponding locations are areas where salars and wetlands exist now and have been more extensive in the past (Rech et al., 2002). As the sensitivity analysis presented in this work shows, applying higher rates of modeled recharge to the calibrated model produces scenarios that are incompatible with the modern system's water table elevation characteristics. However, these scenarios may be compatible with previous, wetter climate regimes. Additoinally, model scenarios with higher recharge rates confirm probable consequences in the lowlands of increased precipitation in the groundwater recharge area, such as the existence of paleowetlands at higher elevations than the modern water table (Rech et al., 2002).

7.7.2 Paleoclimate and the steady-state modeling assumption

Past periods of higher precipitation in the study region have been interpreted as evidence that some of the region's groundwater resources may be "fossil water", or groundwater that was recharged during these past wetter times (e.g. Gayó et al., 2012b). This interpretation is supported by ^{14}C dates from groundwater in the Loa River catchment, which indicate(Godfrey et al., 2014) that recharge occurred no longer ago than 3-5.5 Ka (Godfrey et al., 2014). If this is the case, the groundwater system may not be in equilibrium; total modern discharge rates may be higher than total modern recharge rates because the system is still drawing from groundwater recharge that occurred in the geologic past (Houston and Hart, 2004). Modern decreases in the water table and groundwater discharges could be partially due to the system moving towards a new equilibrium with a hyperarid climate. The model presented here is a steady-state model that assumes that the modern inputs and outputs of water to the groundwater system are in balance. If the system is out of equilibrium to a major degree, the steady-state model may not be an accurate representation of the system. Whether the groundwater system modeled here contains ‘fossil water’ (water recharged during a wetter climate in the geologic past) remains an unanswered and debated question. However, we know that in the time that has passed since wetter climate events, the water table has adjusted to hyperarid conditions at least to some degree. The modern water table is lower in both the Calama Valley and the Central Depression than proxies indicate it was during wetter times (Rech et al., 2002; Gayó et al., 2012a; Gayó et al., 2012b). Therefore, while no natural system is in complete equilibrium, the groundwater system has at least begun to adjust to the changing recharge rates since the last wetter paleoclimate period.

8 Conclusions

In this study we developed a large-scale groundwater model of the Loa hydrologic system with model boundaries far from the surface water catchment boundaries. This model domain allowed us to examine how topography, recharge rates and subsurface geology influence the region’s groundwater flow systems without assuming that the catchment boundary coincides with the groundwater divide. We calibrated the model to both head and flux observations. We then compared the calibrated model with a “pre-human” scenario in which we eliminated groundwater extraction wells. We also applied three hypothetical groundwater extraction scenarios to the calibrated model within the lower aquifer and examined the effects of such pumping.

Our model indicates that there are modeled groundwater discharges, most significantly groundwater flow into the Pacific Ocean, occurring in the Loa hydrologic system that are not taken into account in the current water management budget. Therefore, the assumption that all the system's recharged water that is not lost to evapotranspiration is available for humans to use likely results in an overestimate of the water available for human use. This may lead to over allocation of water rights in the Loa River drainage basin.

This model simulates a net flux of groundwater equal to ~5% of the model's total water budget across the regional topographic divide of the Andes volcanic range from the high Altiplano Plateau to the west. Although the magnitude of this flux is within the bounds of uncertainty associated with the groundwater model, this shows that, from a modeling perspective, it is possible for groundwater to cross the topographic divide. This suggests that water resource managers should consider expanding the recharge area included in the water budget on which they base their decisions. From a trans-national perspective, this model simulates a net flux of groundwater from Chile to Bolivia equal to ~5% of the model's total water budget.. This result is also within the bounds of uncertainty for the groundwater model. However, the spatially variable modeled groundwater fluxes across international and topographic boundaries, show that such water movements can happen and should be considered from a management perspective.

The modeled fluxes of groundwater across the international border and the topographic divide show different characteristics in the north and the south of the model. In the south, where the topographic and international boundaries coincide, only westerly groundwater fluxes (from Bolivia to Chile beneath the Andes volcanic range) are modeled. However, in the north, where the two boundaries diverge, the situation is more complex. Here we see deep, regional modeled groundwater flow system from Bolivia to Chile beneath the Ascotan Region (Figure 18). At the same time local flow systems are modeled that begin in the Ascotan Region and flow in both an easterly direction, from Chile to Bolivia, and a westerly direction beneath the topographic divide. In this northern area, the magnitude of the easterly simulated net groundwater flux from the Ascotan Region to Bolivia is an order of magnitude greater than both the local and regional westerly fluxes. This model shows that it is possible to simulate both regional groundwater flow systems that move from the Altiplano recharge area to the lowlands in the west and local, shallower groundwater flow systems that move in the opposite direction.

Comparison of the ‘modern’ groundwater model to a “pre-human” scenario in which the groundwater extraction wells were eliminated indicates that the water table drawdown has occurred due to human pumping activities. The comparison shows the greatest drawdowns to have occurred in the San Pedro River Basin surrounding the extraction well cites. This result is consistent with historical records indicating a lowering of the water table in the Ojos de San Pedro area since extraction began (Molina Otarola and Montecino, 2006). The measured river reaches in the “pre-human” scenario received from 3% to 30% more groundwater input compared with the calibrated model that included modern human groundwater extraction. This suggests that modern human groundwater extraction activities have lowered the water table elevations near the rivers and reduced groundwater flux to the rivers. This is an example of a trade-off occurring between groundwater extraction at well sites and surface water availability in the river.

In the Calama Valley, simulated pumping from the lower aquifer results in head drawdowns in both the upper and lower aquifers. These drawdown effects are greatest at the western-most simulated well. Hypothetical pumping regimes also result in reductions in simulated groundwater flux to measured river reaches. Any reductions in flux to the surface water system could potentially affect surface water users and reduce water available for minimum ecological flows if pumping from the lower aquifer were to occur.

When modeled recharge rates are increased from the calibrated rates, the model simulates elevated water table elevations that produce surface water in the closed Altiplano basins and in the lowlands of the Calama Valley and the Central Depression. This pattern of modeled ponding is consistent with the results of proxy-based paleoclimate studies.

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Table 1. Reported Hydraulic Conductivities for Modeled Hydrogeologic Units (Adapted from Jordan et. al (submitted)).

Hydrogeologic unit	Geological unit (as named by source)	Hydraulic conductivity range (m/d)	Hydraulic conductivity average (m/d)	Data Source
Upper Aquifer	Opache and Chiquinaputo	1-2		(Houston, 2004)
	Opache and Chiquinaputo	≤120		(Houston, 2004)
	Opache	0.04–2.25	1.2	(Knight Piésold S. A., 2005)
	Lasana conglomerate member	0.53–0.79	0.7	(Knight Piésold S. A., 2005)
	Opache		3.9	(Fuentes Carrasco, 2009)
	Toconce	1-30		(Houston, 2004)
	Upper Aquifer	0.0015-309		(Matraz Consultores Asociados S.A. and Universidad Politécnica de Cataluña, 2012)
Aquitard	Sifón		0.00003	(Houston, 2004)
	Sifón	.000001		(Matraz, 2012)
	detrital	<0.005		(Matraz, 2012)
	Jalquinche	0.000321–0.0062	0.0017	(Knight Piésold S. A., 2005)
Lower Aquifer	Lasana? and Yalqui ("Calama")	1–4		(Houston, 2004)
	Lasana? and Yalqui ("Calama")	40–100		(Houston, 2004)
	mostly Lasana conglomerate; ("Calama")	0.71–23.1	5.5	(Knight Piésold S. A., 2005)
	Calama	2.0	0.02–9.96	(Knight Piésold S. A., 2005)
	Calama	20.6	0.24–106.22	(Knight Piésold S. A., 2005)

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Table 2 Estimated and simulated drain flux for calibration reaches[a]

Reach	Upstream average measured flow (gauged)	Downstream average measured flow (gauged)	Spring average measured flow (gauged)	Industrial surface water use (permitted)	Municipal surface water use (permitted)	Irrigation surface water use (estimated)	Estimated channel evaporation (low range)	Estimated channel evaporation (high range)	Total estimated drain flux (low range)	Total estimated drain flux (high range)	**Simulated drain flux**
A	507	239		122		15	135	518	-4	-387	**-376**
B	721	507		31			170	650	0	-467	**0**
C	1507	721	24.1 369.6	92		165	309	1184	-174	-1049	**-327**
D	644 531	1507		58			156	600	-546	-989	**-811**
E	510	644			550		96	367	-780	-1051	**-782**
F	0	510					118	451	-628	-961	**-718**
S	0	531				6	163	624	-1271	-1733	**-1370**
Total - all measured reaches									-3389	-6637	**-4384**

Values are rounded to the nearest 1 l/s

[a] See Figure 11 for reach locations.

Table 3 "Pre-human[a]" scenario drain boundary flux results

Modeled River Reach[b]	Drain flux to reach in "pre-human" scenario (A)	Drain flux to reach in calibrated model[c] (B)	Increase in drain flux to each reach in "pre-human" scenario (=A-B)	Percent increase in drain flux to each reach (%)
A	-483	-377	-106	28
B	0	0	0	0
C	-426	-327	-99	30
D	-878	-811	-68	8
E	-922	-783	-139	18
F	-740	-718	-22	3
S	-1734	-1370	-364	27
Total for all measured reaches	-5184	-4385	-799	18

Values are rounded to the nearest 1 l/s

[a] In the "pre-human" scenario all groundwater extraction wells have been turned off

[b] Refer to Figure 11 for reach locations.

[c] The calibrated model includes human groundwater extraction activities.

Table 4 Imposed Lower Aquifer Pumping Results

Total lower aquifer pumping rate[a] (l/s)	Maximum water table drawdown (m)	Head drawdown in lower aquifer (m)	Reduction in flux to drain boundary[b] (l/s)					Westward groundwater flux from the lower aquifer (l/s)	Groundwater flux from the Central Calama Basin to the southwest	
			Reach C	Reach D	Reach E	Reach S	Total (all measured reaches)		Within sedimentary rocks (l/s)	Total model flux (l/s)
none	n/a	n/a	n/a	n/a	n/a	n/a	n/a	28	69	97
105.1	-7	10	38	109	1	97	245	28	69	97
525.5	-80	-96	168	514	7	558	1,250	25	70	98
1,051	-456	-490	315	811	143	1,095	2,408	5	63	86

Modeled fluxes are rounded to the nearest 1 l/s and head drawdowns are rounded to the nearest meter

[a]Lower aquifer extraction is distributed among five simulated wells.

[b]See Figure 11 for reach locations.

Table 5 Model Sensitivity Analysis Quantitative Results

Hydrologic characteristic	Varied simulated value	Change from calibrated value (%)	Resulting Changes							
			Calibration criteria				Simulation results			
			Averaged absolute values of observation head residuals (m)	Stream reaches with groundwater flux rates outside of calibration bounds	Deepest simulated ponding (m)[a]	Range of water table elevation changes (m)	Westward groundwater flux from the lower aquifer (l/s)	Groundwater flux from the Central Calama Basin to the southwest		Greatest water table drawdown from imposed lower aquifer extraction (m)[b]
								Within sedimentary rocks (l/s)	Total model flux (l/s)	
Recharge	Varies	+10%	18	A (too high)	47	0 to +106.4	28	68	96	-79
	Varies	0%	18	none	2	n/a	28	69	97	-80
	Varies	-10%	19	E, F, and S (too low)	1	-106.5 to 0	28	70	98	-80
Drain Conductance[c]	1,000	+900%	18	none	2	-1.5 to 0	28	69	97	-80
	100	0%	18	none	2	n/a	28	69	97	-80
	10	-90%	18	A (too high) and E (too low)	3	0 to +9.5	28	69	97	-79
	1	-99%	17	A (too high), E and S (too low)	41	0 to +68.3	29	69	98	no convergence
Hydraulic Conductivity (total model)	Varies	+10%	18	A (too high), F (too low)	1	-95.7 to +15.9	31	77	108	-67
	Varies	0%	18	none	2	n/a	28	69	97	-80
	varies	-10%	18	E (too low)	47	-19.5 to +117.0	25	61	86	-95
Hydraulic Conductivity Anisotropy[d]	6x	-40%	19	A (too high)	1	-97.2 to +26.9	31	71	99	-85
	8x	-20%	19	none	1	-47.2 to +12.2	29	70	98	-82
	10x	0%	18	none	2	n/a	28	69	97	-80
	12x	+20%	18	none	3	-10.4 to +44.9	28	69	97	-77
	14x	+40%	18	none	5	-19.9 to +87.9	27	68	96	-75
	18x	+80%	18	none	8	-36.8 to +169.1	27	67	95	-71
Hydraulic Conductivity of Aquitard	0.0525 m/d	+50%	18	none	2	-2.5 to +1.8	28	69	97	-82
	0.035 m/d	0%	18	none	2	n/a	28	69	97	-80
	0.0175 m/d	-50%	18	none	2	-5.4 to +6.5	28	69	97	-73

Modeled fluxes are rounded to the nearest 1 l/s and heads are rounded to the nearest meter

[a] Difference between the elevation of the simulated water table and the modeled topography when the water is above the surface.

[b] Combined imposed lower aquifer extraction rates are 50% of total upper aquifer groundwater extraction rates. A combined pumping rate of 525.5 l/s imposed at 5 wells within the lower aquifer. Greatest drawdown occurs in model column 41, row 64.

[c] Drain conductance is per unit length of modeled drain. $C=(S_r*K_{rb}*W)/T_{rb}$ where C is drain conductance, S_r is relative river sinuosity (additional sinuosity of the actual river in comparison to the modeled drain), K_{rb} is hydraulic conductivity of the river bed sediments, W is the width of the river and T_{rb} is the thickness of the river bed sediments.

[d] Model is calibrated with 10x vertical anisotropy in hydraulic conductivity. This means that $K_z=K_x/10$.

