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DEPARTMENTS OF GEOSCIENCES, MATHEMATICS, AND AGRICULTURAL
ECONOMICS, SOCIOLOGY, AND EDUCATION

NUMERICAL MODELING OF THE HYDROLOGIC-AGRICULTURAL-ECONOMIC
SYSTEM IN PUNJAB, INDIA: AN ANALYSIS AND REFLECTION ON
INTERDISCIPLINARY MODELING FOR SUSTAINABILITY

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Abstract

Water is the lifeblood of our planet coursing through the water cycle veins, creating and destroying all things on the Earth's surface. We do not know life without it; yet, we are depleting our freshwater reserves in glaciers, groundwater, and surface water through greenhouse gas emissions, irrigation overdraft, and pollution. As the human population grows, climate stability plummets, and ecosystems collapse, we face a water crisis for ourselves, for future generations, and for our interdependent natural community. This global, intractable problem requires an integration of thought across all knowledge. No complete solution of equitable sustainability exists, but I believe experts and local communities can make progress by working alongside one and other. This thesis is an exploration of this process. Tess Russo, Kate Zipp, Ludmil Zikatanov and I have explored the extreme groundwater overdraft in Punjab, India through interdisciplinary modeling encompassing the fields of hydrology, mathematics, and economics. This model will be used to assess and optimize crop choice scenarios based on farmer welfare, food production, and hydrologic system constraints. The results can be used to further understand the hydrologic system response to government policies and climate change, and to assess the effectiveness of possible water conservation solutions. This thesis is an analysis of the complex system and model, a reflection on all that I have learned, and the questions I have yet to answer.

*Humble yourself in the sight of the Earth
 You have to ask her what she knows
 Humble yourself in the sight of the Earth
 You have to know what she knows
 We shall lift each other up
 Higher and higher and
 We shall lift each other up*

– Camp Song from Merrowvista

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I would also like to thank the many mentors I have had throughout my undergraduate career at Penn State. I am grateful to Erica Smithwick for teaching me about landscape ecology and the complexities of agricultural modeling. I am thankful for Caitlin Grady for taking the time to meet with me to share her knowledge on useful and useable water research and ethics. Additionally, I would like to thank Ted Alter for challenging me to critically analyze my education. He taught me the importance of community-based work grounded in local knowledge. Lastly, I would like to extend my gratitude to Maureen Feineman for advising me through this degree and this thesis.

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*Humble yourself in the sight of your friends
You have to ask them what they know*

Chapter 1

Introduction

1.1 Overarching Question

The United Nations (UN) aims to completely eradicate world hunger by 2030, as part of their seventeen sustainable development goals (UN, 2015a). Human ingenuity has previously overcome past concerns of global malnourishment. In the 1960s new high-yield crops and fertilizers increased global food supply, launching the world into the Green Revolution (Giordano, 2009). However, this tremendous increase of food production requires a tremendous increase of resource inputs, such as water for irrigation. Today, irrigation accounts for roughly 90% of all water used globally, and 40% (or more) of which is extracted from groundwater aquifers (Aeschbach-Hertig & Gleeson, 2012; Famiglietti, 2014). The growth in global groundwater consumption parallels the growth in food production, but the groundwater revolution has been silent: it has gone largely unnoticed due to groundwater's concealed nature and easy accessibility (Giordano, 2009). In many areas around the world, groundwater extraction rates now exceed the rate of aquifer recharge, leading to regional declines in groundwater levels that threaten global food security (Aeschbach-Hertig & Gleeson, 2012; Brahmanand et al., 2013; Famiglietti, 2014; Fishman et al., 2015). The world's growing population further complicates the goal of global food security (Famiglietti, 2014). By 2050, food production must grow by 70% to accommodate the 2.3 billion more people projected to populate Earth (FAO, 2009). A sustainable food production system to feed the projected 11.2 billion people by 2100 (UN, 2015b) can only be established if appropriate groundwater levels are maintained (Aeschbach-Hertig & Gleeson, 2012) or else alternative water sources will be necessary.

On our predicted trajectory of climate change, our freshwater resources will decline and spatially shift (Kundzewicz et al., 2008), challenging our current way of life. All we know for certain is the great uncertainty of our future, and uncertain water resources heighten tensions and may lead to conflict (Newton, 2015). The water resource management required of the 21st century goes beyond environmental resource management for ecological preservation for maintenance of large-scale ecosystem services that benefit society. Water resource management is fundamentally managing people's right to life.

So how will the world manage this resource? Some speculate that the next war will be fought over water (Engelke, 2016) and some already claim the conflict in the Syria was exacerbated by a preceding drought (Hammer, 2013). But I hope we can do better. Sustainable water management for all people is a global community problem. We are all connected. As a hydrologist, how do I contribute knowledge on physical science for this common good of our community? What is my role as an expert citizen of this country and this world on the path towards freshwater sustainability for all people? How do I practice science in alignment with my values and my goals?

This thesis explores these questions through my experience of interdisciplinary water management research. My goal is to develop guiding principles for my professional practice in sustainable and equitable water management by connecting challenging ideas from my classes and research to my experiences through intentional reflection. This work is not simply a technical write-up of the hydrologic, agricultural, and economic model results, but a story and reflection of my experience. This thesis is an exploration in the processes of conducting valuable science in pursuit of equitable sustainability.

1.2 Experiential Learning Theory

Experiential Learning Theory (ETL) (Kolb & Kolb, 2005) provides a framework to learn from my experience in order to develop an answer to my question: how do I conduct useful and useable research in pursuit of sustainable and equitable management of freshwater? ETL, as outlined by (Zull, 2011), has four steps in the iterative process of deep learning: concrete experience, reflective observation, abstract hypothesis, and active testing (Figure 1.1):

- Experience is physical information from the world.
- Reflection is the search for connections between concrete experiences and everything you know.
- Abstraction is the manipulation of reflections to generate new ideas.
- Active testing is the process of converting these new ideas into physical action to create new concrete experiences.

Learning happens as we continually transform our knowledge along this cycle. We reflect on our experiential data and begin to create ideas, plans, and then action to cross the transformation line of learning depicted in Figure 1.1.

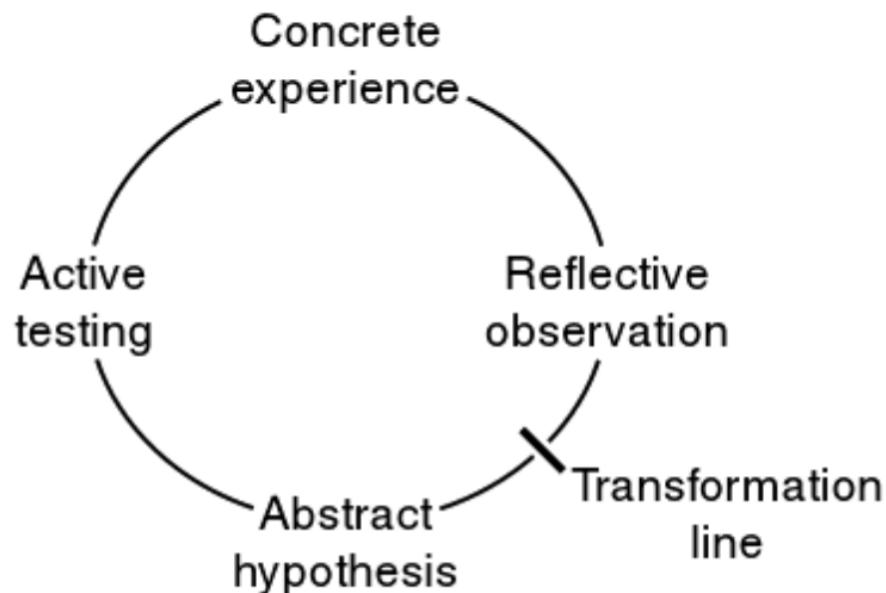


Figure 1.1: The learning cycle. *Reproduced from (Zull, 2011)*

The process of reflection requires time and often some degree of sensory deprivation so the brain can process the preceding information and experiences (Zull, 2011). Zull 2011 notes that the typical college experience does not involve much reflection because rewards (grades) are given for

fast processing and reiteration of information. In order to personally complete the learning cycle and deeply learn from my college experience, this thesis is my time to reflect on the process of this work and its relation to my college classes and my life experiences. Through this reflection, I develop abstract hypothesis about how I want to practice hydrology to create a personal philosophy of practice. As I continue on as a hydrologist, I will actively test my philosophy of practice and continue the learning cycle indefinitely.

1.3 The Story of my Thesis Experience

1.3.1 Project Formation

After studying abroad in Bhutan for the Fall 2015 semester, I was eager to get involved with international research that would matter to people. My interests were broad but focused on human-environment interactions and sustainable development. I decided to study geosciences to develop a comprehensive understanding of the earth, with a focus on water, a vital resource at the heart of many human-environment challenges. Tess Russo, a professor of Geosciences at the time, offered me the project on modeling groundwater in Punjab, India, a continuation of her previous work at the Columbia Water Center. She had data from several colleagues in Punjab which she had previously used to model groundwater in three districts in Punjab using bayesian statistics (Russo et al., 2015). I began organizing spreadsheets of data and reading about the hydrologic situation during the Spring 2016 semester:

India surged towards food self-sufficiency thanks to the Green Revolution (Abrol, 1999; Badiani et al., 2012) but now experiences extreme groundwater overdraft as a result (Briscoe & Malik, 2008; Chatterjee & Purohit, 2009; Rodell et al., 2009; Aeschbach-Hertig & Gleeson, 2012; Famiglietti, 2014; Fishman et al., 2015). As seen in Figure 1.2, the highest rate of groundwater depletion in the world is found in the Indo-Gangetic Plain, which encompasses northwestern India (Aeschbach-Hertig & Gleeson, 2012). India produces 1.8 million tons of groundwater-based agricultural outputs each year (Zaveri et al., 2016) using roughly 230 billion cubic meters of groundwater (Chatterjee & Purohit, 2009). Between 2002 and 2008, India lost 109 km³ of groundwater, double the volume of their largest surface-water reservoir (Rodell et al., 2009). The Indo-Gangetic Plain, which encompasses Northwestern India, has the current highest rates of groundwater depletion globally (Aeschbach-Hertig & Gleeson, 2012), reaching an average of 20 gigatonnes/yr between 2003 and 2012 (Chen et al., 2014). This unsustainable use of groundwater coupled with the uncertain effects of climate change present critical threats to India's food security (Aeschbach-Hertig & Gleeson, 2012; Zaveri et al., 2016) and puts India on the brink of a water crisis (Briscoe & Malik, 2008).