Table 6 Model Sensitivity Analysis Qualitative Results

Hydrologic characteristic	Range of tested changes from calibrated value (%)	Results
Recharge	-10% to +10%	Largest changes in water table elevation occur in the Altiplano, especially the southern Altiplano. Changes in water table elevation within the Central Calama Valley (CCV) are less than +/- 2 m most places
Drain conductance	-99% to +900%	Largest changes in water table elevation occur just west of reach F in the Upper Loa River. Changes in water table elevation in the CCV are less than +11 m most places.
Hydraulic conductivity (total model)	-10% to +10%	Largest changes in water table elevation occur in the Altiplano, especially the southern Altiplano, and the Upper Loa Headwaters. Changes in water table elevation within the CCV are less than +/- 2 m most places
Hydraulic conductivity anisotropy	-40% to +80%	Largest changes in water table elevation occur in the Upper Loa Headwaters. An opposite, but smaller magnitude, change occurs in the Central Depression and the Coastal Cordillera. Changes in Water table elevation within the CCV are between -3.5 m and +5 m most places.
Hydraulic conductivity of confining unit	-50% to +50%	Water table elevation changes are concentrated in the CCV and are between -5 m and +6 m most places within the CCV.

CCV= Central Calama Valley

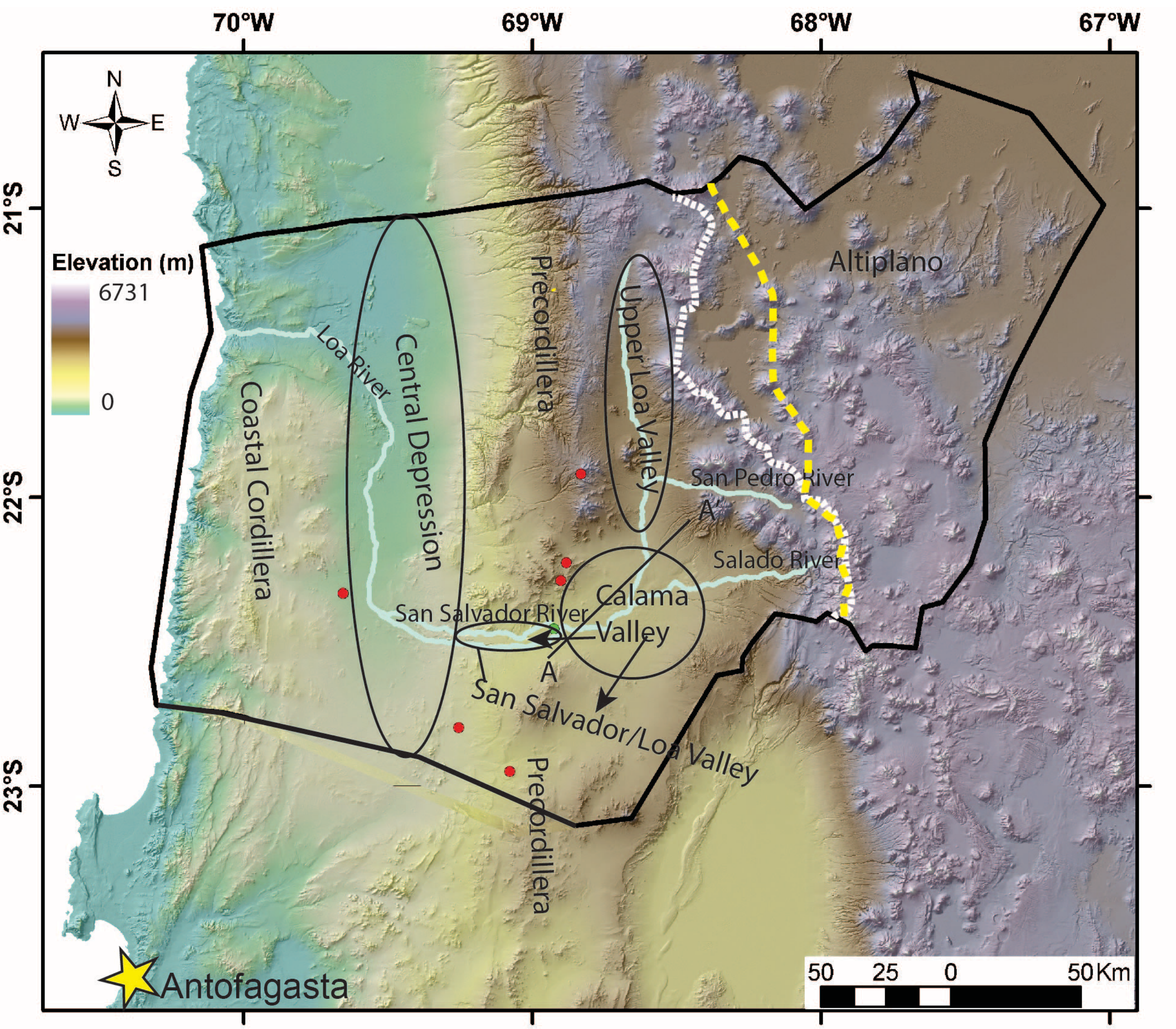


Figure 1: Shaded relief map of study area showing elevation. Bold black line indicates the boundaries of the modeled system (except where purple for now in south). Rivers are shown in light blue. The topographic divide of the Andes volcanic range is shown by a white dashed line. The Chile-Bolivia international border is shown as a dashed yellow line. Red circles show locations of mining operations. Yellow star shows location of the city of Antofagasta. Location A-A’ corresponds to cross section shown in Figure 2. Black arrows indicate the directions of groundwater flows of interest.

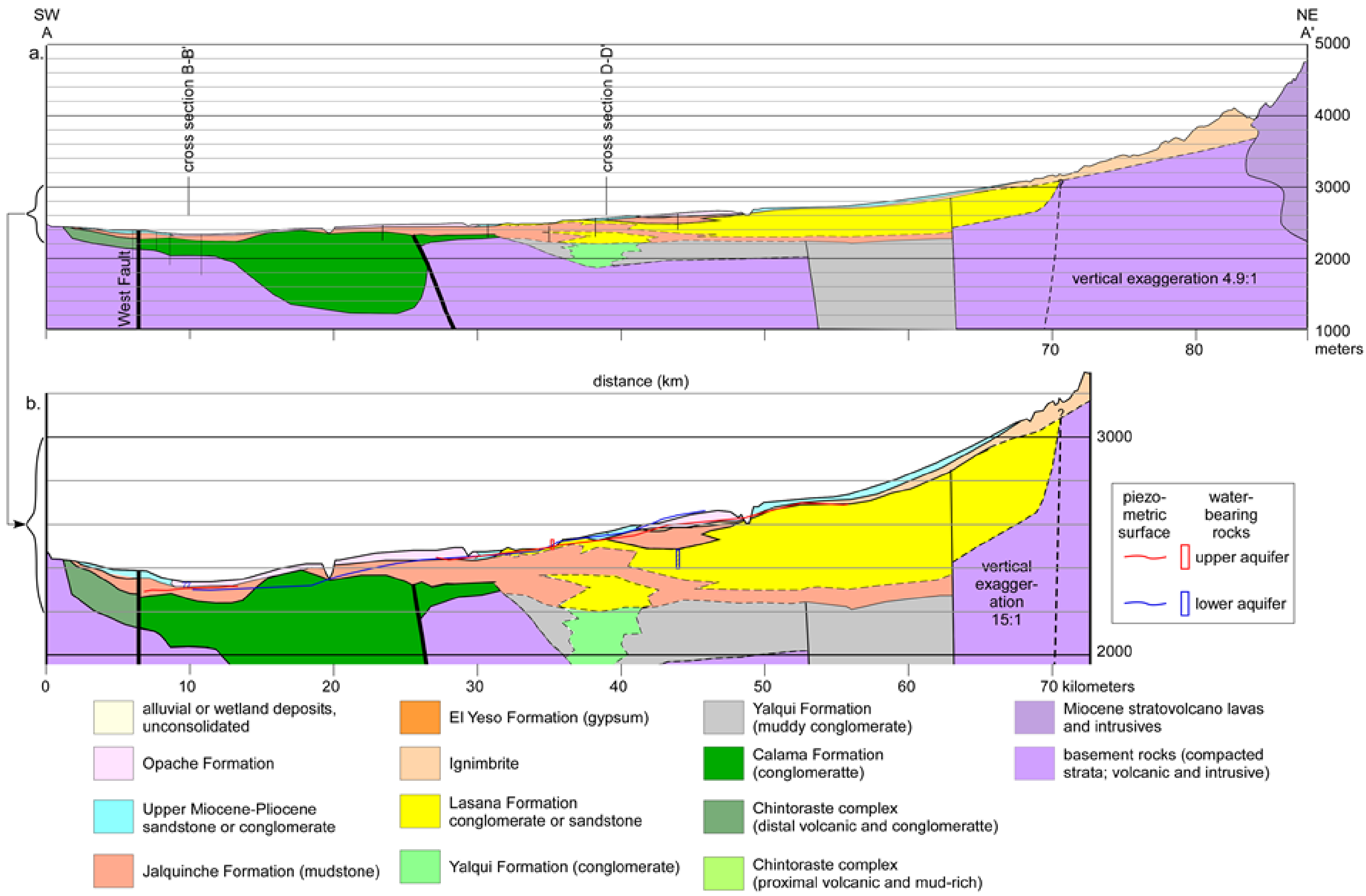


Figure 2: Hydrogeology cross section from A to A'. The location of the cross section is shown in Figure 1. Figure is adapted from Jordan and others (submitted).

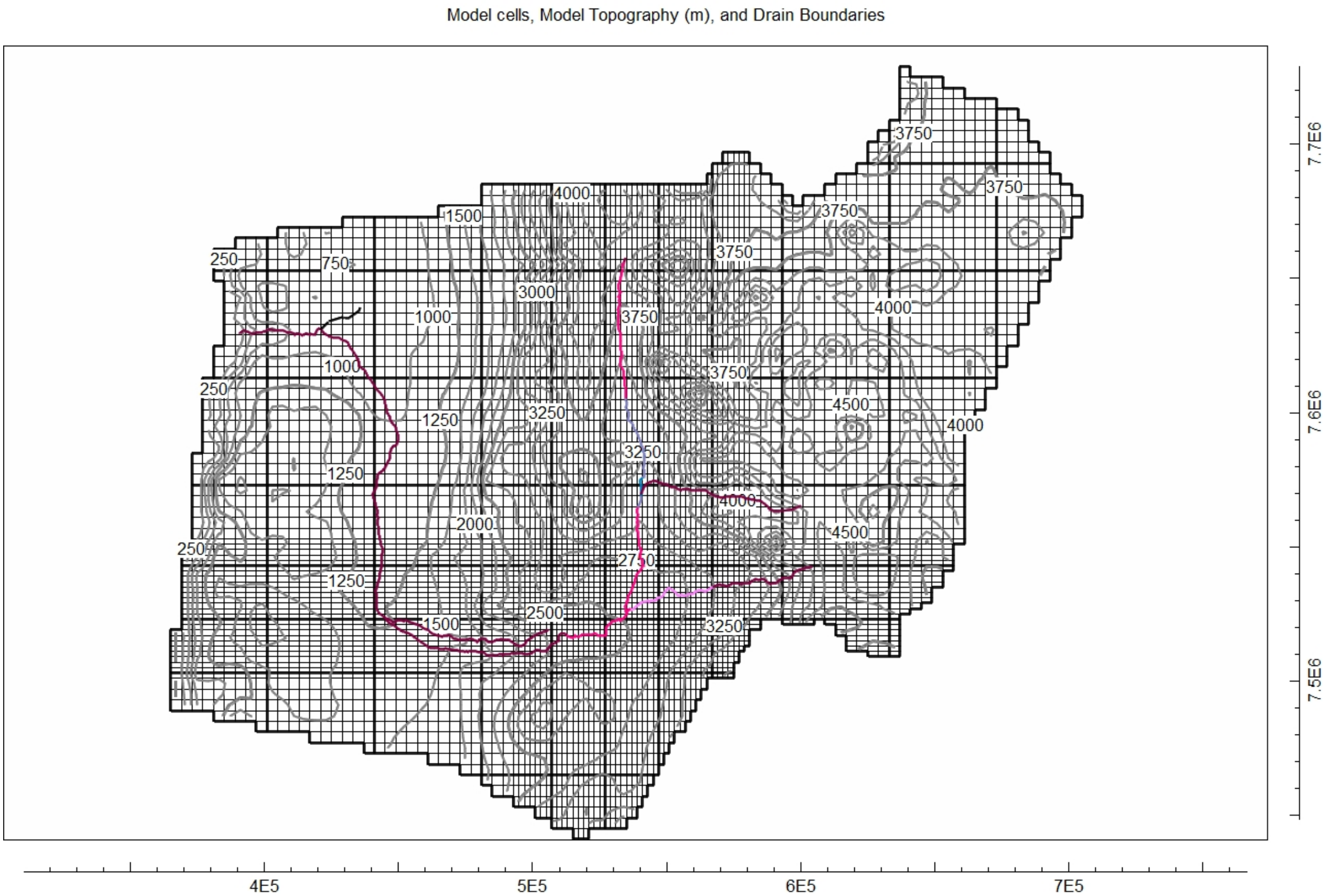


Figure 3: Map of the model grid is illustrated. Cell sizes range from 4 square km to 2 square km. Topographic contours are shown in grey. Horizontal and vertical scales are UTM east and north coordinates and represent meters of linear distance.

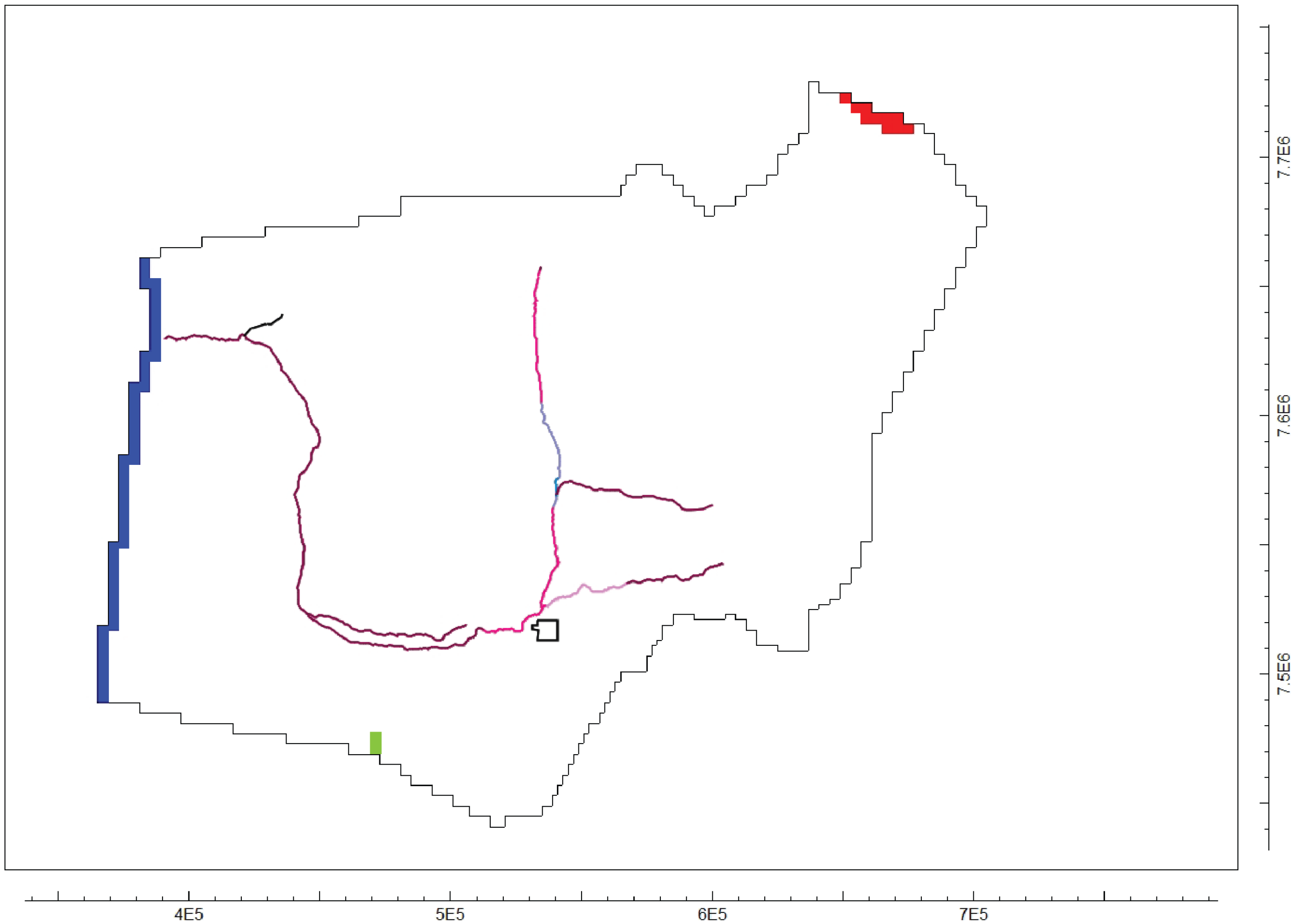


Figure 4: Map of the model domain with rivers and constant head boundaries. Blue represents the Pacific Ocean constant head boundary at 0 m elevation. Red represents the Salar de Uyuni constant head boundary at 3640 m elevation. Green represents the Sierra Gorda constant head boundary at 1615 m elevation. The colored lines show the location of the drain boundaries that represent the region's rivers. The black polygon within the model shows the cells in the Salar Llalqui region which are modeled as evapotranspiration boundaries. Horizontal and vertical scales are UTM east and north coordinates and represent meters of linear distance .

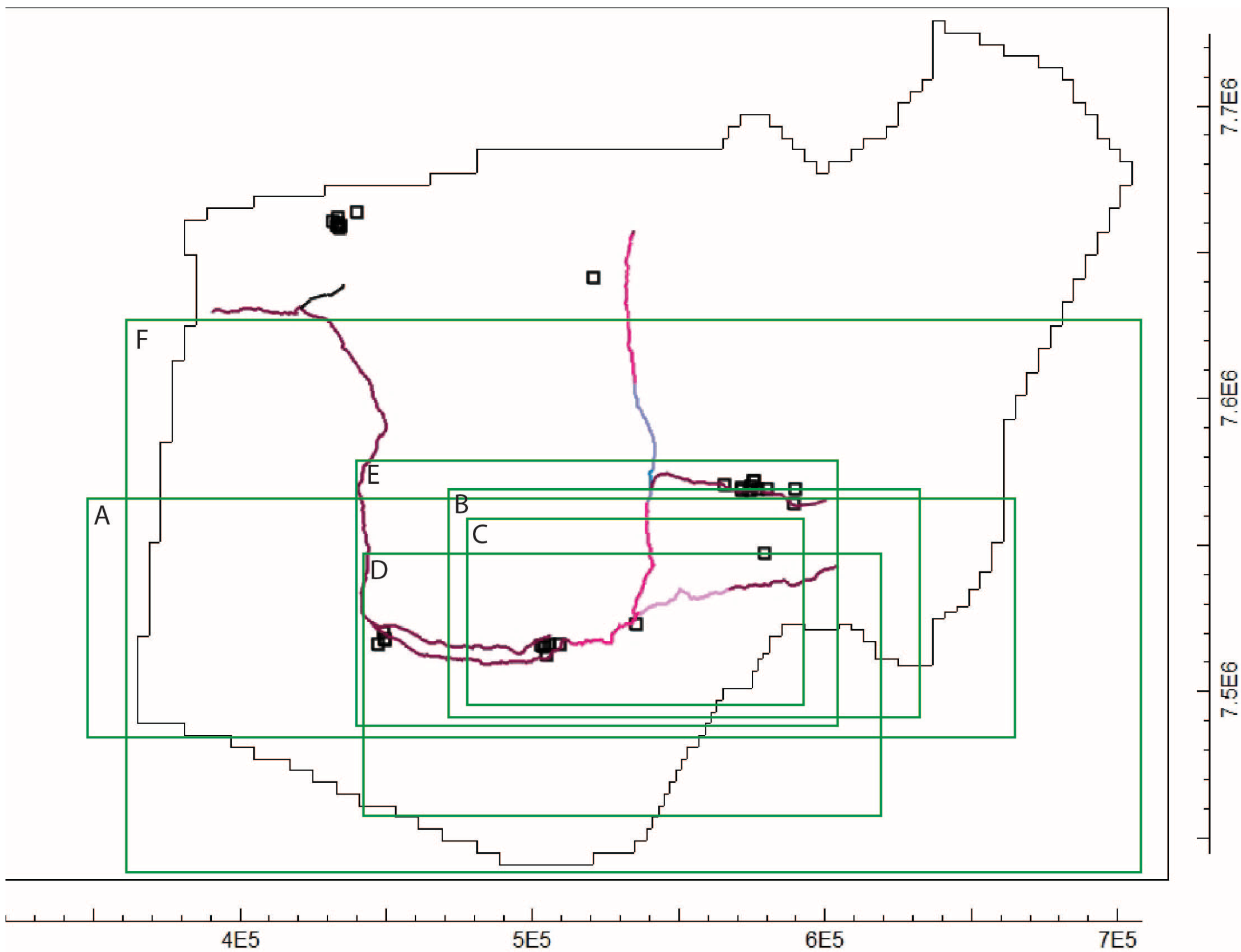
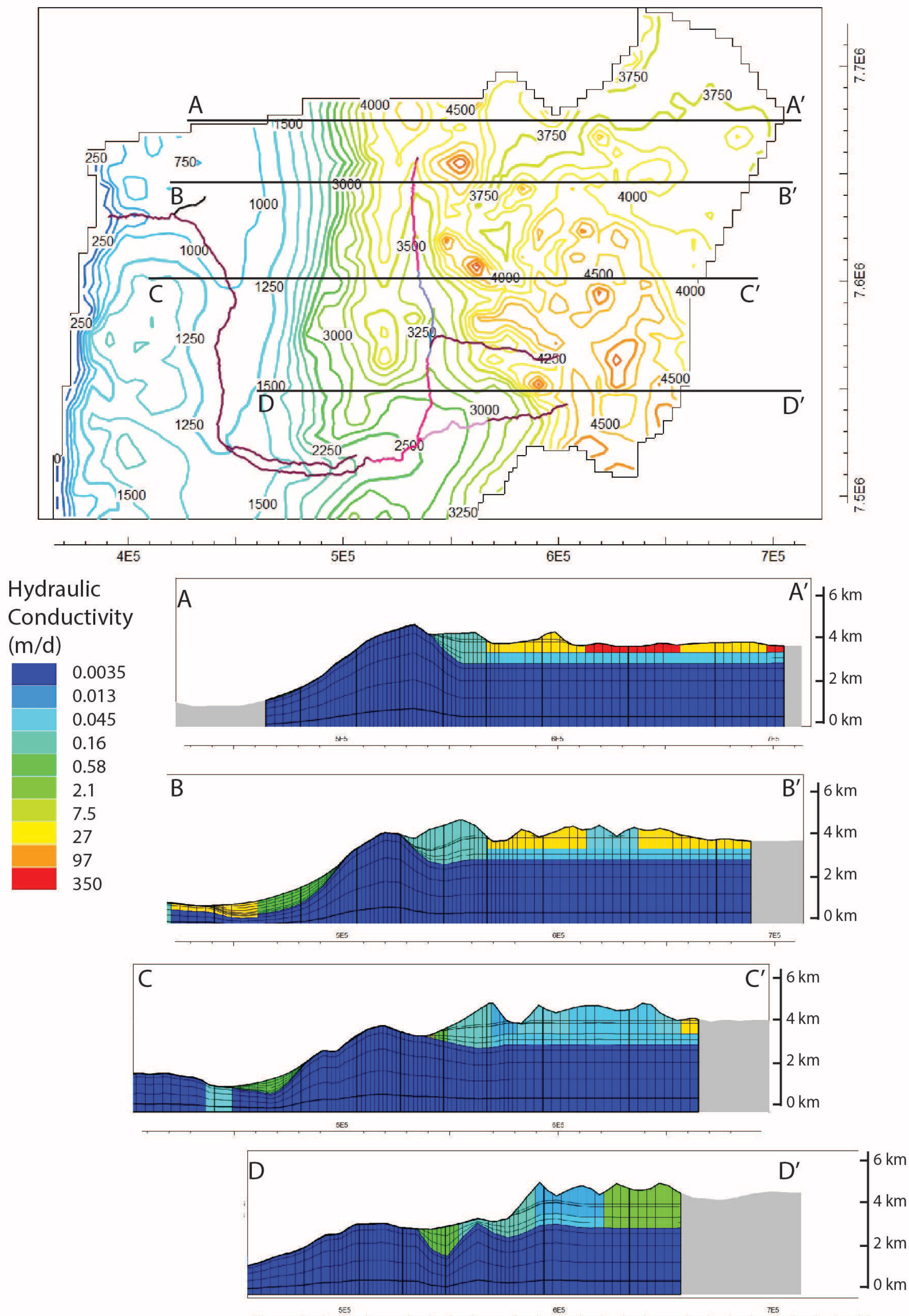


Figure 5: Map of the model domain and rivers with locations of human groundwater extraction shown as small black squares. These are modeled as pumping wells. Green rectangles indicate the locations of maps shown in subsequent figures: A)Figure 7, B) Figure 10, C) Figure 13, D) Figure 17, E) Figure 20, F) Figures 21 and 22. Horizontal and vertical scales are UTM east and north coordinates and represent meters of linear distance.

Figure 6: Map of a portion of the modeled area with 250 m topographic contours. Map shows cross section locations model cross sections of the Altiplano Region. Cross sections are at 10x vertical exaggeration and show the model grid and modeled hydraulic conductivities. The sub-horizontal black lines illustrate the layers in the model. The colors represent the hydraulic conductivities. The horizontal scales are the same for the map and the cross sections. Horizontal and vertical scales are UTM east and north coordinates and represent meters of linear distance.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7.7E6
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4E5
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6E5
7E5
Hydraulic
Conductivity
(m/d)
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0.013
0.045
0.16
0.58
2.1
7.5
27
97
350
6 km
4 km
2 km
0 km