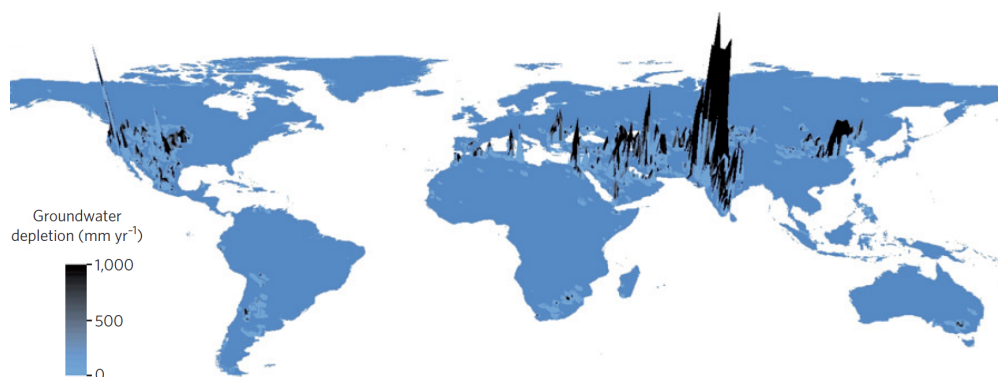


Figure 1.2: Groundwater depletion worldwide. Lighter blue represents renewable surface and groundwater depletion and dark blue to black represent nonrenewable groundwater depletion *Re-produced from (Aeschbach-Hertig & Gleeson, 2012).*

One of India's northwestern states experiencing the most extreme groundwater overdraft is Punjab, which produces 40 - 50% of the rice and 60 - 65% of the wheat consumed by India (Aggarwal et al., 2009; Tripathi et al., 2016). This agricultural production is supported by 230 billion cubic meters of groundwater per year, an irrigation demand that vastly exceeds groundwater recharge (Chatterjee & Purohit, 2009). This depletion is observed in the declining water table across the state, averaging around 0.4 m/yr from 1997 - 2002 (Russo et al., 2015; Perveen et al., 2012; Ambast et al., 2006). Between 2002 and 2008, Punjab lost 10 times more groundwater volume than California's Central Valley (Aggarwal et al., 2009; Zaveri et al., 2016).

1.3.2 Expanding the Scope

In need of a job for the summer of 2016, I reached out to a math professor I worked with on ski patrol at Tussey Mountain, Ludmil Zikatanov, to see if he had funding for a summer undergraduate researcher. I ended up working as a Penn State Math REU student with Ludmil, funded through his National Science Foundation (NSF) grant. As it turned out, Ludmil is an expert in computational mathematics, specifically finite element/difference/volume methods and multilevel methods which are used as discretizations and solvers in groundwater modeling. So, I decided to continue my research on Punjab as an interdisciplinary hydrology and mathematics project. I spent the summer learning to code in Python and writing the geology framework for the hydrologic model. By August, we had run a simple steady state model of Punjab using MODFLOW, the USGS's 3D modular version finite-difference one-water hydrologic-flow model (USGS, 2016).

To incorporate the state-of-the-art numerical techniques, Ludmil began working to design and implement efficient numerical algorithms as part of the software package HAZMATH (a simple finite element, graph, and solver library) to use as a basic suite of routines to numerically model groundwater systems. In December, Ludmil and Tess submitted a proposal to the Computational Mathematics Program in NSF to develop multilevel methods for numerical modeling with application in hydrogeology.

In the Fall of 2016, I took classes in hydrogeology and microeconomics as well as continued to research the groundwater situation in Punjab, India. As I began to synthesize this interdisciplinary

knowledge in relation to my research in Punjab, I came to a deeper understanding: the hydrologic system in Punjab is fundamentally related to agriculture and therefore economic policies set by the government.

This problem requires solutions that consider both the bio-physical and socio-economic contributions (Dillon, 2005; Giordano, 2009; Rodell et al., 2009; Aeschbach-Hertig & Gleeson, 2012; Brahmanand et al., 2013; Perveen et al., 2012). Government policies in Punjab are largely faulted for the decline in groundwater because they do not incentivize water conservation (Jalota et al., 2007; Perveen et al., 2012). Specifically in India, the government subsidizes electricity for irrigation and fixes the minimum prices for water-intensive crops (Jalota et al., 2007; Perveen et al., 2012). However, changing weather patterns and shifting cropping systems effect groundwater levels as well.

1.3.3 Integrating Dicipines

The questions a hydrologic model could answer would not provide all the information needed in order to catalyze change. I presumed hydrologic model outputs were more useful when incorporated into an economics analysis. They mean little if they sit in an academic paper (or undergrad thesis) without being translated into their relation to the human system. So, as my final project in both my microeconomics and hydrology class, I began to research the economics of groundwater and government policies in place in Punjab that drive this unsustainable use. Based on recommendations from a friend, I reached out to Kate Zipp, an assistant professor of environmental resource economics, to figure out what I needed to learn on the economics side of this problem. The conversations we had that semester sparked my interest (despite my boredom in my microeconomics class) and I decided to expand my thesis again to include another discipline.

As part of my science writing class in the spring of 2017, I wrote an extensive literature review on the entire hydrologic, agricultural, and economic system in Punjab, India. More complexities and interdependencies began emerging through my research. Cropping patterns, crop yields, minimum support prices for rice and wheat, subsidized electricity for irrigation, water-use technologies, and climate change have impacts on the groundwater levels. Many studies call for models and analyses that consider these many factors to predict and plan for a sustainable future (Abrol, 1999; Mukherji & Shah, 2005; Jalota et al., 2007; Rodell et al., 2009). While these factors have been individually investigated and several models have started to examine their relationships (Jalota et al., 2007; Zaveri et al., 2016), no study comprehensively explores the relationships between the hydrologic, and economic setting in Punjab, India since the onset of the Green Revolution.

Given this gap in the research, I decided to develop a coupled economic, agricultural, and hydrologic model for Punjab, India that accounted for the complexities in both systems. The overall goal was to calculate the shadow price of groundwater and test the effect of different policies on this unsustainable system. I spent the rest of the semester compiling the necessary economic data from unorganized government reports and began a cursory analysis.

Also during the Spring 2017 semester, I took a class on Landscape Ecology with Erica Smithwick. As part of my final project, I researched ecosystem and agricultural models. Again, I learned of the vital intricacies missing from generalized agricultural models in both economic and hydrologic studies. I used the NASA satellite SMAP (Soil Moisture Active Passive) imagery (NASA, 2016b) to obtain estimates of soil moisture throughout the year of 2015, with the intention to include this information into the agricultural model.

I was awarded the Erickson Discovery Grant to continue my research over the 2017 summer. Tess and Ludmil were also awarded their NSF grant in July 2017 and began working to create HydroLena, a software package that models the interdependent hydrogeology, economics, and agriculture system, with the overall goal to develop a coupled multiscience model for Punjab, India. Through the summer and fall of 2017, we worked to run a steady state model of Punjab with HydroLena and compare the results to the previous MODFLOW model.

During a class on Community, Local Knowledge and Democracy, I began thinking about the role of scientists and experts in our democracy and in the process of creating a more sustainable equitable world. How can I conduct useful and usable research beyond just adding an economic analysis? How does change really happen and what is my role in creating that change? At the AGU Fall Meeting, I attended many sessions discussing different facets of these questions and explored many of the existing and possible alternative science methods within geosciences that may help catalyze change. I now see the flaws in this Punjab model, but also how much I have learned since I started this project. This is my reflection on what I have learned and the outline of how I want to pursue research in the future.

Because of this project, strong professional relationships and friendships were built between Tess Russo, Ludmil Zikatanov, Kate Zipp, and myself. Kate and Ludmil have already begun collaborating on another environmental economics project related to invasive species and Tess and Ludmil have plans to continue developing HydroLena. While my future career path is uncertain, I know I too continue to benefit from these professional relationships and friendships.

1.4 Thesis Map

This Thesis is organized into chapters on each of the model dimensions: geology, hydrogeology, agriculture, and economics. These chapters explore the discipline frameworks, methods, results, and discussion within this coupled model. In the following chapter, I discuss the integration of these models, the missing perspectives on our team, and the major questions we have left. Then, I reflect on the entire process in the next chapter, specifically the methods of interdisciplinary research, the challenge of modeling complexity, and the research structures of Academia. Finally, I conclude the thesis with my living philosophy of professional practice developed based on this experience.

*Humble yourself in the sight of the Earth
You have to ask her what she knows*

Chapter 2

Punjab Geology

2.1 The Geology Frame

The geologist views the world from an expansive timeframe, where rates of change are considered relative to the Earth's age of 4.6 billion years. Knowledge about Earth's change through time is developed through comparisons between rock records and current earth processes using physics, chemistry, and biology. The geologist asks the questions:

- What is the structure of the landscape and how did it form?
- What are the characteristics of the rocks within the landscape and how did they form?
- What does this landscape tell us about Earth's history and Earth's future?

The information revealed from this scientific exploration is used to locate natural resources (minerals, coal, oil, water), evaluate current hazards, and expand our understanding of how the Earth and our universe works.

2.2 Geologic Setting

Punjab is an agricultural state in the alluvial plain of the Himalayas (Abrol, 1999) accounting for 1.5% of India's total land mass (Aggarwal et al., 2009). The Indian subcontinent collided with Asia around 55 million years ago, with major uplifting beginning 20 million years ago to form the Himalayas (Aitchison et al., 2007). The increased load depressed the continental crust to form a foreland basin that filled with sediments eroding from the uplifting Himalayas (Singh, 1996). The resulting alluvial plain extends along the southern boundary of the Himalayas to form the Indo-Gangetic Plain, which covers most of Punjab as seen in Figure 2.1. The northeastern edge of Punjab includes Piedmont and the beginning of the Himalayan foothills.