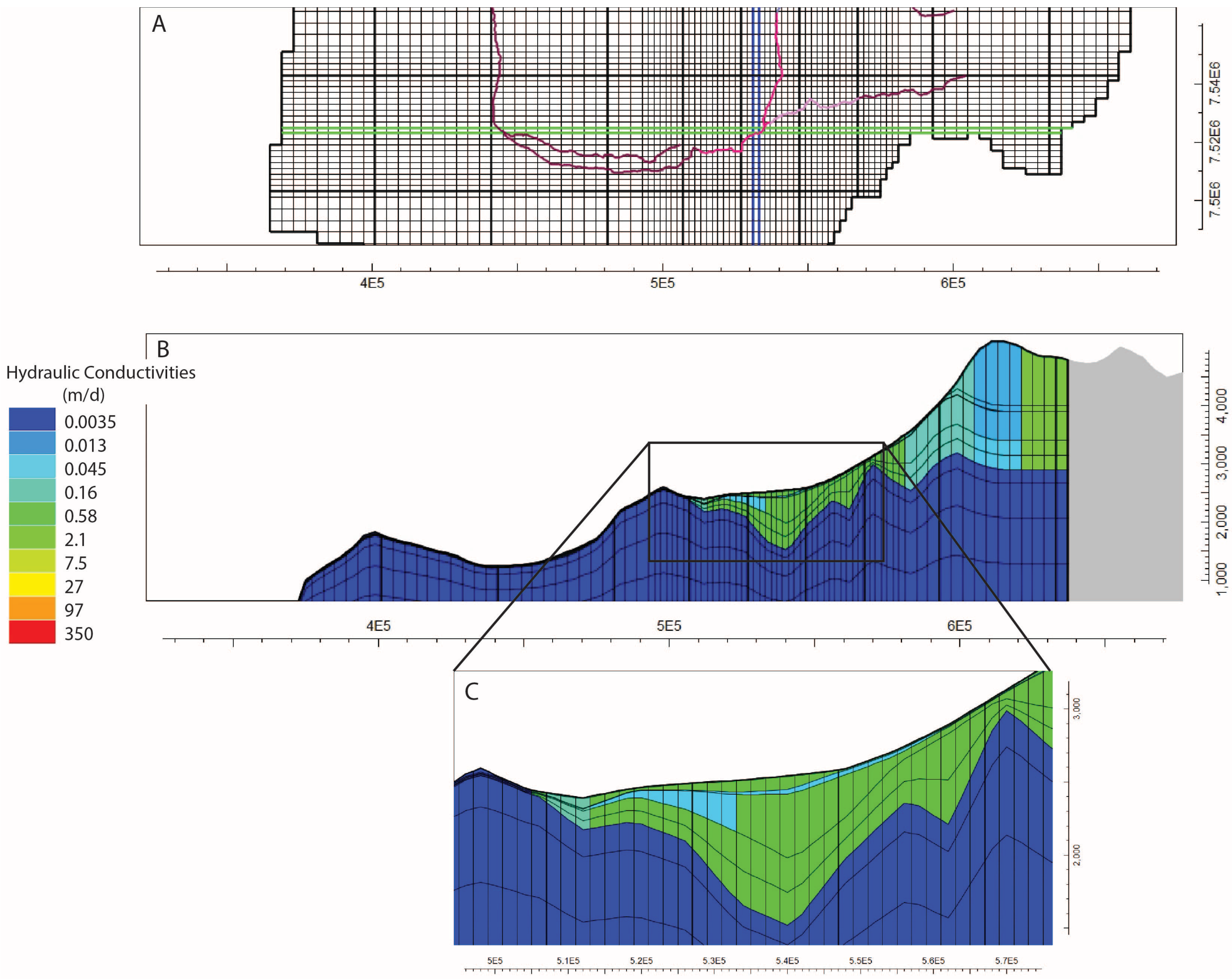


Figure 7: East-west cross section of model at 10x vertical exaggeration. A) The location of the model row is shown in plan view in green. The location of the map is shown in Figure 5, rectangle A. B) Cross section showing model grid and modeled hydraulic conductivities. The sub-horizontal black lines illustrate the layers in the model. The colors represent the hydraulic conductivities. Green colors represent aquifer materials, light blues represent aquitards and dark blue represents hydraulic basement rocks. C) Enlargement of Calama Valley region showing upper and lower aquifers and the aquitard. The uppermost model layer is too thin to be visible at this scale. Horizontal and vertical scales are UTM east and north coordinates and represent meters of linear distance.

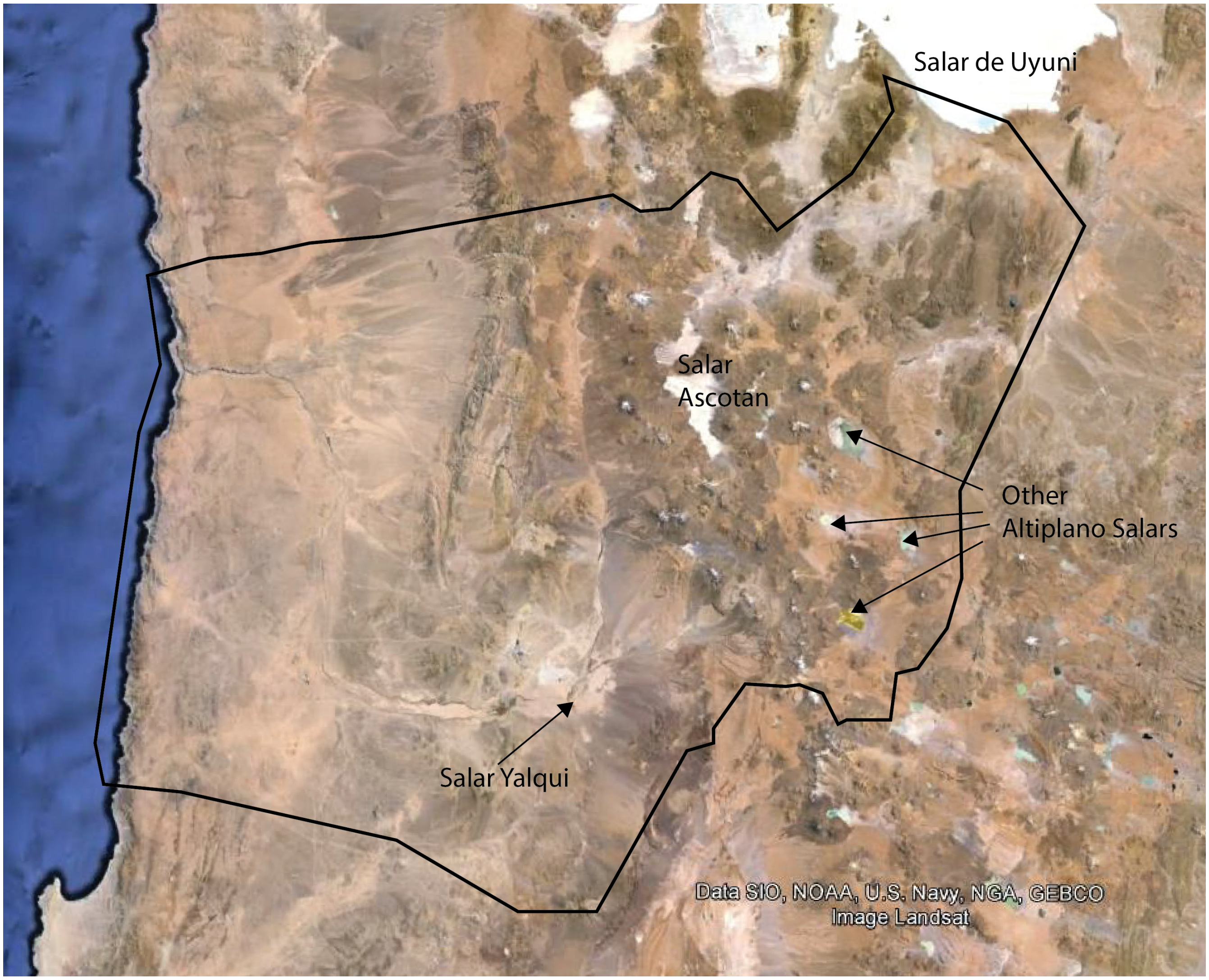


Figure 8: A Landsat image of the study area shows the locations of the salars of interest within the model boundary (black polygon). The background Landsat image of the study region was acquired from GoogleEarth.

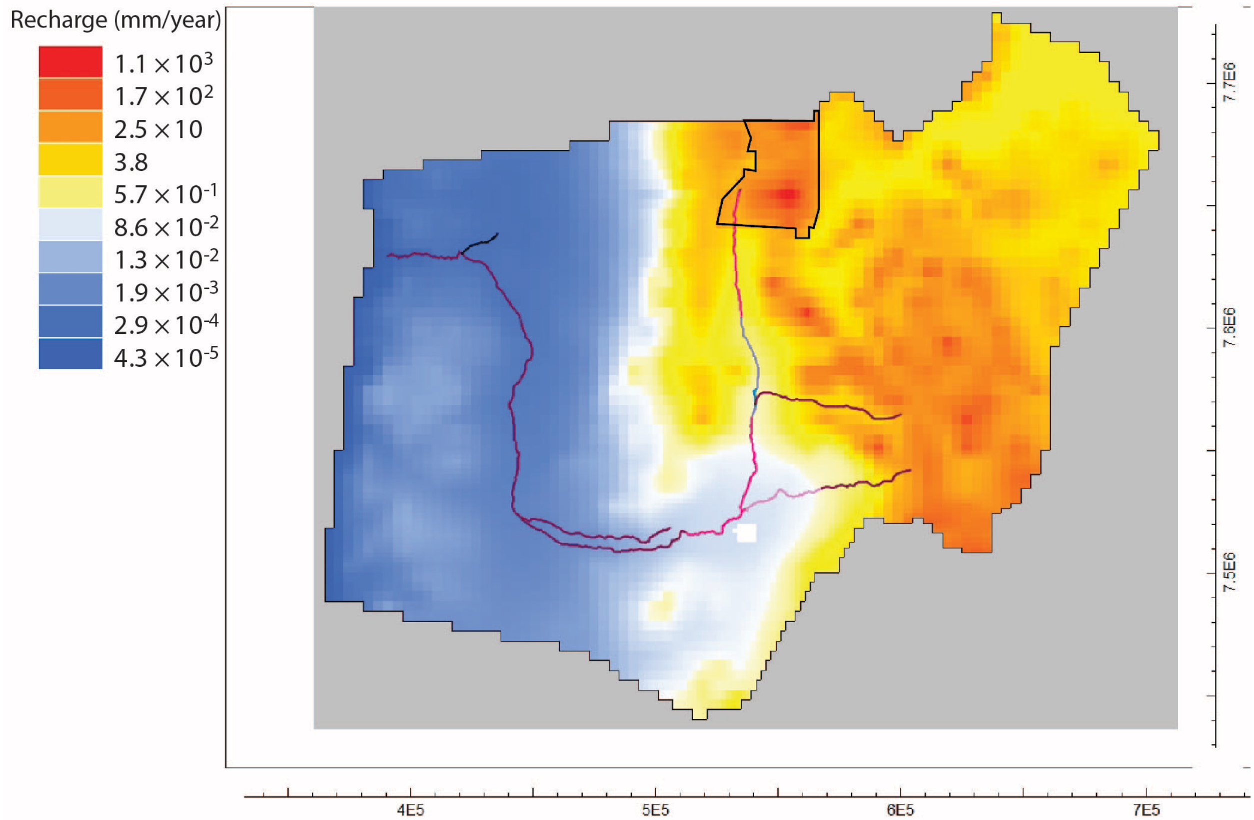


Figure 9: Post-calibration modeled recharge rates shown in mm/year. Blue colors show areas of less than 1 mm/year of recharge. The black polygon shows the area for which the recharge rates are magnified by ~3x compared with recharge rates across the rest of the model. Horizontal and vertical scales are UTM east and north coordinates and represent meters of linear distance.

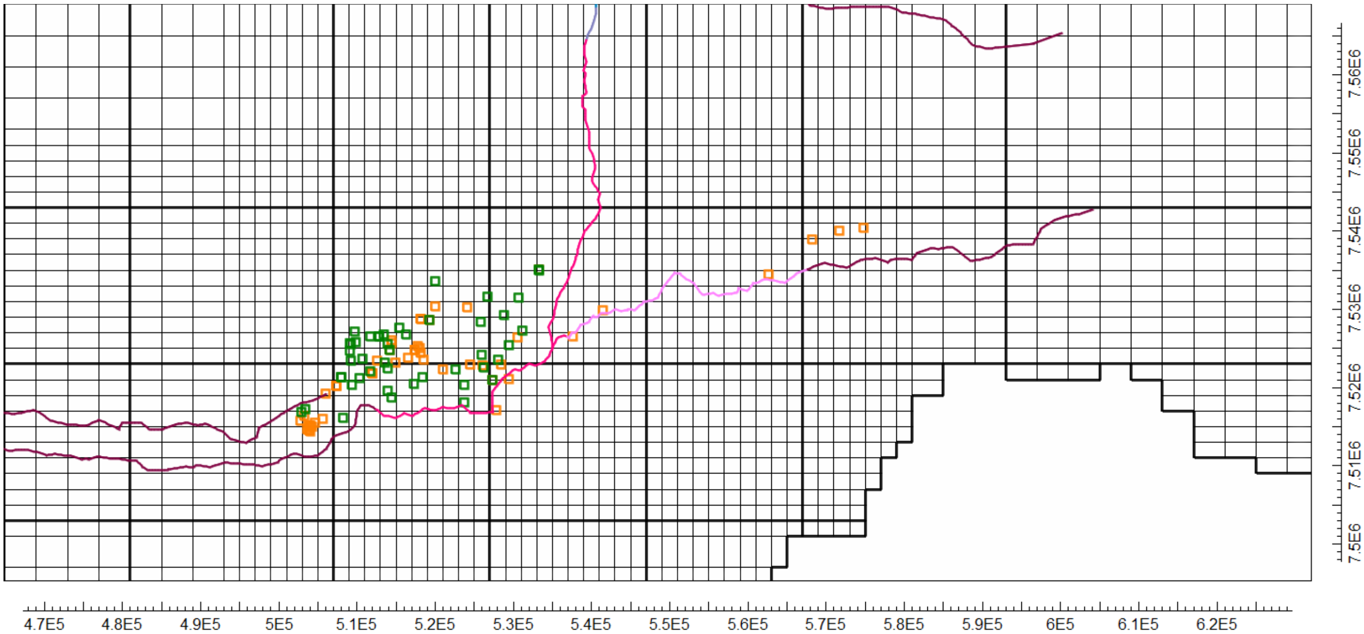


Figure 10: Map of a part of the study area with observation wells used for calibration represented by small squares. The location of the map is shown in Figure 5, rectangle B. Green squares show the locations of observation wells in the lower aquifer while orange squares show those in the upper aquifer. Horizontal and vertical scales are UTM east and north coordinates and represent meters of linear distance.