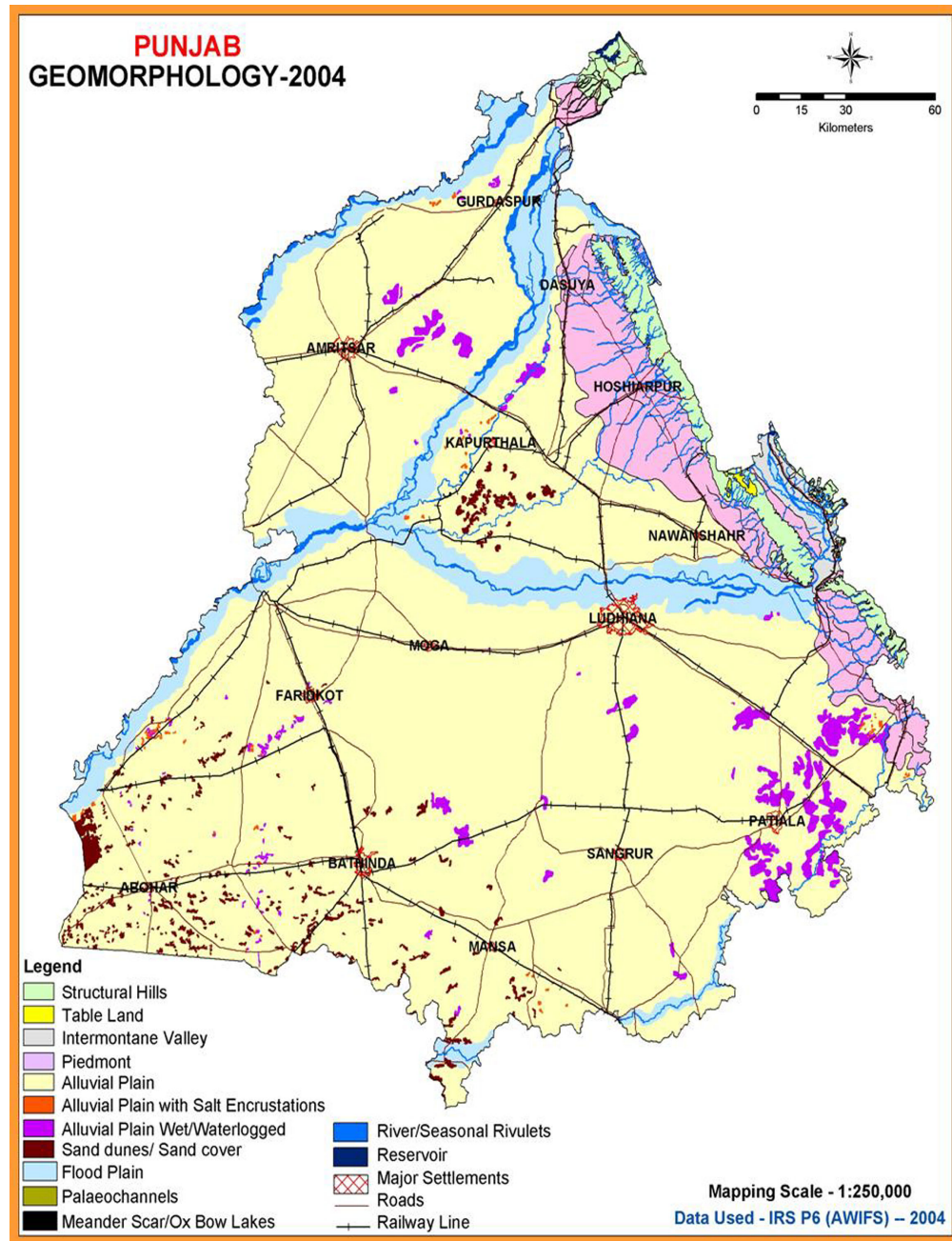


Figure 2.1: Geomorphology of Punjab, India. *Figure reproduced from (Punjab Remote Sensing Centre, 2004).*

As described in the Groundwater Year Book of Punjab (CGWB, 2015), the expansive plains of Punjab are composed of alluvial deposits from the Indus-river system ranging from Pleistocene to Recent (Figure 2.3). Khadar, new alluvium of current river floodplains (Upper Pleistocene to Recent age) ranges from coarse gravel to lenticular sand beds, decreasing in sediment size with distance from the Himalayas. The accumulation of this fluvial deposit resulted in sand and gravel aquifers interspersed with clay aquitards. The upper aquifers are interconnected and therefore unconfined, but deeper horizons show some confined and semi-confined aquifer conditions. The

rapid changes in textures and thickness of this unit results in a wide variation in hydraulic conductivity and transmissivity. Bhangar, older alluvium of abandoned floodplains and bar upland regions (Upper Pleistocene), ranges from sandy clay to medium sand and forms good groundwater reservoirs.

The Siwalik formation (Middle Miocene to Pleistocene) lies underneath this alluvium and is only exposed along the northwestern part of the state (Figure 2.3). This formation is divided into lower, middle, and upper based on lithology and vertebrate fossils. The Upper Siwaliks consist of friable medium to coarse-grained sandstones interbedded with clays and lenticular conglomerates. This formation provides good to moderate supplies of water. The Middle Siwaliks consist of medium-grained sandstones interbedded with clays. Overall, this formation has low permeability leading to poor yields in groundwater. The Lower Siwaliks contains massive micaceous sandstones interbedded with thick clays in coarsening upwards sequences. This formation also provides poor yields of groundwater.

Table 2.1: Geologic Formations

Formation	Aquifer Quality	Characteristics	Source
Basement	extremely poor	granite	(Mahajan, 1995; CGWB, 2015)
Lower Siwalik	poor yields of water	fine-medium grain sandstones interbedded with clays and conglomerate	(Mahajan, 1995; CGWB, 2015)
Middle Siwalik	poor permeability	sandstone interbedded with clays	(Mahajan, 1995; CGWB, 2015)
Upper Siwalik	moderate yields of water	friable sandstone and conglomerates interbedded with siltstone and clay	(Mahajan, 1995; CGWB, 2015)
Old Alluvium	moderate to high permeability	massive clay with compact sand, gravel, conglomerate beds	(Mahajan, 1995)
New Alluvium	low to very high permeability	gravels, sands, sandy clays and clay	(Mahajan, 1995)

The thickness of the Siwalik formation increases towards the Himalayas to reach a depression with a maximum depth of 4500 m below the surface. The bedrock encountered at Kheliwala was Dheli Quartzite. The overall geologic cross section is summarized in Figure 2.2

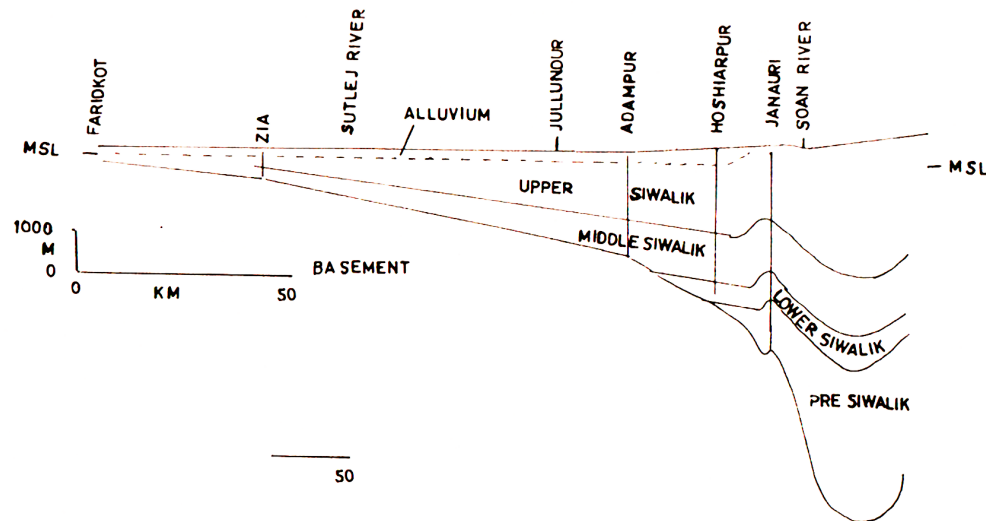
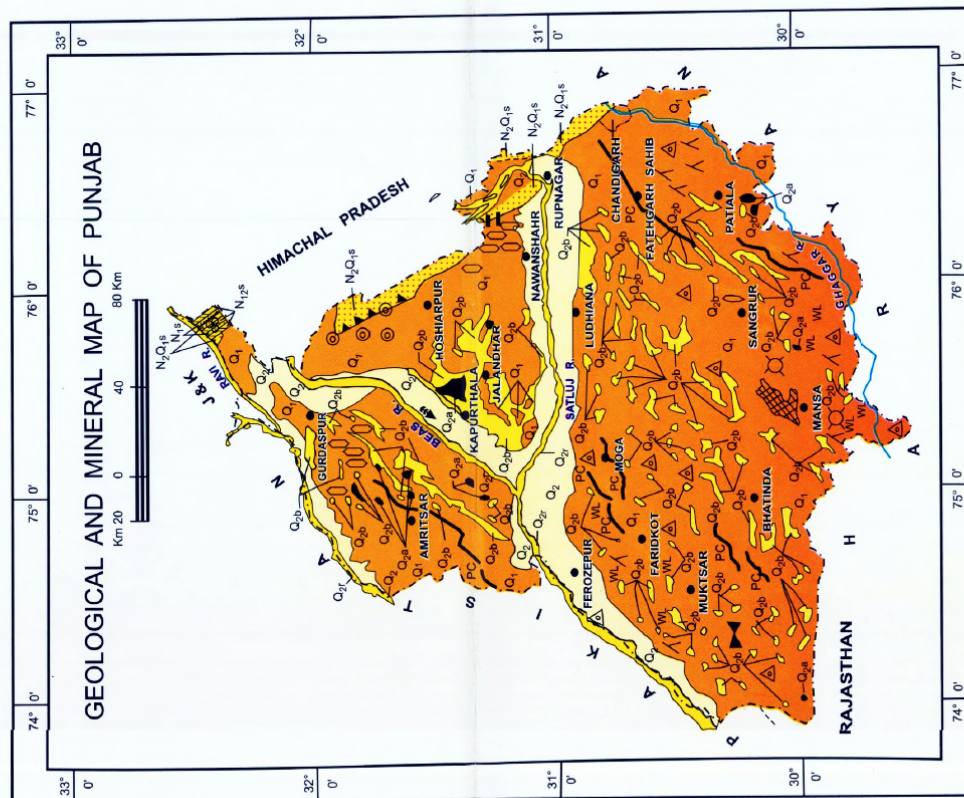


Figure 2.2: Generalized geologic cross-section of Punjab India from the SW to NE. *Figure reproduced from (Mahajan, 1995).*



LEGEND



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Based upon Survey of India map with the permission of the Surveyor General of India.
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The administrative headquarters of Chandigarh, Haryana and Punjab are at Chandigarh.
The external boundaries of India agree with the Record / Master Copy certified by the Survey of India.

Figure 2.3: Geologic map of Punjab, India. Figure reproduced from (Surveyor General of India, 2004).

A seismic survey from Rao, 1973 (Figure 2.4) shows the depth to bedrock trend shown in the Figure 2.2 cross section holds across Punjab, with a basement high of just above 400 meters and a basement low of over 4,000 meters.