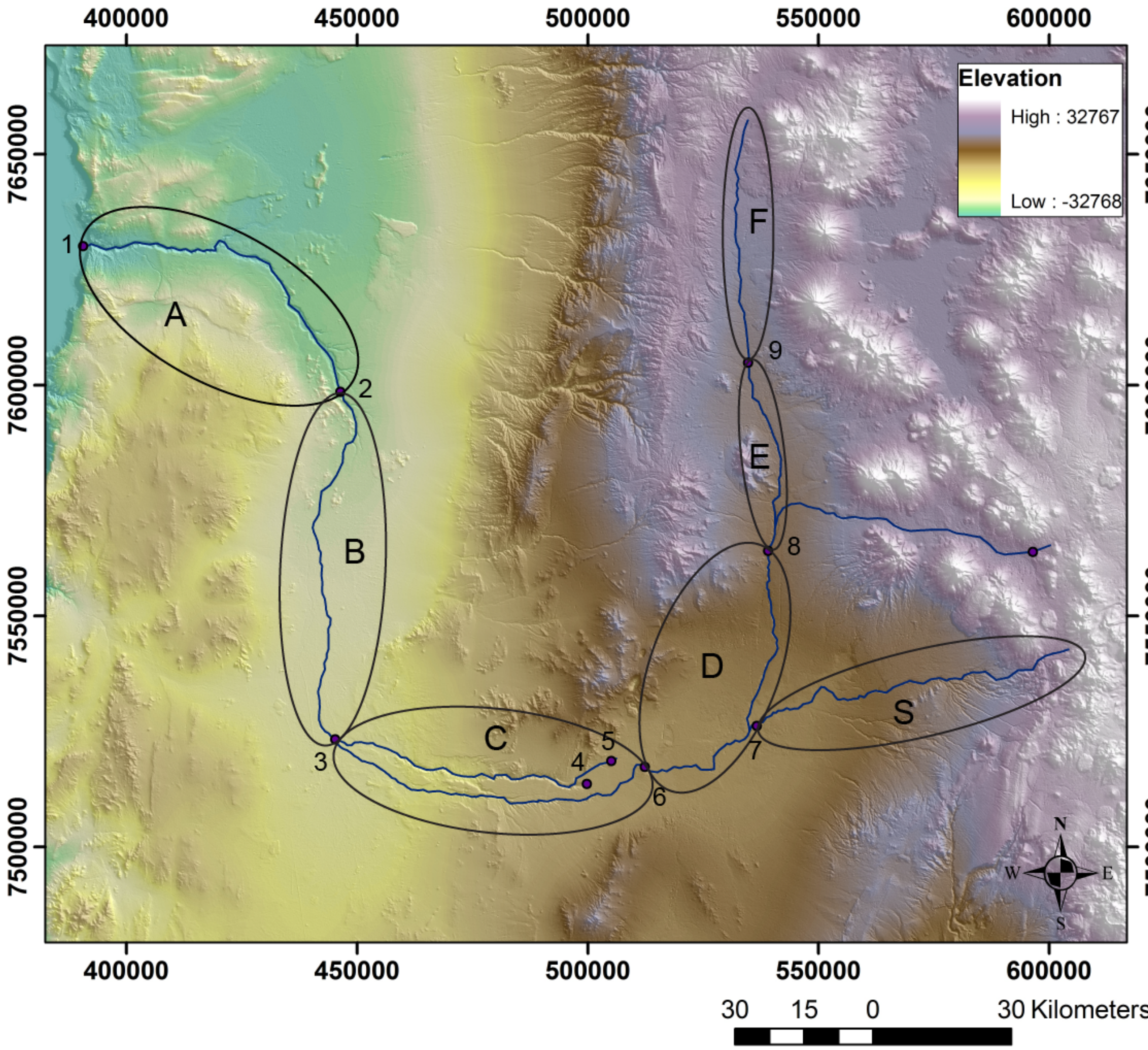


Figure 11: A shaded relief digital elevation model shows with ovals stream reaches used during calibration. The following flow stations are shown also: 1) Loa River outflow at the Pacific Ocean, 2) Upstream of Quillagua, 3) Downstream of the confluence with the San Salvador River, 4) Ojos Opache (spring), 5) San Salvador Nacimiento (spring), 6) Yalquinche, 7) Rio Salado upstream of the confluence with the Rio Loa, 8) Outflow from Conchi Dam, 9) Lequena.

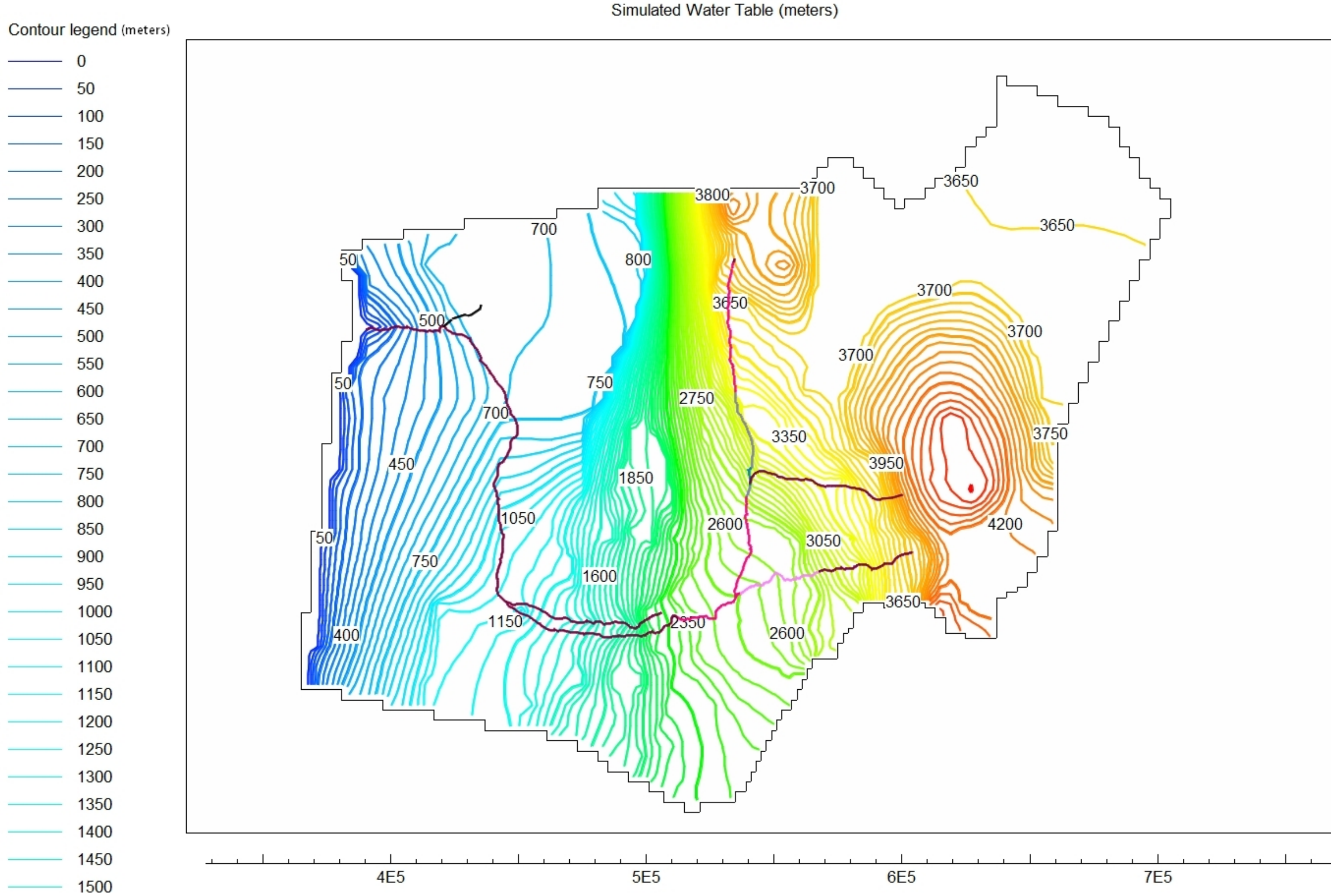


Figure 12: A map of the simulated water table elevation for the calibrated, unstressed model. Contours are shown in meters. Horizontal and vertical scales are UTM east and north coordinates. Horizontal and vertical scales are UTM east and north coordinates and represent meters of linear distance.

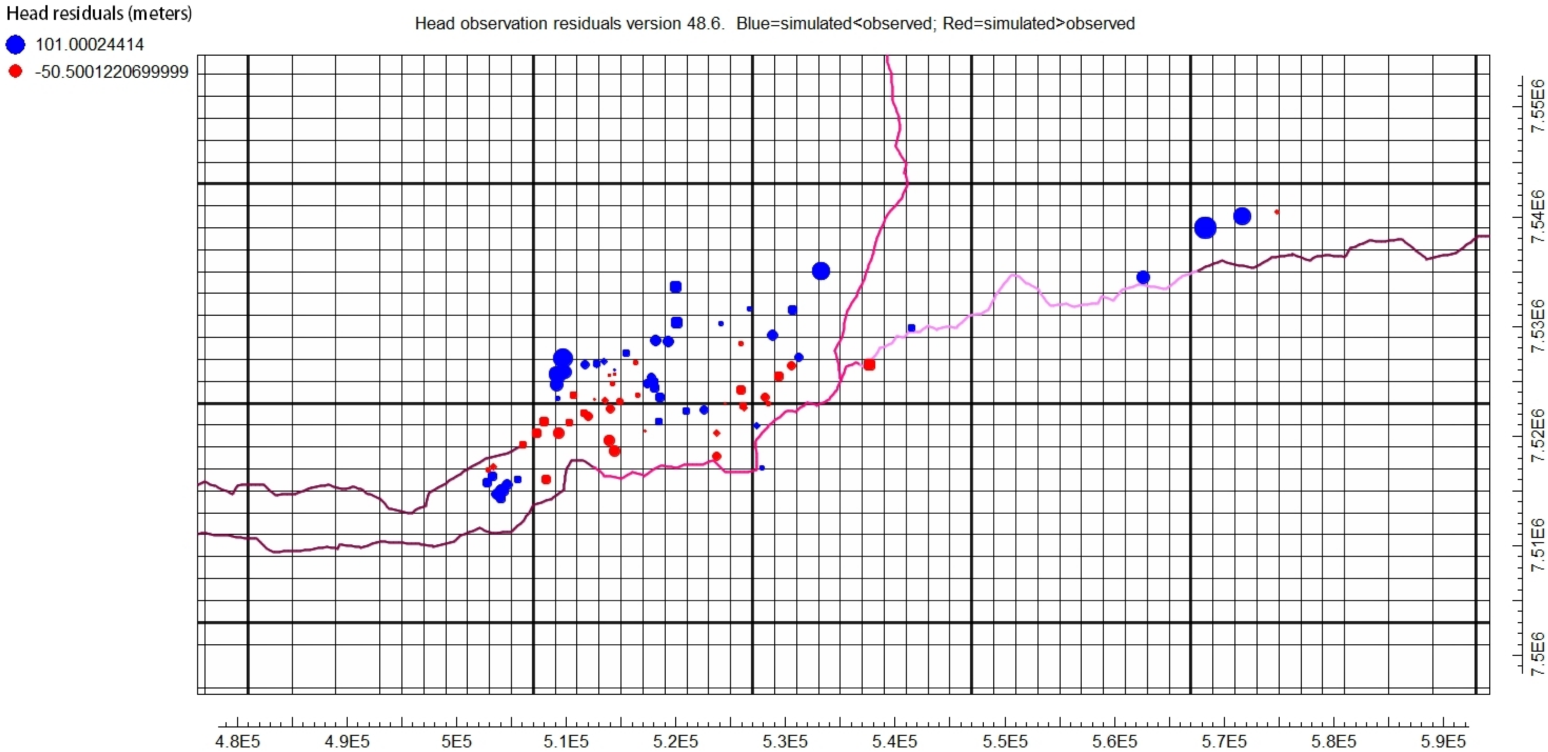


Figure 13: A map of part of the model grid that shows the difference between simulated and observed heads (residuals) in meters. The location of the map is shown in Figure 5, rectangle C. Blue colors indicate simulated heads less than observed heads, red colors indicate simulated heads greater than observed heads. The diameter of the circle indicates the magnitude of the residual relative to the maximum and minimum cases, illustrated at the upper left. Horizontal and vertical scales are UTM east and north coordinates and represent meters of linear distance.

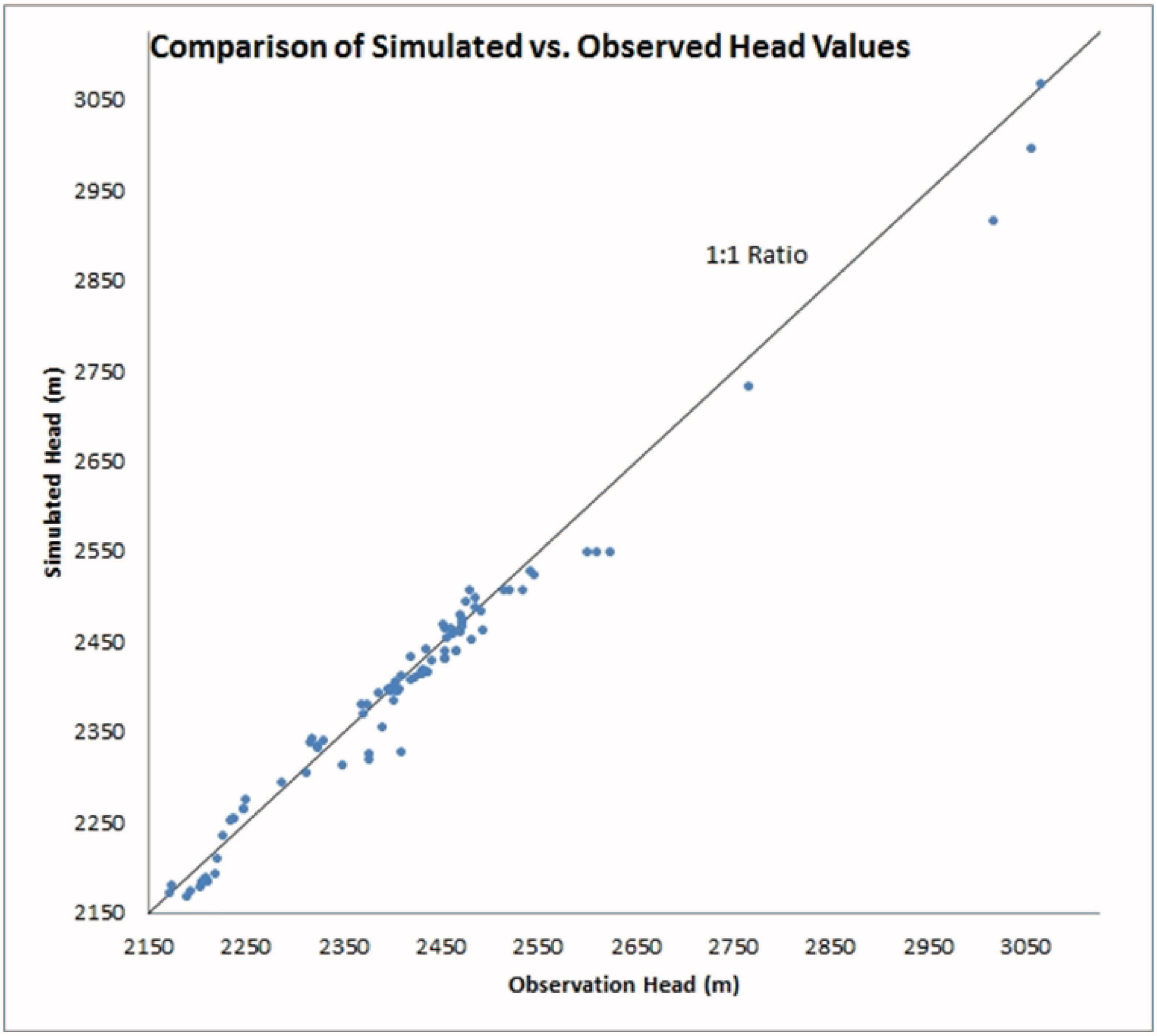


Figure 14: Simulated heads are plotted versus 94 observed heads. The absolute values of the residuals (the difference between simulated and observed heads) range from ~0 m to ~101 m. The average of the absolute values of the residuals is ~18 m. The root mean squared of the residuals is ~25 m. The mean of the residuals is ~9 m. The normalized root mean squared of the residuals is ~0.25.