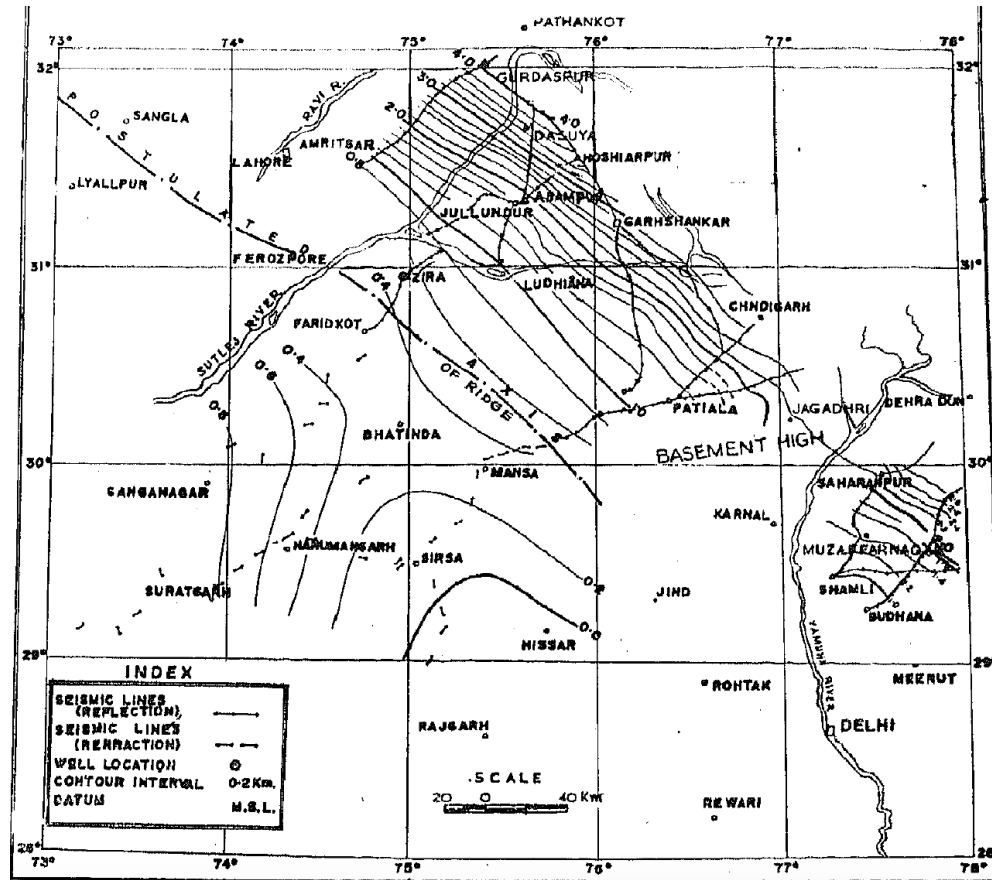


Figure 2.4: Seismic survey results show depth to bedrock across Punjab, India. *Figure reproduced from (Rao, 1973).*

2.3 Methods

The geologic data was compiled from seismic surveys (Rao, 1973) and well data from groundwater surveys (Mahajan, 1995) and the groundwater yearbook (CGWB, 2015) to determine the depth to the various formations discussed above. Based the overall geology of the Indo-Gangetic Plain foreland basin as described in (Singh, 1996), the geology was assumed to change only along the diagonal perpendicular to the Himalayas. A diagonal cross section was developed by projecting each data point from the compiled set onto the diagonal cross section. The overall trends were smoothed to create reasonable curves that resemble the predicted cross sections (Figure 2.2), geophysical surveys (Rao, 1973), and tectonic principles of forelands basins (Singh, 1996). The cross section was extended to the entire state to create the 3-D geologic model. Elevation was modeled from the NASA Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) (NASA, 2016a) and resampled to fit the model grid.

2.4 Results

The geologic data points reveal the overall trend of the Siwalik Formation and the basement rock (Figure 2.5).

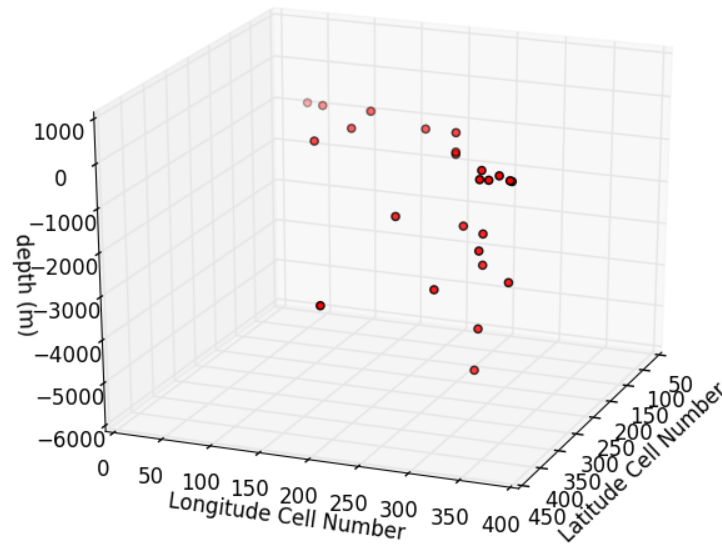


Figure 2.5: Data points for Alluvium and Siwalik Formation geologic data collected and used to generate the cross section.

Once compiled and smoothed, the data was used to generate a cross section, seen in Figure 2.6, where the basement rises slightly then deepens approaching the Himalayas. The Lower, Middle, and Upper Siwalik Formations fill in the basins on both sides of this basement high and are topped with alluvium. Note that the model ends in the foothills of the Himalayas before the elevation quickly increases.

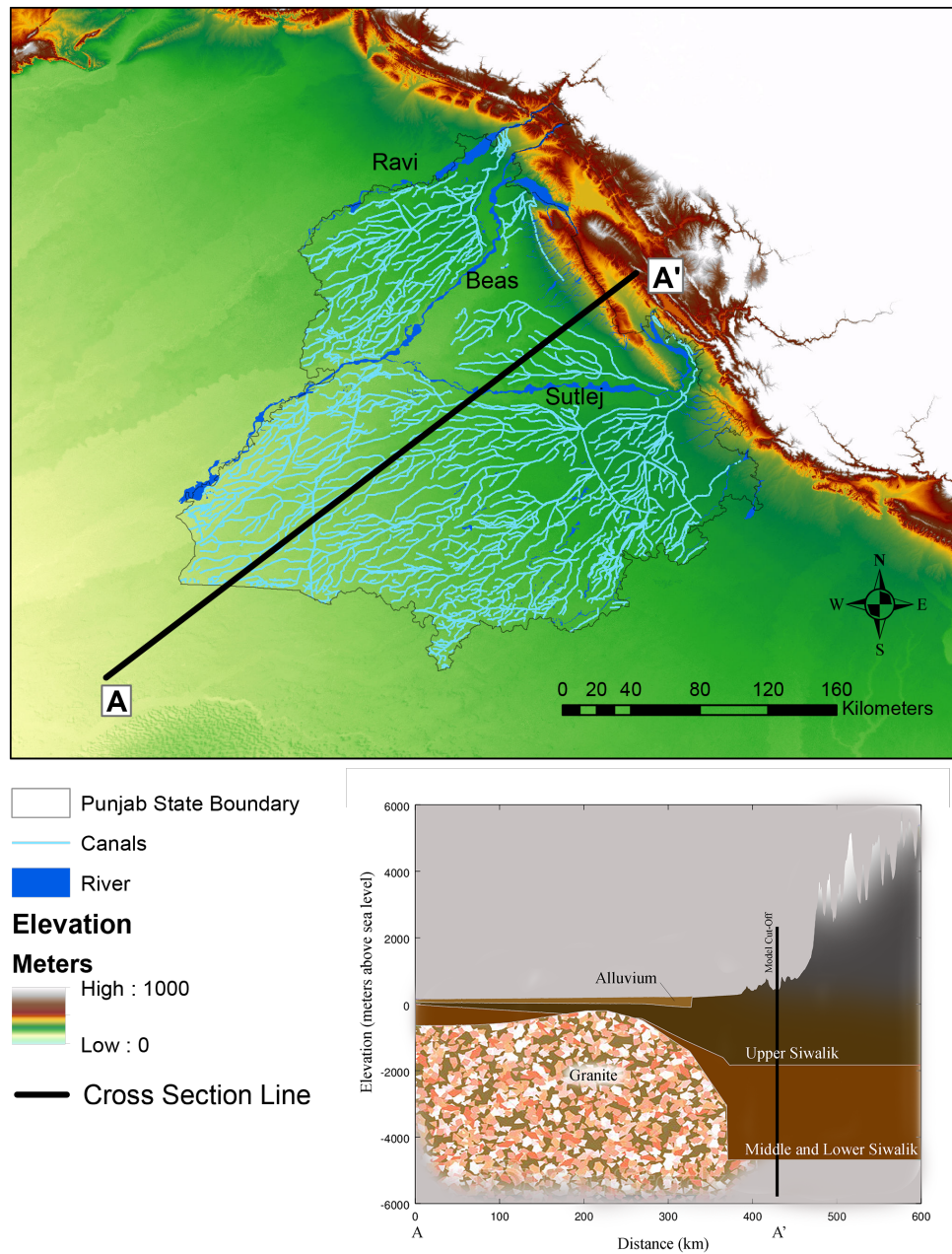


Figure 2.6: Elevation map and modeled geologic cross section *Elevation data from (NASA, 2016a)*

The pattern shown in the cross section was extended to all of Punjab to create this 3D model, Figure 2.7.

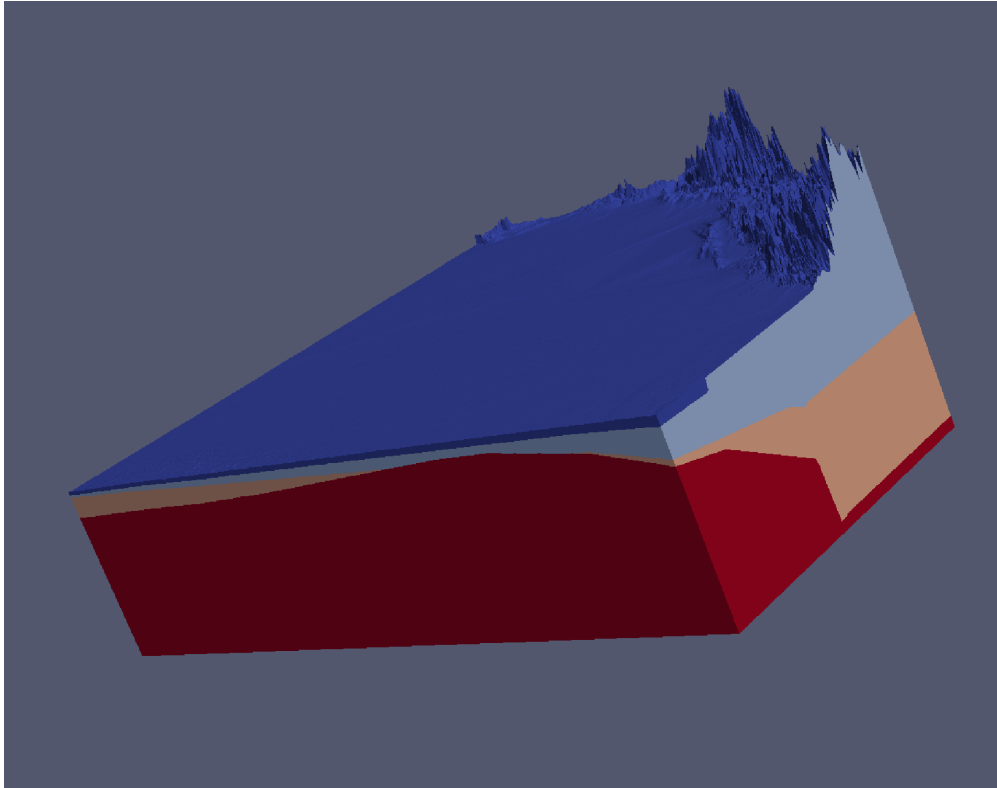


Figure 2.7: 3D model of Punjab Geology

2.5 Discussion

The generated cross section shows the expected geologic structures of a foreland basin as described in (Prothero & Dott, 2010). With the basement rock deepening closer to the Himalayas, the created foreland basin filled with sediments to form the sedimentary Siwalik Formation (Singh, 1996). These Siwalik units of sandstone boulder conglomerates, gravels, sands, and clays are characteristic of fluvial deposits of sediments eroding off of uplifting mountains adjacent to the foreland basin characterized in (Prothero & Dott, 2010). This sediment deposition continues today in deposits of new alluvium.