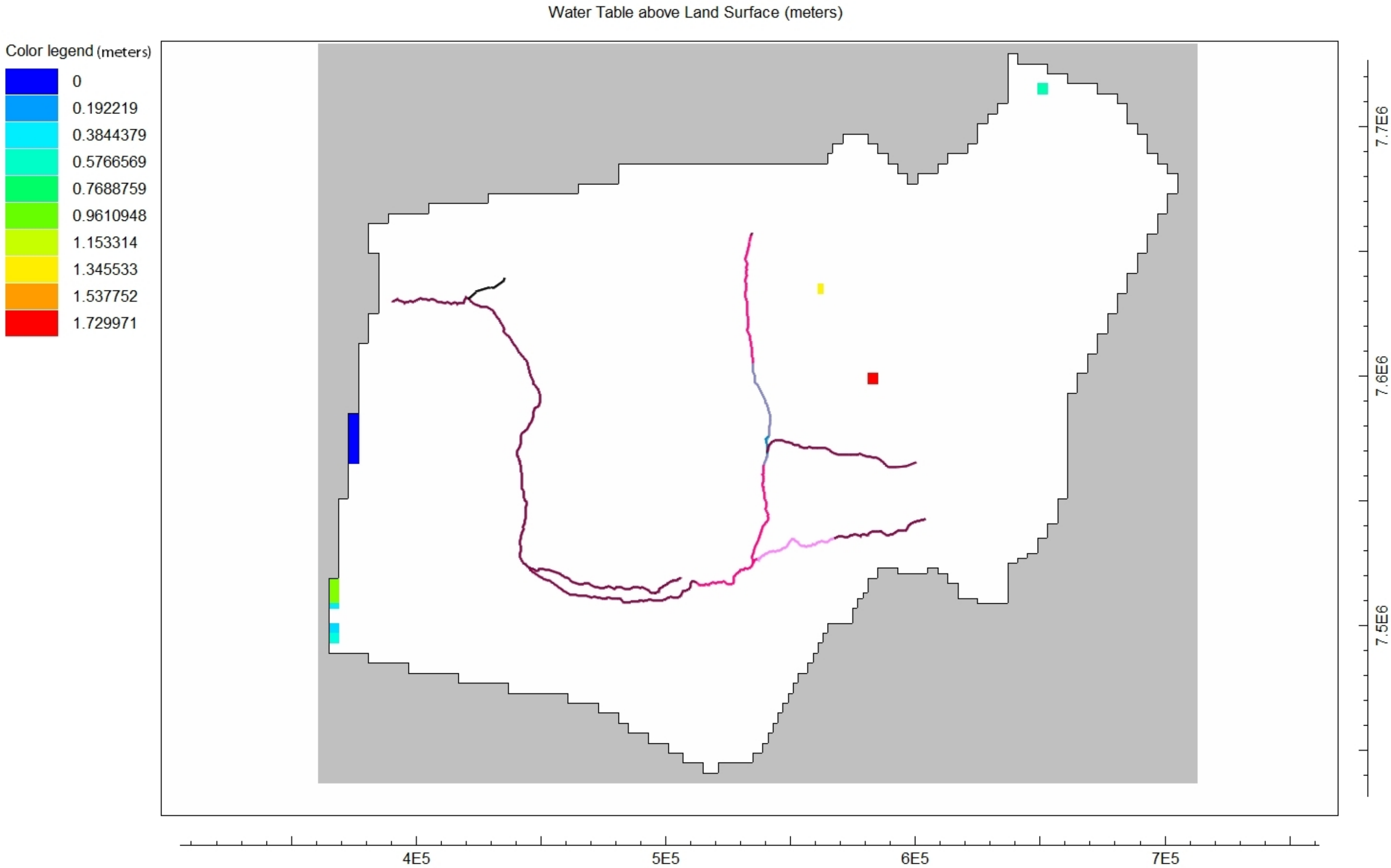


Figure 15: A map of the model domain that shows the cells for which the simulated water table elevation is above the model topography for the calibrated, unstressed model. Drain boundary locations are shown for orientation purposes. Along the coast the simulated water table exceeds the modeled topography by less than ~1 m. The yellow area shows one cell in the northern part of Salar Ascotan with simulated ponding of 1.3 m. The red area shows one cell in the southern part of Salar Ascotan with simulated ponding of 1.7 m. The blue-green area in the northeastern part of the model shows one cell with simulated ponding of 0.6 m in the Salar de Uyuni region. Horizontal and vertical scales are UTM east and north coordinates and represent meters of linear distance..

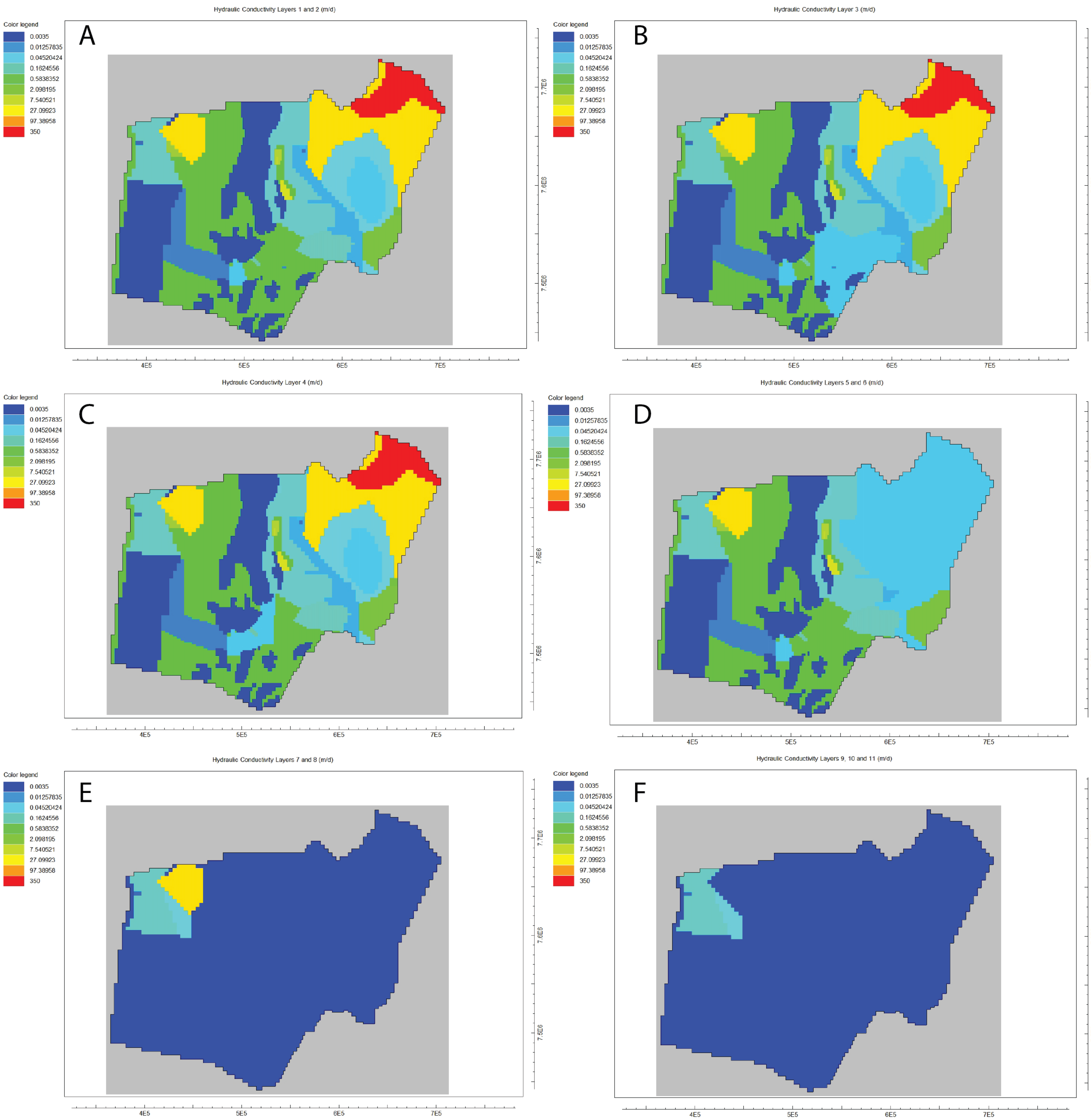


Figure 16: Maps of the calibrated hydraulic conductivities for model layers (m/d). A) Layers 1 and 2, B) Layer 3, C) Layer 4, D) Layers 5 and 6, E) Layers 7 and 8, F) Layers 9, 10 and 11.

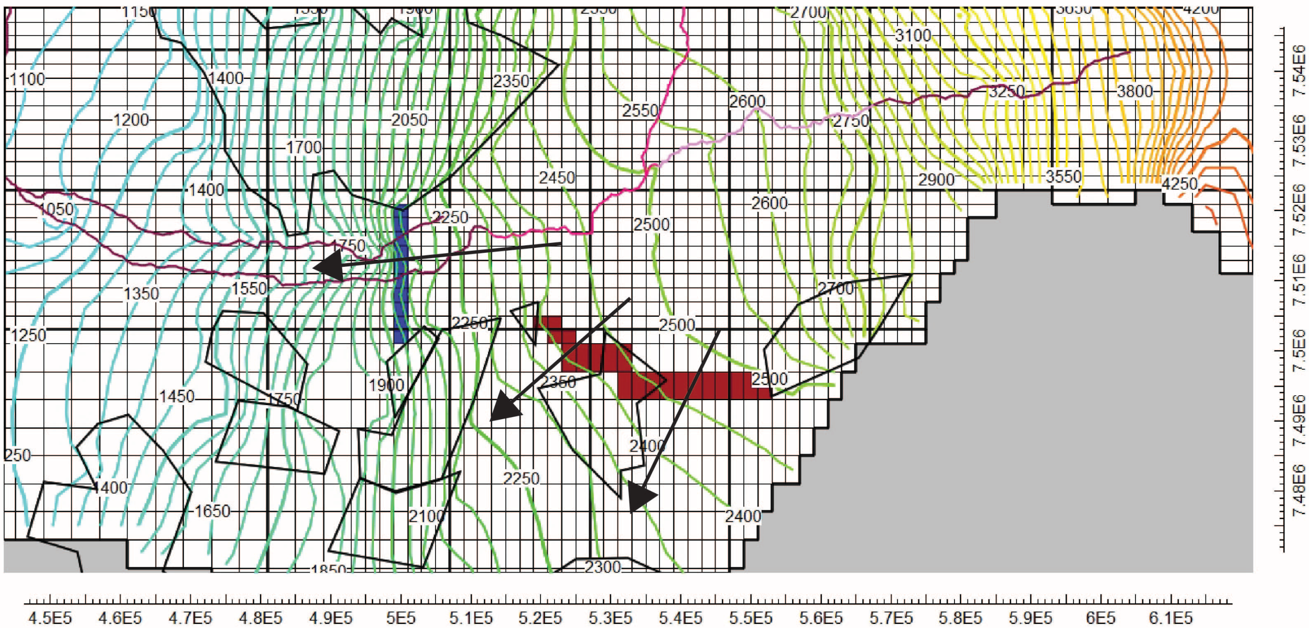
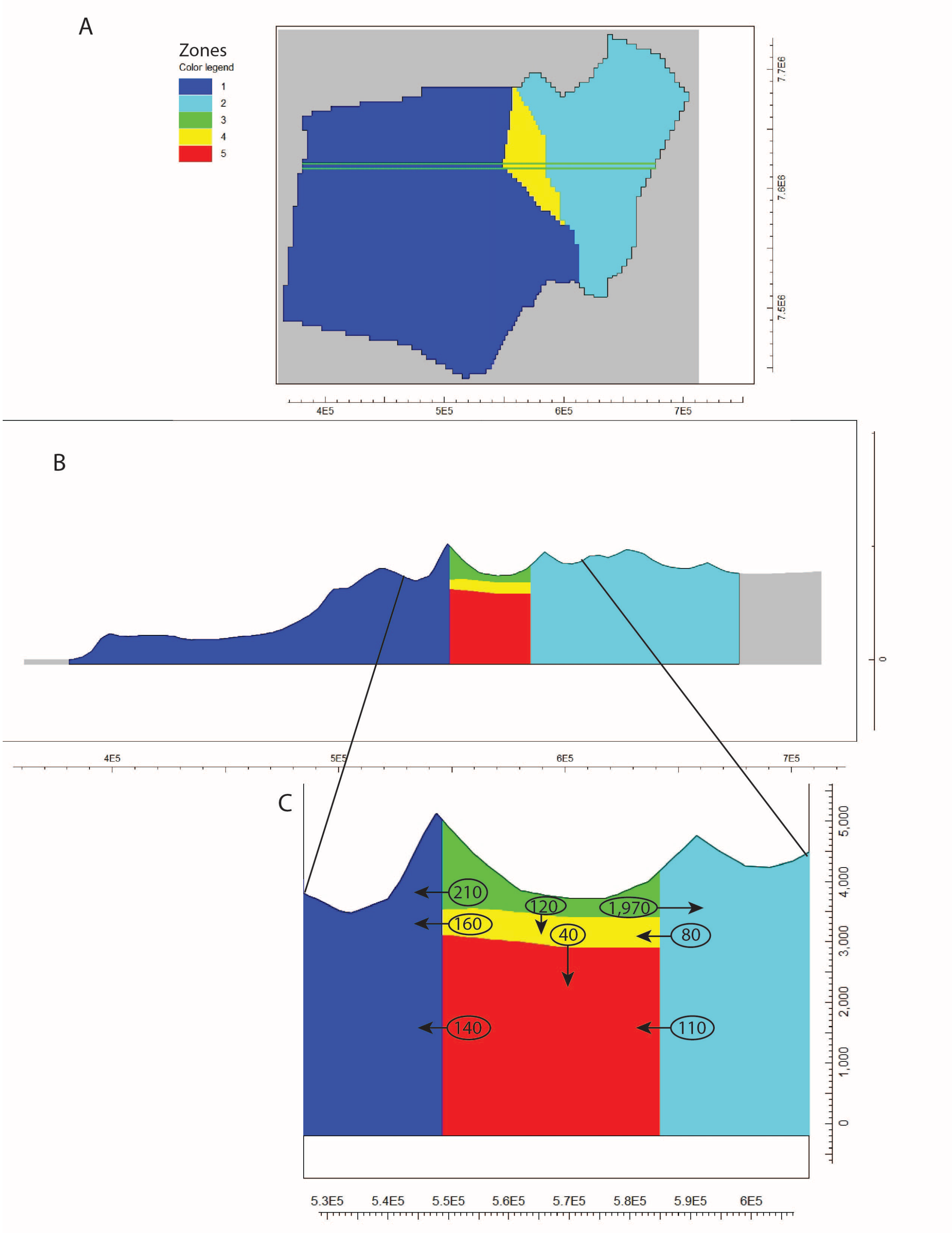