The basement rock bulges roughly 300 km from the start of the Himalaya foothills. This ridge is likely the forebulge of this foreland basin system, as depicted in Figure 2.8. The DSR ridge appears a bit farther southeast in Figure 2.8 than the ridge revealed in the seismic survey (Figure 2.4). Sediment deposition of the Siwalik Formation continues after this bulge, as seen in the model cross section Figure 2.6.

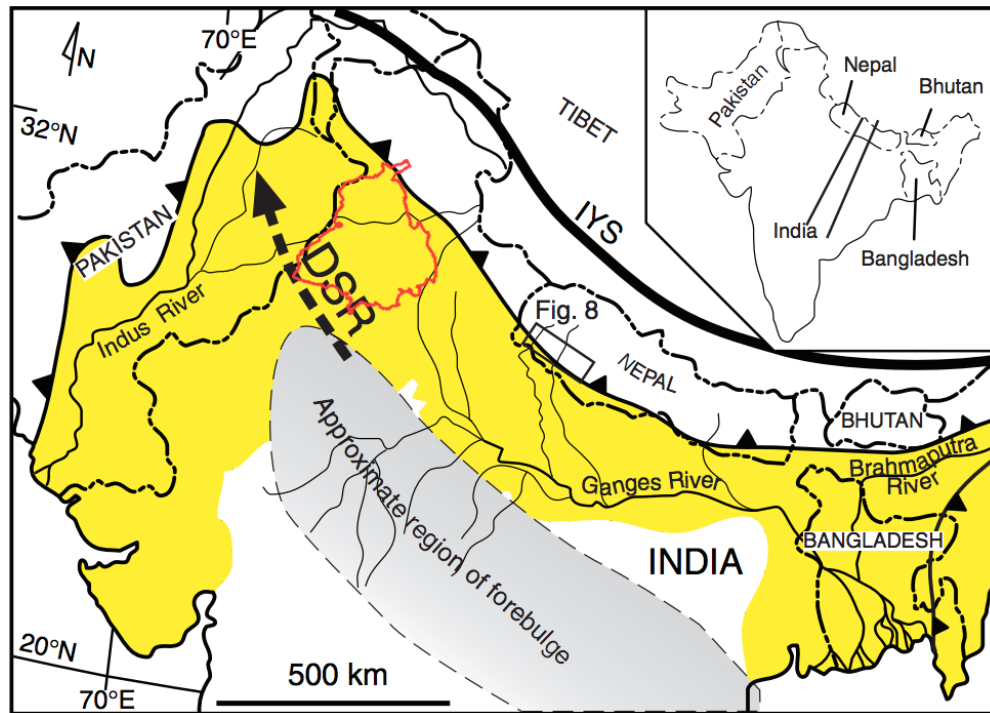


Figure 2.8: Forebulge in the Indo-Gangetic Plain. Yellow depicts the foreland basins associated with Indo-Asian intercontinental collision. The Delhi Sargoda Ridge (DSR) depicted by the dash line is interpreted to be the continuation of the forebulge. Red outlines the state of Punjab, India. *Modified from (DeCelles, 2012)*

The alluvium was modeled to end at 350 km along the cross section even though it likely tapers out closer to the mountains. This simplification was made because cells within the MODFLOW model cannot pinch out over space. Future model runs using HydroLena will capture the gradual thinning of the alluvium layer.

The geologic model reveals the underlying structure of aquifers in Punjab, India. How does this geology influence the movement of surface and groundwater through Punjab? What are the interdependencies between this freshwater and agricultural irrigation?

Humble yourself in the sight of Water
You have to know what she knows

Chapter 3

Punjab Hydrology

3.1 Frameworks

3.1.1 The Hydrology Frame (Russo, 2018)

The hydrologist views the world as a system of processes governing the fluxes, quantity, and quality of water. Knowledge is derived from controlled physical experiments that reveal the physics of fluids and from field tests and observations that reveal real-world relationships and conditions. Hydrologists ask the questions:

- What are the physical and chemical processes governing all parts of the hydrologic cycle?
- How can we simulate (model) these processes more accurately and effectively?
- How are humans impacting these processes?
- How will climate change impact these processes?

In order to develop accurate, complex models, hydrologist use advanced modeling solvers and frameworks. The knowledge generated from this field of study is used to make predictions about hydrologic changes under different forcing terms to inform water management and improve our knowledge of the hydrologic system.

3.1.2 The Applied Mathematics Frame (Zikatanov, 2018)

Mathematicians view the world through math: all natural and social phenomena cannot be completely understood unless the phenomena can be put into a mathematical framework. Applied mathematicians are interested in questions emerging from other disciplines and incorporating mathematical formalism in other fields. Knowledge is discovered through posing questions and solving problems. Since models are aimed at approximating phenomena from the real world, to know something “approximately” means not only to know the approximant (the model) but also to know what is the behavior of the error of approximation.

3.2 Hydrologic Setting

As a result of the Green Revolution, Punjab moved away from crop diversification to a rice-wheat monoculture (Panigrahy et al., 2011; Perveen et al., 2012; Tripathi et al., 2016). In the last 35 years, food grain cultivation in Punjab increased by 62% (24,200 sq km), and rice and wheat output per area increased by 77% (0.14 kg/m²) and 49% (0.21 kg/m²) respectively (Aggarwal et al., 2009). This switch and production growth lead to an increase in number of tubewells from 0.192 to 1.165 million and irrigated area from 71 to 95% of the state between 1974 and 2009 (Aggarwal et al., 2009). The transition to a predominantly rice-wheat agriculture system transformed Punjab from a ‘water-surplus’ to a ‘water-scarce’ state (Perveen et al., 2012).

This irrigation water comes from both surface and groundwater. Rainfall is highly variable and often does not meet the requirements for water intensive crops (Tripathi et al., 2016). Punjab experiences an average 650 mm (250 - 900mm) of rain per year while rice requires 1800 mm of

water per year (Ambast et al., 2006; Baljinder, 2011; Perveen et al., 2012). Therefore, permanent irrigation sources are necessary, including groundwater pumps and canals channeling surface water from rivers and reservoirs (Tripathi et al., 2016). The canal network reaches 94% of all cultivated area (Jalota et al., 2007), yet 72-75% of the farms are irrigated by groundwater (Jalota et al., 2007; Tripathi et al., 2016).

The rate of groundwater extraction vastly exceeds the rate of groundwater recharge. The estimated rate of groundwater storage loss in Punjab is about $1 \times 10^{10} \text{ m}^3/\text{yr}$ (Chatterjee & Purohit, 2009). This depletion is observed in the declining water table across the state, averaging around 0.4 m/yr from 1997 - 2002 (Ambast et al., 2006; Perveen et al., 2012; Russo et al., 2015), 0.75 m/yr from 2002 - 2006 (Perveen et al., 2012) and 0.34 m/yr from 2006 - 2013, as seen in Figure 3.1. The groundwater decline is present in central Punjab, as seen in the comparison between groundwater depth in 1973 (Figure 3.3) and 2003 (Figure 3.4). However, this comparison shows increasing water table elevation in the southwestern corner of the state, in the Bathinda, Jalandhar, Nawan, and Gurdaspur districts.

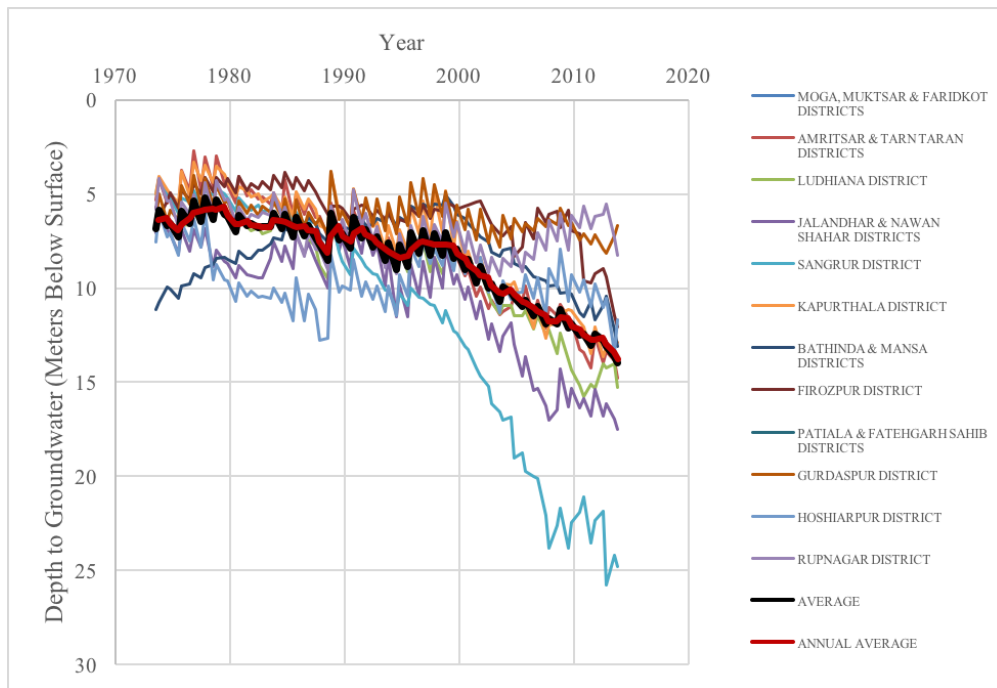


Figure 3.1: Plot of average groundwater depth in each district between 1973 and 2013. Biannual fluctuations result from data points taken before (June) and after (October) the Monsoon. An average decrease in groundwater level from 6.9 meters to 13.4 meters can be seen in red. All districts roughly follow this decreasing trend, but vary in the amount of decline. For district locations, see Figure 3.2. Data compiled from (CGWB, 2013).



Figure 3.2: Map of Punjab districts. *Reproduced from (Punjab Remote Sensing Centre, 2004)*

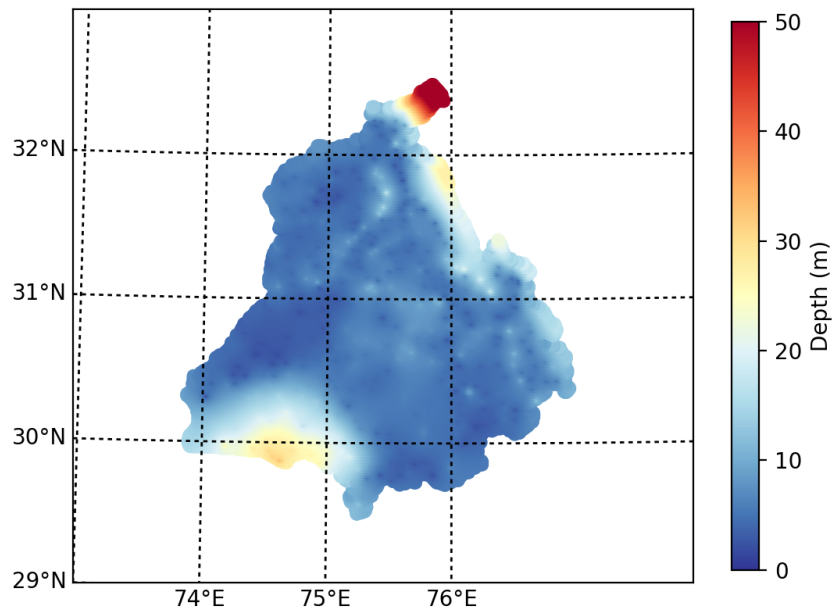


Figure 3.3: Depth to groundwater in 1973. Data from (CGWB, 2013) interpolated over Punjab.

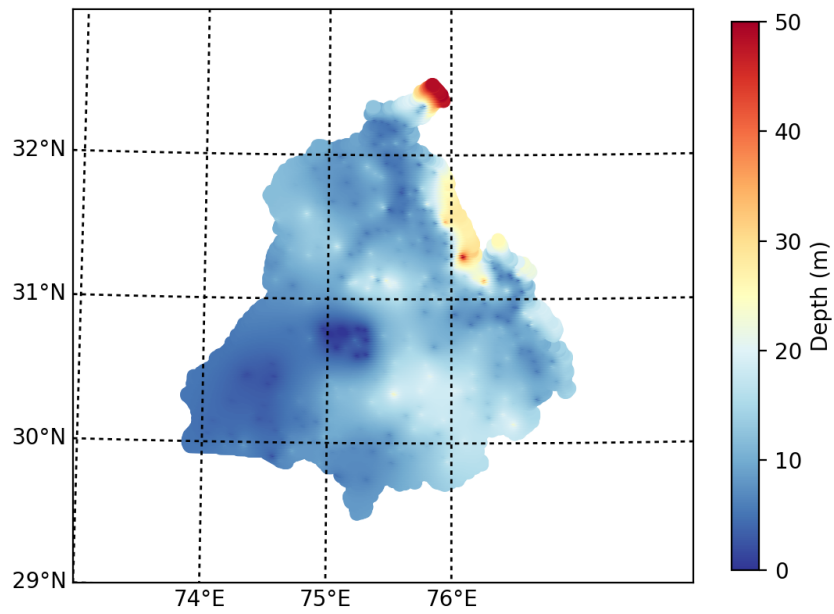


Figure 3.4: Depth to groundwater in 2003. Data from (CGWB, 2013) interpolated over Punjab.

This rising groundwater in the southwest corner of Punjab is highly saline (Figure 3.5). Poor irrigation and drainage techniques have left approximately 28% of irrigated lands in Punjab contaminated with salt (Abbas et al., 2010). Groundwater levels need to be stabilized at the optimal depth of 6-7 meters below the surface where agricultural inputs cannot pollute the water, but farmers can easily access it (Ambast et al., 2006).

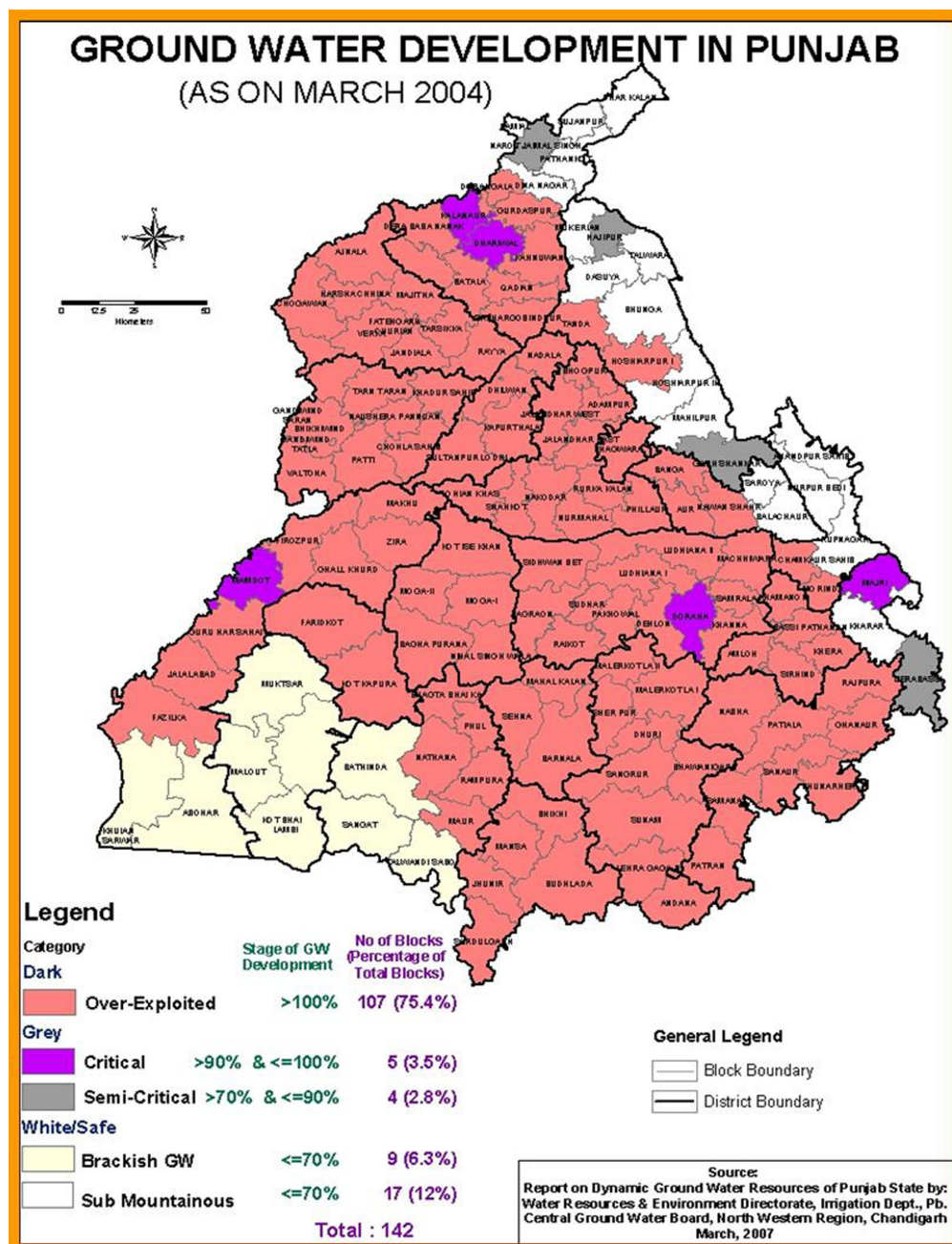


Figure 3.5: Groundwater depletion and contamination severity across Punjab, India. *Figure reproduced from (CGWB, 2007).*

3.3 Methods

3.3.1 Hydrologic Model Inputs and Parameters

- The computational domain for the model is at and below Earth's surface from 29 - 33 degrees North and 73.25 - 77.5 degrees East. The northeast corner of this rectangle is excluded from the model because of the extreme elevation changes of the Himalayas are difficult to model. The input data for the model is interpolated over a 512 by 512 grid.
- Water requirements for each time-step for each cell (I)
- Precipitation - part of the normal components of the flow for the surface cells at the surface elevation ($\mathbf{q} \cdot \mathbf{n} = g$), where g is the precipitation.
- Surface Water - part of the normal components of the flow for the surface cells (incorporated in the right hand side g of the flow boundary condition from the previous item and also the source term W .)
- The head values are specified on east/west and front/back boundaries.
- No flow condition is specified at the bottom surface ($\mathbf{q} \cdot \mathbf{n} = 0$ for the bottom surface)
- The geologic framework described in the previous chapter was used as the structure with different hydrologic parameters for each layer (Table 3.1). The geology model dictates the permeability K for cells in each geologic layer. This is a matrix valued function

$$\bar{K} = \begin{pmatrix} \bar{K}_x & 0 & 0 \\ 0 & \bar{K}_y & 0 \\ 0 & 0 & \bar{K}_z \end{pmatrix}.$$
- Head - $h(x)$ [unit length, meters]
- Specific Storage for each layer: S_s [one over unit length, often m^{-1}], $S_s = 0$ at steady state
- Vertical Anisotropy

Table 3.1: Steady State Hydrologic Model Parameters

Layer	Horizontal Hydraulic Conductivity (m/day)	Vertical Anisotropy	Confining Condition
Alluvium	20	0.1	Unconfined
Upper Siwalik	1	0.1	Unconfined
Middle and Lower Siwalik	0.1	0.1	Unconfined
Basement	0.0001	0.1	Unconfined

3.3.2 MODFLOW

A steady state solution was computed using MODFLOW (USGS, 2016). The goal of the hydrologic model was to develop a model for the alluvial plains of Punjab not accurately represent the groundwater flow from the Himalayas through the state. Therefore, the model was modified to reduce the predicted flooding and match the data by adjusting the maximum elevation of the surface.

All four sides of the model were held at a constant head of 25 meters below the surface. Along the northeast corner boundary, the head was held at 300 meters above sea level. The surface boundary condition was described by recharge from the precipitation. Precipitation was assumed to be 563 mm/year (the average annual precipitation from 1970 - 2010 given by ENVIS, 2012 with 10% recharge recommended by Fetter, 2001. This was run for 1,000 time-steps and plotted using Python.

3.3.3 HydroLena: Adaptive Finite Element Package

In addition to MODFLOW, a finite element package for simulating groundwater flow (HydroLena) was developed using the state-of-the-art discretization and multilevel solvers. A steady state solution was also calculated using HydroLena with the same model parameters as described above, except the groundwater head was capped at 300 meters (rather than capping the elevation) in order to create a non-flooded and accurate model. This solution is compared to the MODFLOW result. Because of the enhanced capabilities of HydroLena, this groundwater model will be used to develop the overall coupled model.

Discretizations and numerical model

The partial differential equation (PDE) describing the pressure heads in an aquifer is as follows:

$$S_s \frac{\partial h}{\partial t} - \text{div } K \nabla h = W, \quad (3.1)$$

with boundary conditions as specified earlier. The computational domain is bounded by surface elevation on the top, a specified depth at the bottom, and a polyhedral domain along its sides determined by the Punjab's borders. On the surface the domain is a union of a rectangle and a quadrilateral with the NE corner cut near Himalayas foothills.

To obtain a quantitative estimates on the depth to groundwater using the pressure heads, the PDE above is discretized. Usually a finite difference, finite volume or finite element method is used to approximate the PDE and such discretizations are called *primal discretization*, because this above is the primal formulation of Darcy's equation.