Figure 17: A map of the zone budget locations that are used for measuring groundwater fluxes of interest, with colors denoting the locations. The location of the map is shown in Figure 5, rectangle D. Arrows indicate the direction of flows of interest. The dark blue zone is within the lower aquifer (layers 5 and 6) and measures flux out of the lower aquifer to the west. The red zone measures flux from the Calama Valley to the southwest. Black polygons show the locations where hydraulic basement reaches the surface. The contours show the simulated water table elevation for the calibrated, unstressed model. Horizontal and vertical scales are UTM east and north coordinates and represent meters of linear distance.

Figure 18 A) A map of the model domain which shows three model zones: west of the topographic divide in dark blue, Bolivia in light blue, and the area between the topographic divide and the international border, termed the Ascotan Region in yellow. B) A cross-section of the model showing five zone budget zones including three depth dependent zones within the Ascotan Region. The location of the cross-section is shown with green lines in A. C) A magnified cross-section of the Ascotan Region and adjacent modeled area along the same transect as B. Circled numbers represent the net groundwater fluxes rounded to the nearest 10 l/s based on the zone budget analysis. Arrows indicate the direction of groundwater flux between adjacent zones. For A, B and C, horizontal and vertical scales are UTM east and north coordinates and represent meters of linear distance.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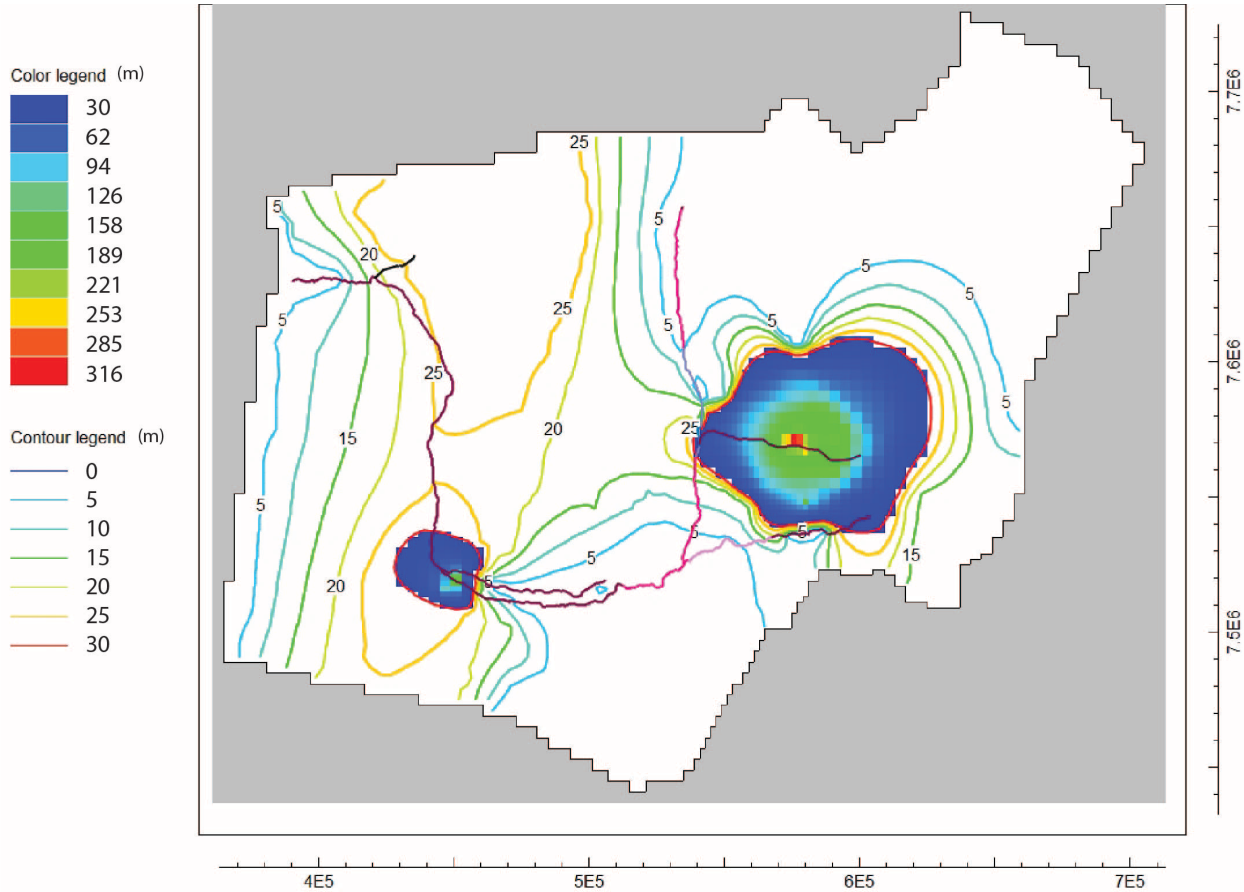

Figure 19: A map of the model domain that shows increases in simulated water table elevations in a “pre-human” model scenario, in which groundwater extraction wells were turned off, compared with the calibrated model. In order to make the figure comprehensible, increases in water table elevations of 30 m and less are shown with 5 m contours, whereas increases in water table elevation of more than 30 m are shown using a color scale. The effects of eliminating groundwater extraction are concentrated near the San Pedro River and, to a lesser extent, near the confluence of the Loa and San Salvador Rivers. Horizontal and vertical scales are UTM east and north coordinates and represent meters of linear distance.

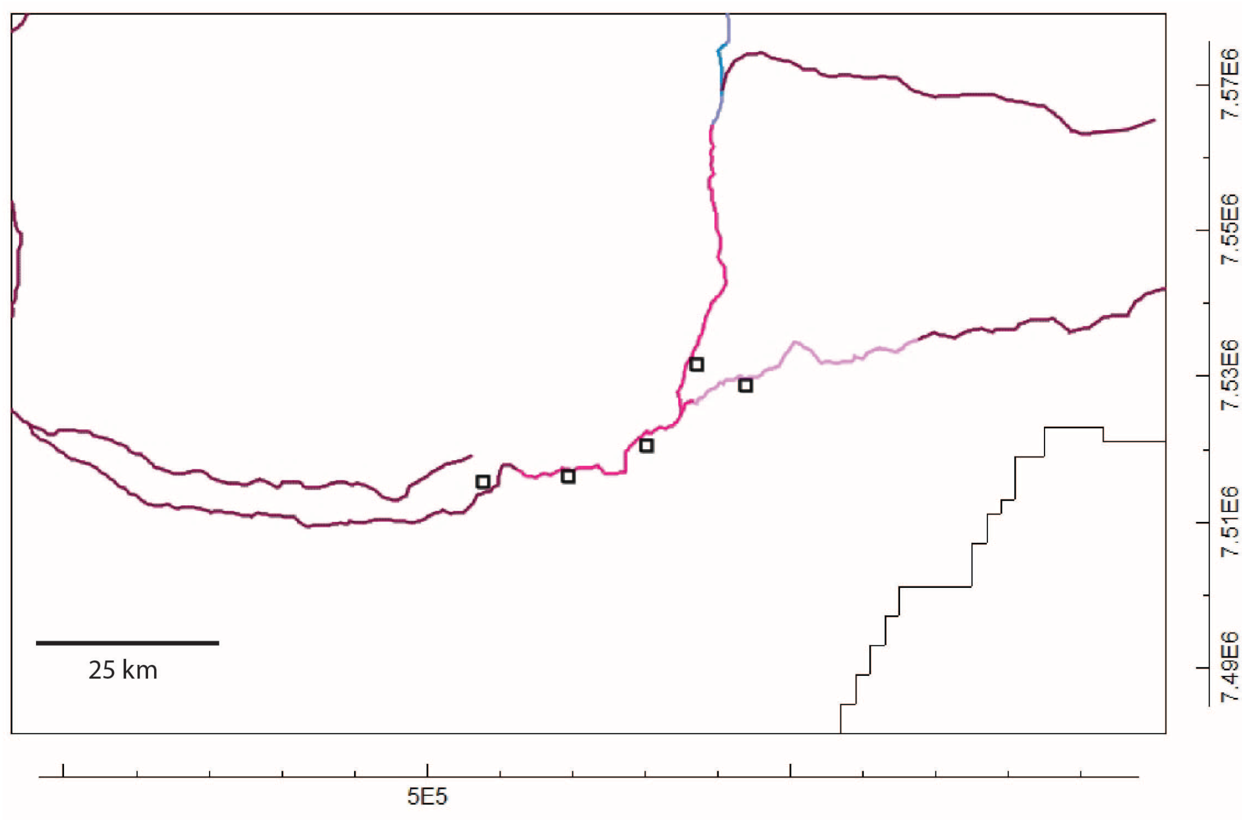

Figure 20: A map of part of the model domain which shows the locations of simulated lower aquifer pumping wells used to stress the model. The location of the map is shown in Figure 5, rectangle E. Pumping rates at all five wells are set equal to one another and were then varied together. Horizontal and vertical scales are UTM east and north coordinates and represent meters of linear distance.

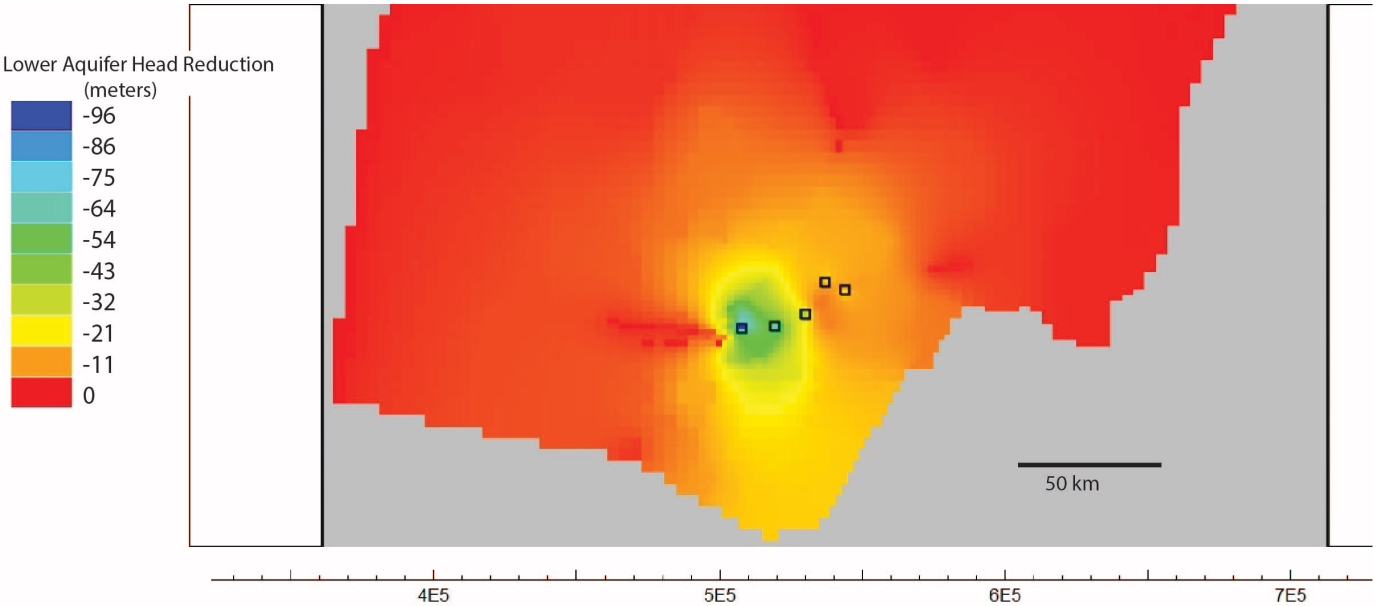

Figure 21: A map of the reduction in the head (meters) within the lower aquifer due to a total imposed groundwater extraction rate of 525.5 l/s from the lower aquifer. The location of the map is shown in Figure 5, rectangle F. Black Squares show the locations of the simulated groundwater extraction wells, all of which are pumped at equal rates. Horizontal and vertical scales are UTM east and north coordinates and represent meters of linear distance.