We used alternative discretizations with exact mass conservation our hydrology model obtained by the mixed form of the PDE. Such models use an additional variable $\mathbf{q}$, which is the *flow*, or the Darcy velocity. This is defined by the constitutive equation: $\mathbf{q} = K \nabla h(x)$ (in meters per day). We then have the following *mixed form* of our problem:

$$S_s \frac{\partial h}{\partial t} - \text{div } \mathbf{q} - W = 0, \quad K^{-1} \mathbf{q} - \nabla h = 0. \quad (3.2)$$

The first of these equations is the mass balance. It is a common requirement in computational hydrology to have this mass balance equation is satisfied exactly after discretization, specifically when discretizing (3.1) or (3.2).

Discretizing the *primal formulation* by (3.1) leads to a positive definite system of equations, which are, in general, easier to solve, although they still require multigrid multilevel methods for efficient solution. Such discretizations in general do not guarantee local mass conservation and require flow approximation to be obtained with post-processing (from h). Therefore this discretization is not as accurate as the mixed method. The mixed method leads to a system of equations that is indefinite twice or even 3 times the size of the system obtained by primal method. This is not a problem for the solver (HX preconditioner) we have implemented in HydroLena as its optimality is guaranteed (see (Hiptmair & Xu, 2007)). The mixed finite element discretizations are used in our software package, HydroLena. In the HydroLena numerical model, the heads $h(x)$ are approximated by function constants w.r.t. on every tetrahedral cell from our mesh. The flux is approximated by a linear function on every tetrahedron in such a way that its normal component of the flux is continuous across every face shared by two tetrahedrons.

Non-dimensionalization

To simplify the coding, we non-dimensionalize the PDE, by introducing a characteristic length scale, L , and a characteristic time scale, T . This also non-dimensionalizes the differential operators. Then, we define the following new variables, which are all unit-less:

$$\begin{aligned} \mathbf{x} &= \frac{\bar{\mathbf{x}}}{L} & t &= \frac{\bar{t}}{T} \\ h &= \frac{\bar{h}}{L} & \mathbf{q} &= \bar{\mathbf{q}} \frac{T}{L} \\ S_s &= \bar{S}_s L & K &= \bar{K} \frac{T}{L} & W &= \bar{W} T. \end{aligned}$$

Plugging in yields the non-dimensionalized equations:

$$S_s \frac{\partial h}{\partial t} - \operatorname{div} \mathbf{q} - W = 0, \quad (3.3)$$

$$K^{-1} \mathbf{q} - \nabla h = 0. \quad (3.4)$$

Thus, we solve the above equations given the dimensionless parameters, then multiply h by L to get $\bar{h}$ and multiply $\mathbf{q}$ by $\frac{L}{T}$ to get $\bar{\mathbf{q}}$, the physical quantities.

After discretization, the approximations to the pressure head values and the fluxes across faces in the mesh are sought as a solution to the following linear system of equations:

$$A\mathbf{Q} + B^T \mathbf{H} = \mathbf{G}, \quad (3.5)$$

$$B\mathbf{Q} = \mathbf{W}. \quad (3.6)$$

Here, the unknown flow (for every face in the mesh) and head values (for every tetrahedron in the mesh) are as follows:

$$\mathbf{Q} = \begin{pmatrix} q_{F_1} \\ \vdots \\ q_{F_m} \end{pmatrix}, \quad \mathbf{H} = \begin{pmatrix} h_{T_1} \\ \vdots \\ h_{T_n} \end{pmatrix}, \quad \mathbf{W} = - \begin{pmatrix} \int_{T_1} W \\ \vdots \\ \int_{T_n} W \end{pmatrix}, \quad (3.7)$$

The components of the vector $\mathbf{G}$ which is m dimensional is given by

$$G_j = \begin{cases} \int_{F_j} \varphi_{F_j} = 1, & \text{if } F_j \text{ is on } \Gamma_D, \\ 0, & \text{if } F_j \text{ is not on } \Gamma_D. \end{cases} \quad (3.8)$$

For the matrices involved in (3.5)-(3.6) we have

$$A_{ij} = \int_{\Omega} (K^{-1} \varphi_{F_j} \cdot \varphi_{F_i}), \quad B_{kj} = \int_{T_k} \text{div } \varphi_{F_j}, \quad (B^T)_{jk} = B_{kj}. \quad (3.9)$$

If the mesh has n tetrahedrons and m faces in the mesh, then A is $m \times m$ matrix, B is $n \times m$ matrix. The linear system has $(n + m)$ equations for the $(n + m)$ unknowns and in matrix form is written

$$\begin{pmatrix} A & B^T \\ B & 0 \end{pmatrix} \begin{pmatrix} \mathbf{Q} \\ \mathbf{H} \end{pmatrix} = \begin{pmatrix} \mathbf{G} \\ \mathbf{F} \end{pmatrix}. \quad (3.10)$$

Discretizing the time dependent problem

For simulating transient processes, currently under development in HydroLena, we use an implicit Crank-Nicolson method with time step τ . In such setting, on every time step we solve the following linear system which is similar to the indefinite system discussed earlier and the same tools are used for its solution.

$$\frac{1}{2} \begin{pmatrix} A & B^T \\ B & -\frac{2S_s}{\tau} M \end{pmatrix} \begin{pmatrix} \mathbf{Q}^{(k+1)} \\ \mathbf{H}^{(k+1)} \end{pmatrix} = \begin{pmatrix} \mathbf{G}^{(k+1/2)} \\ \mathbf{W}^{(k+1/2)} \end{pmatrix} - \frac{1}{2} \begin{pmatrix} A & B^T \\ B & \frac{2S_s}{\tau} M \end{pmatrix} \begin{pmatrix} \mathbf{Q}^{(k)} \\ \mathbf{H}^{(k)} \end{pmatrix}. \quad (3.11)$$

Here, $\mathbf{Q}^{(k+1)} \approx \mathbf{q}$ approximates the flux at time $t_{k+1} = (k + 1)\tau$ and $\mathbf{H}^{(k+1)} \approx h$ approximates the values of the heads at the same point in time. Also, M is the $n \times n$ diagonal matrix.

HydroLena Summary

Although we currently have only run steady state models to simulate the groundwater flow in Punjab, let us summarize some of the features in HydroLena in comparison to MODFLOW (USGS, 2016) and ParFlow (Colorado School of Mines et al., 2018).

1. **Basic discretization:** In HydroLena we have irregular, locally refined grids and do full 3D Darcy flow. Similar features are also present in MODFLOW albeit the adaptive mesh refinement is less robust. HydroLena can handle anisotropies not aligned with the coordinate directions because we use finite element model unlike both Parflow and MODFLOW which are both based on finite differences.

2. **Mesh adaptation:** In HydroLena, we have implemented Adaptive Mesh Refinement (AMR) in any spatial dimension (2D, 3D, 4D, ...). In 3D, we can refine grids over areas of importance, such as the state boundaries and specific groundwater wells. An example showing AMR around the wells in Punjab is shown in Figure 3.6 In 4D, we can solve space-time as one system because time is just another independent variable. Such AMR is not present in either ParFlow or MODFLOW.

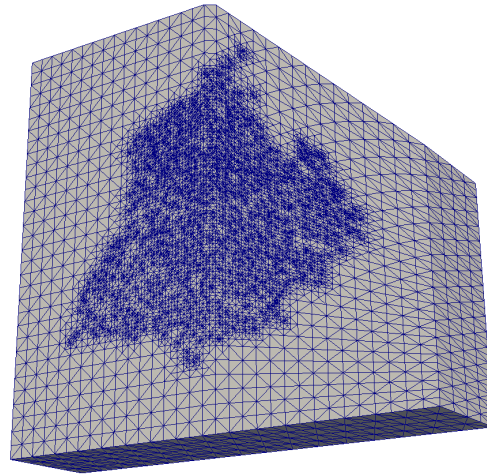


Figure 3.6: Locally refined grid around the wells in Punjab. The grid is refined 18 levels from $5 \times 5 \times 5$ initial grid.

3. **Robustness:** HydroLena can have different permeability in every cell, allowing layers to effectively pinch out and disappear in the model. The current ad-hoc mesh generation needs some improvement to be more flexible so that it can be used at different sites around the world. This is currently being implemented in MODFLOW and is difficult to implement in the ParFlow framework.
4. **Mass conservation:** HydroLena has mass conservation not only cell by cell but also in any volume in the computational domain because it uses a cell based mixed FE model. The mass conservation in MODFLOW and ParFlow Finite Difference models has the conservation cell by cell. In addition to the mixed FE, we plan to implement a conservative and monotone primal discretization on tetrahedral grids. Monotone refers to discretization that guarantees that in absence of sources/sinks the max and min of the head will be on the boundary.
5. **Solvers:** We have implemented efficient multilevel solver for definite problems (on par or better than MODFLOW and ParFlow). In addition, HydroLena has a solver for indefinite systems from mixed method (better than MODFLOW and ParFlow).

3.4 Results

We present steady state computations using both MODFLOW and HydroLena numerical models. Both models were compared to the groundwater interpolated head values in 1973, a dataset that most-accurately captures groundwater depths prior to intensive groundwater pumping (Figure 3.7). These heads have higher elevations to the northeast and lower elevations to the southwest ranging from 300 meters to 150 meters. This variation in depth suggests groundwater flows from the higher elevations in the northeast across the state to the southwest. Angular lines present in this interpolation result from the NASA SRTM DEM used to calculate head values from recorded depths to groundwater. Some of these lines correspond to rivers, but some appear to be a projection error in the DEM file.

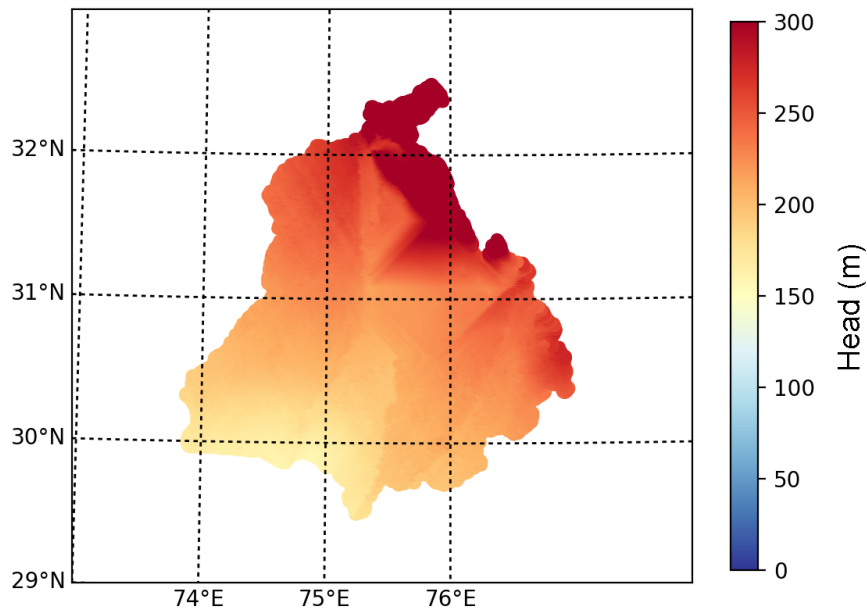


Figure 3.7: Groundwater head in 1973 *Data from (CGWB, 2013) and interpolated over Punjab*

MODFLOW Steady State Solution The MODFLOW steady state groundwater model of Punjab (Figure 3.8) is similar to the actual head values in 1973 (Figure 3.7) show a range of head values from 300 meters in the northeast corner to just under 200 meters in the southwest corner. This suggest a flow direction from high heads in the northeast to lower heads in the southwest. The MOFLOW model predicts higher heads in the southwest corner of the state than observed in 1973.