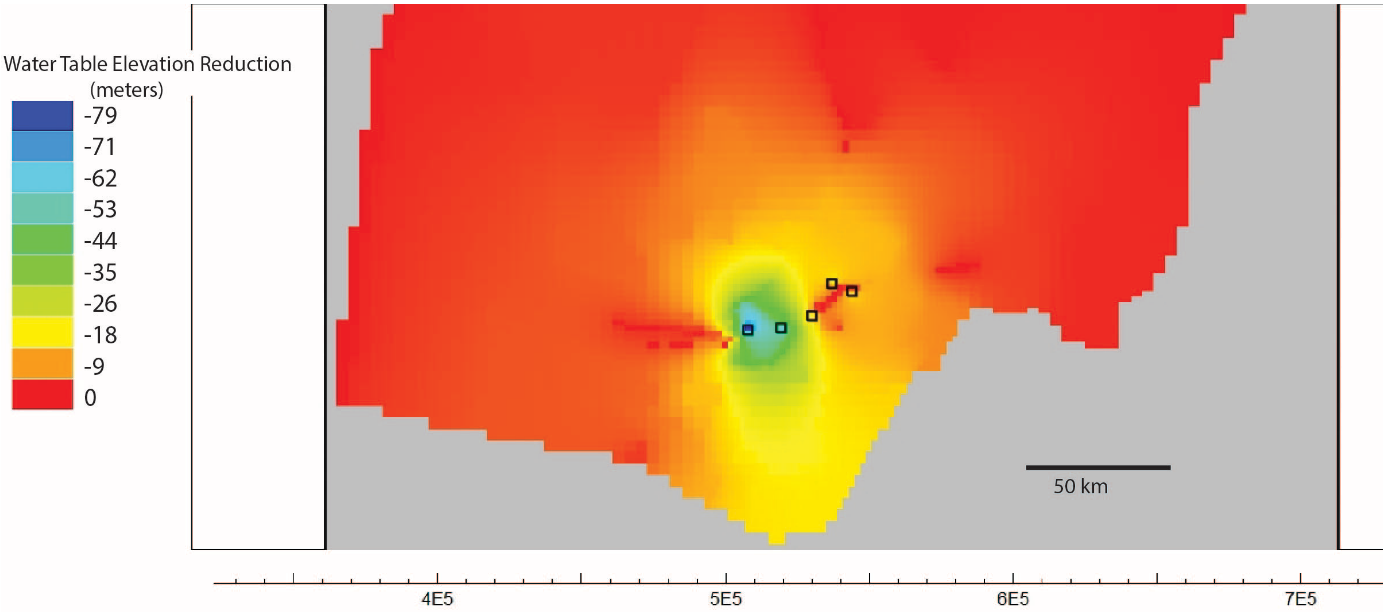

Figure 22: A map of the reduction in the simulated water table (meters) due to a total imposed groundwater extraction rate of 525.5 l/s from the lower aquifer pumping. The location of the map is shown in Figure 5, rectangle F. Black Squares show the locations of the simulated groundwater extraction wells. Horizontal and vertical scales are UTM east and north coordinates. Horizontal and vertical scales are UTM east and north coordinates and represent meters of linear distance.

CHAPTER 6

CONCLUSION

The theme of aridity runs through this thesis. Within the context of aridity, this thesis addresses the coupled feedbacks between the human response to water scarcity and the natural hydrologic system response to human water usage. Collectively, these chapters demonstrate that the human and natural systems that influence water resource availability cannot be well studied in isolation from one another. This supports the necessity of cross-disciplinary and intercultural research collaborations, which are themselves studied in this work.

Human actions often have the largest effect on changes in natural hydrologic systems (e.g. Viviroli et al., 2011; Vörösmarty et al., 2000). In the hydrologic system of the Atacama Desert of northern Chile, humans are huge drivers of change. This is demonstrated in Chapter 5 of this thesis with the groundwater model of the Loa hydrologic system through the comparison between the calibrated model, which includes human groundwater extraction activities, and a hypothetical scenario without human groundwater extraction. Climate changes and landscape evolution changes have also affected water availability in the past, as addressed in Chapter 2 of this thesis. However, on a human decision-making timescale of decades to centuries, our own actions have had the largest effect on water availability.

From a utilitarian perspective, it makes sense to study hydrologic systems in which humans are actively using water; there is a pressing need for knowledge about the water resources in these locations. However, in such cases, the researcher must acknowledge that the human and natural water resource systems are inexorably linked. This human-natural systems coupling is explored in the hydro-economic aquifer modeling (Chapter 3) and three-dimensional groundwater modeling (Chapter 5) portions of this thesis. When studying such coupled systems, cross-disciplinary research collaborations can be extremely helpful. The utility of such cross-disciplinary collaborations, and of intercultural research collaborations, is addressed in Chapter 4 of this thesis. These collaborations allow researchers to study more dimensions of a system, in this case a water resource system, and to understand it in new and useful ways. Additionally, cross-disciplinary collaboration during the writing and publication stage ensures that the final research product will be obtainable and understandable to researchers from multiple disciplinary backgrounds.

The development of the hydro-economic aquifer model presented in Chapter 3 is an example of the kind of work that can emerge from such a cross-disciplinary collaboration. The model is simple enough to be a powerful tool for economists – its simplicity allows for the analytical solution to economic value equations – and yet it is consistent with natural scientists' understanding of aquifer systems on a fundamental level. Such simplified models are often useful in cross-disciplinary research because they are transferable between multiple study areas (Schaefli et al., 2011) and can be used by researchers in varying fields in different ways.

One of the most interesting and useful results to come out of the research into cross-disciplinary, intercultural teams presented in Chapter 4, is that translation is a useful tool for communicating across disciplines even when colleagues speak the same language. The strategy of describing a cross-disciplinary colleague's ideas back to the research team can significantly aid cross-disciplinary communication and team integration. This lesson will be directly applied to future cross-disciplinary collaboration between me and Eric Edwards, my economist colleague who coauthored Chapter 3, as well as other researchers' cross disciplinary collaborations.

When reflecting on this thesis as a whole, the question arises of how the hydro-economic model of Chapter 3 and the three-dimensional groundwater model of the Loa River system of Chapter 5 might be applied to one another and used together. Fully and carefully linking the two models is a project for the future. However, we can attempt to categorize different locations in the Loa River system as having different value classifications within the hydro-economic model.

To elaborate, the hydro-economic aquifer model allows for natural outflows from a groundwater system to provide different levels of value depending on whether these outflows are depleted and by how much they are depleted due to human groundwater extraction. A natural outflow could provide its full benefit if the outflow rate has not been diminished due to human extraction, it could provide a decreased benefit if the outflow rate has declined due to extraction, or it could provide no benefit at all if the outflow has ceased because the threshold has been crossed. We can categorize reaches of the Loa River and its tributaries as within each of those value categories (full benefit, decreased benefit, and no benefit). A reach of the river that provides the full benefit of natural outflow should show no difference in groundwater flux to the river between the calibrated model, which incorporates human groundwater extraction actions, and a 'pre-human' version of the model in which groundwater extraction has been eliminated. A reach of the river that provides a decreased benefit should show more groundwater flux to the reach in the 'pre-human' scenario than in the modern scenario. Finally, a reach that provides no benefit from natural outflows would have no groundwater flux into the reach.

In the groundwater model presented in Chapter 5, the groundwater flux to six of the seven calibrated reaches is lower when human groundwater extraction is included in the model than in the 'pre-human' scenario. In one reach (reach B) the groundwater flux to the river is zero in both scenarios, providing no outflow benefit. Therefore, for six of the seven calibrated reaches, the natural outflow benefit has been reduced and these reaches are in the 'decreased benefit' value category of the hydro-economic model.

The San Pedro River, a tributary of the Loa River, is not used as a calibrated reach in the groundwater model. However, based on the case study history presented in Chapter 3 of this thesis, the groundwater in the San Pedro River region has been so depressed due to human dredging and pumping activities that the groundwater no longer flows into the natural riverbed. The lake and subsequent wetlands ecosystems supported by the river no longer exist. Therefore, along the San Pedro River, the natural outflow that once provided a benefit has been reduced to zero, eliminating that benefit completely.

The research projects presented in the chapters of this thesis have the potential to evolve in many directions. Here I will briefly outline some interesting future work that could be explored. The research into disciplinary and cultural diversity within research teams could be extended to explore other dimensions of diversity within a team, for example generational (age) diversity and gender diversity. How do these other components affect collaboration and how do they interact with disciplinary and cultural diversity? It would be interesting to re-interview the case study respondents in the future and ask them whether and how the experience of being part of a cross-disciplinary, intercultural team has changed their approach to collaboration. Have the respondents become more interested in seeking out such diverse collaborations, or having experienced working in such teams, have they decided to focus their efforts in other areas?

The hydro-economic aquifer model presented in Chapter 3 could be applied to another case study area with more available economic, hydrologic and water resource data, both historical and contemporary. The hydro-economic aquifer model could also be integrated with a three dimensional groundwater model, either within the San Pedro Basin, the Loa River System as a whole, or elsewhere. Valuation studies of the benefits provided by natural groundwater outflow could be undertaken. These types of studies are difficult and controversial, but if a monetary value could be assigned to modeled natural outflows, the economic analysis of different aquifer management decisions could be more readily understood.

There are many avenues for future work on three-dimensional groundwater model presented in Chapter 5. A validation of the model and the model calibration could be undertaken. Pumping wells were installed in the lower aquifer after 2006 in the area between the San Salvador and Loa Rivers. Information on extraction rates and hydraulic heads in observation wells in available (Montgomery and Associates Consultores Limitada, 2010) and could be used to validate the model. The results from such a validation procedure could be compared with the model results of imposed pumping presented in Chapter 5. Future work could also explore variations in hydraulic conductivity within the aquitard. This could be done both by exploring a greater range of possible hydraulic conductivity values for the aquitard and by exploring the possibility of local variations in hydraulic conductivities in different regions of the aquitard. Jordan and others (submitted) have interpreted that the aquitard in the Calama Valley is laterally variable in hydraulic conductivity, in some areas it is less confining than in other areas. Such heterogeneity could be incorporated into future model versions. Then the results could be examined to see if the model is sensitive to lateral variations in hydraulic conductivity within the aquitard.

Taken as a whole, this thesis provides insight into the past, present and future hydrogeology of Atacama Desert of northern Chile. It further demonstrates that, in this arid environment where water is extensively used by humans, natural and human systems should not be studied in isolation from one another. Lastly, the thesis provides concrete strategies for conducting the type of cross-disciplinary research necessary to address the pressing water resource problems in the study region.

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APPENDIX

Online Interview Questions (English)

1) Please describe why you decided to take part in this project and what your goals are for the project. What, if anything, appealed to you about cross-disciplinary research and research involving international collaborators (ie. do you see any benefits to collaboration across disciplines and nationalities)?

2) Please describe communication within the team, both the team as a whole and with your disciplinary colleagues. Did you encounter any challenges in communication across distances, disciplines, cultures or languages? Please give specific examples if possible.

3) In what ways did you, or the team as a whole, work to overcome communication challenges related to distance, disciplines, cultures or languages? Were these strategies effective?

4) Has the research group developed a common terminology (across disciplines) to discuss the project? If so, how and when did it develop? Can you cite specific examples or terms that the group has come to use?

5) Did you feel you were listened to and respected by other team members and was the team open and responsive to different viewpoints? If so, can you give examples? Did you change the way you speak or your behaviors to make team members from other cultures feel comfortable? If so, can you describe how?

6) Have your understandings of Calama Basin water resources, and the goals of this project, changed or developed through cross-disciplinary interactions with your team members? If so, how have you incorporated these changes (in theory, terminology, methods, models, world views, etc.) into your thinking?

7) Has your understanding of your own discipline been affected by exposure to and interaction with members of the cross-disciplinary research team? If so, how?

8) Was visiting field site (Calama and surroundings) and meeting with stakeholders and regulators useful? Did the field trip or meetings change the way you envisioned the research project? If so how?

9) In what ways do you think this research project or research team could be improved?

10) Please describe what would constitute a successful outcome for this project in your mind.

Online Interview Questions (Spanish)

1) Por favor, describa por qué decidió participar en este proyecto y cuáles son sus metas para el proyecto. ¿Encontró Ud. de especial interés la colaboración interdisciplinaria o la colaboración internacional generada a partir de este proyecto (es decir, ve algún beneficio en estos tipos de colaboraciones)? Por favor explaye su respuesta.

2) Por favor, describa la comunicación dentro del equipo tanto entre el equipo completo, como entre sus colegas de la misma disciplina. ¿Encontró dificultades en la comunicación a distancia, entre disciplinas, intercultural o multilingue? Por favor, dé ejemplos concretos si es posible.

3) ¿De qué manera Ud. personalmente, o el equipo completo, trabajó para superar los retos comunicacionales relacionados con la distancia, las disciplinas, las culturas o las lenguas? ¿Fueron efectivas estas estrategias?

4) ¿Desarrolló el grupo de investigación una terminología común a todas las disciplinas para discutir el proyecto? Si es así, ¿cómo y cuándo se comenzó a desarrollar? ¿Puede dar ejemplos o términos específicos que el grupo utiliza?

5) ¿Siente Ud. que fue escuchado y respetado por los demás miembros del equipo? y, ¿fue el equipo abierto y receptivo a distintos puntos de vista? Si es así, ¿puede dar ejemplos? ¿Cambió su forma de hablar o sus comportamientos para que los miembros del equipo de otras culturas se sientan cómodos? Si es así, ¿podría describir de qué manera?

6) ¿Ha cambiado o evolucionado su comprensión de los recursos hídricos de la cuenca de Calama y de los objetivos de este proyecto, a través de la interacción interdisciplinaria con los miembros de su equipo? Si es así, ¿cómo ha incorporado estos cambios (en teoría, terminología, métodos, modelos, visiones del mundo, etc.) en su forma de pensar?

7) ¿Ha sido alterada su concepción de su propia disciplina por la exposición a, y por la intereacción con los miembros de otras disciplinas? Si es así, ¿cómo?

8) ¿Fueron útiles la visita a terreno (Calama y alrededores) y las reuniones con las distintas partes interesadas? ¿Ha cambiado su visión del proyecto de investigación por la visita a terreno o por las reuniones? Si es así, ¿cómo?

9) ¿De qué manera cree Ud. que este proyecto de investigación o este equipo de investigación se podrían mejorar?

10) Por favor, describa desde su perspecitva lo que podría ser un o unos resultados exitosos de este proyecto.