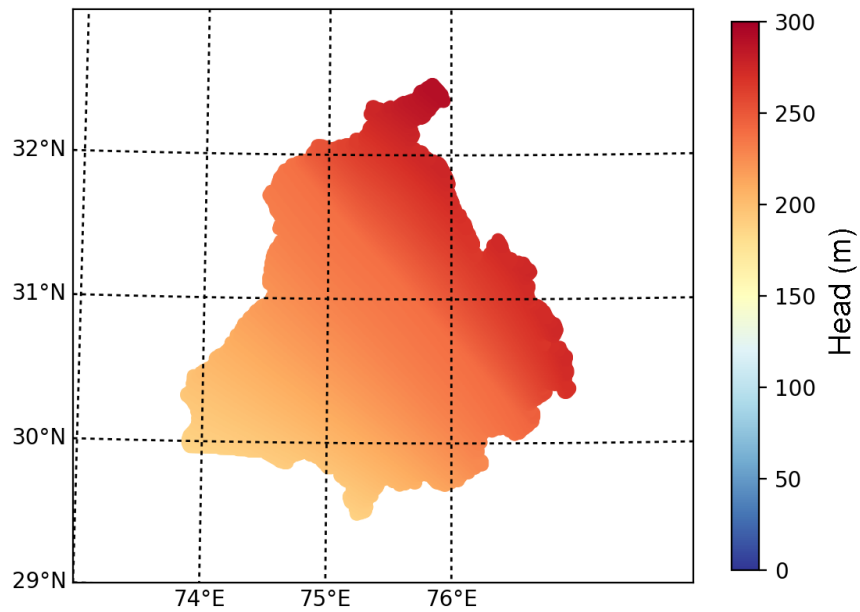


Figure 3.8: MODFLOW steady state solution groundwater heads when the elevation was capped at 300 meters above sea level.

HydroLena Steady State Solution The HydroLena steady state solution shows a transition from groundwater head at 250 meters above sea level in the northeastern part of the state to 100 meters above sea level in the southwestern part of the state (Figure 3.9). This trend and elevation is similar to the 1973 groundwater data presented in Figure 3.7 and the resulting flow direction from northeast to southwest across the state. The line crossing diagonally across the state matches with the cut-off of the alluvium layer.

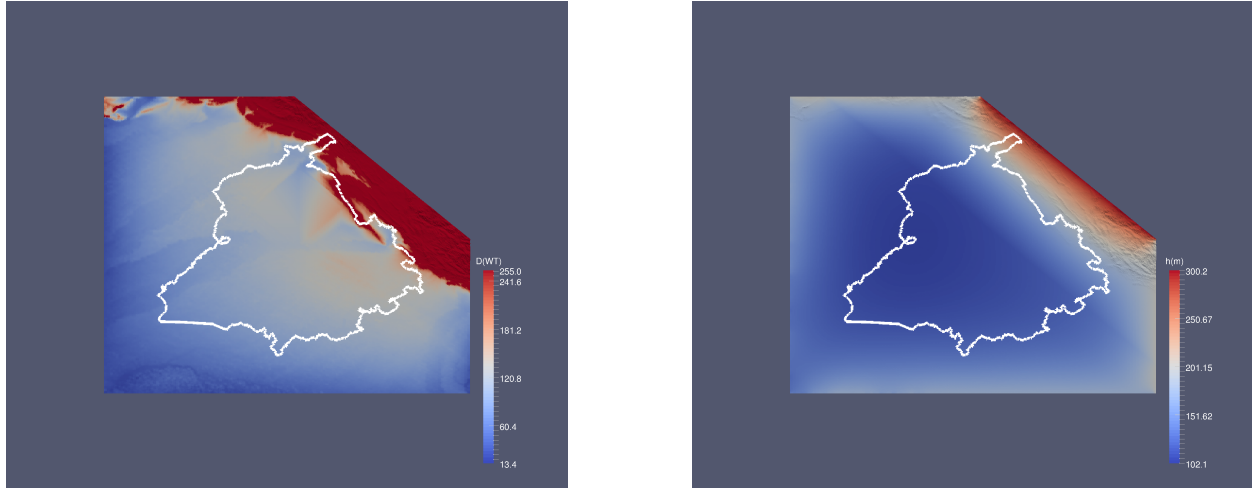


Figure 3.9: HydroLena steady state solution results: depth to water table ($D(wt)$) and head ($h(m)$) plots plot in 2D with Punjab outline.

Both MODFLOW and HydroLena produce steady state solutions with similar head values to groundwater data from 1973. The models predict the general flow direction from the Himalayas and southwest across the state. Both models struggled to model groundwater flow given the dramatic increase in elevation at the foothills of the Himalayas. In both models, this elevation change resulted in flooding at the based of the foothills or even across the state depending on the boundary conditions. To reduce the flooding, the elevation was capped at 300 meters in the MODFLOW model and the groundwater head was capped at 300 meters in the HydroLena model. These tricks kept the model from predicting an excess in water flowing onto the plains of Punjab causing flooding and instead allowed the model to accurately represented the physical system described in the data.

3.5 Discussion

The Alluvium and the Upper Siwalik make up the groundwater reservoir for Punjab given the low hydraulic conductivity of lower units (Table 3.1). If the average decline of 0.4 m/yr continues across all of Punjab, this reservoir (about 100m deep) will be depleted in roughly 180 years.

According to these models, groundwater head prior to pumping was a uniform gradient from high in the northeast to low in the southeast across Punjab. This is drastically different than the groundwater table today with cones of depression reaching 25 meters below the surface elevation in 2013 (Figure 3.1). This steady state model can be improved through evaluating the sensitivity of these models to changes in the capped elevation and maximum groundwater head. Furthermore, the northwest corner of the model could be cut off more to exclude any significant increase in elevation at the foothills.

A sensitivity analysis should also be done with variations in the geologic layer depths and parameters for both MODFLOW and HydroLena. Given the uncertainty of both the geologic unit layers and their properties. Additionally, this sensitivity analysis could determine the effect of the back bulge and the alluvium cut-off on groundwater levels. Based on the sensitivity analysis,

the geologic model should be reconstructed to reflect the more realistic geology (with alluvium pinching out) that also reflects the appropriate uncertainty with the geologic information.

The next steps include adding surface water from both the river and canal network and agricultural pumping and irrigation. This transient model will be calibrated with the historical data from 1973 - 2013 and run into the future to determine the future rate of decline under the current system. Then, this hydrologic model will be coupled with the agricultural model and economic model to consider more complex questions about the interconnected system: How does agriculture drive change in groundwater depth? What relationships are present in the historical data? What are the predicted effects of different cropping systems going forward?

*Humble yourself in the sight of Plants
You have know what they know*

Chapter 4

Punjab Agriculture

4.1 Agriculture Framework

An agricultural scientist views the world as an ecological equation and relationships of system inputs and system outputs. Knowledge is derived from field and lab experimentation across many disciplines and areas of focus. In general, an agricultural scientist ask the questions:

- What inputs are required to produce the desired crop at the maximum yield and maximum efficiency?
- What variables and ecological system components reduce the total yield of a given crop?
- How does the agricultural field interact with the larger ecological system?

This knowledge is used to help farmers produce crops more efficiently with greater yields, in order to provide food for people around the world.

4.2 Agriculture Setting

The state moved away from crop diversity to a rice-wheat monoculture in the 1970s (Panigrahy et al., 2011; Perveen et al., 2012; Tripathi et al., 2016) when higher-yielding rice and wheat crop varieties were introduced. This agricultural advancement was part of the Green Revolution, a revolution that substantially increased global food supply and food security (Giordano, 2009). As a result of the Green Revolution, grain cultivation in Punjab increased by 62% (24,200 sq km), and rice and wheat output per area increased by 77% (0.14 kg/m²) and 49% (0.21 kg/m²) respectively between 1974 and 2009 (Aggarwal et al., 2009).

Permanent irrigation sources are necessary such as surface water canals and groundwater pumps because rice and wheat water requirements are not met by the highly variable rainfall in Punjab (Tripathi et al., 2016). The rate of groundwater extraction in Punjab exceeds the groundwater recharge rate by about 10¹⁰ m³/yr (Chatterjee & Purohit, 2009). Extreme groundwater overdraft in Punjab threatens to undo the gains in agricultural production and food security established by the Green Revolution (Abrol, 1999; Badiani et al., 2012; Russo et al., 2015).

4.2.1 Cultivated Area

Net cultivated area in Punjab increased between 1973 to 2006, and the major crops grown have changed, seen in Figure 4.1. Cotton, maize, and wheat were the dominant crops in 1973, but rice and wheat gained dominance by the late 1970's. Most noticeably, the cultivated area of rice has significantly and steadily increased to 450% from 1973 to 2006. At the same time, cultivated area of groundnut, bajra, maize, gram, and cotton steadily declined. Groundnut, bajra, and gram accounted for roughly 10% of the cultivated area in 1973 and only accounted for 0.1% in 2013.

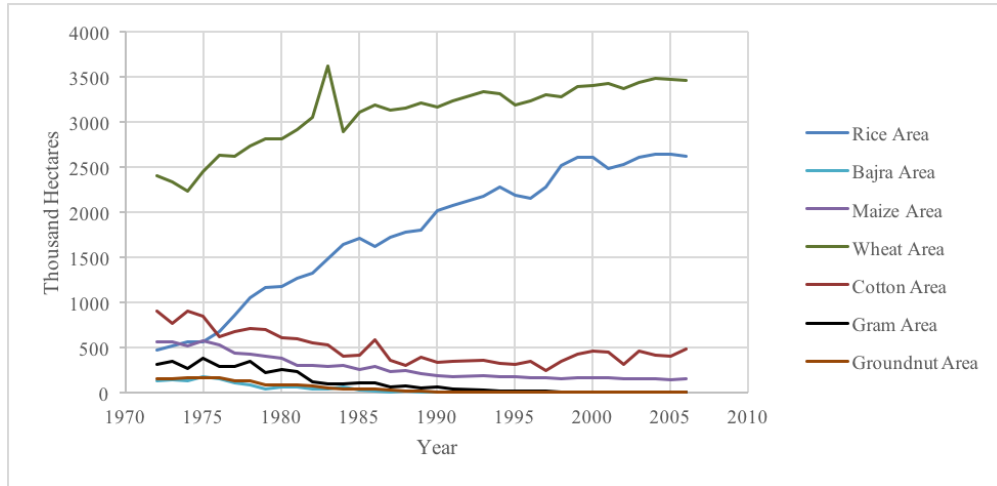


Figure 4.1: Plot of cropped area for major crops in Punjab, India from 1973 to 2006. *Data from (Vatta, 2015).*

4.2.2 Soil Moisture

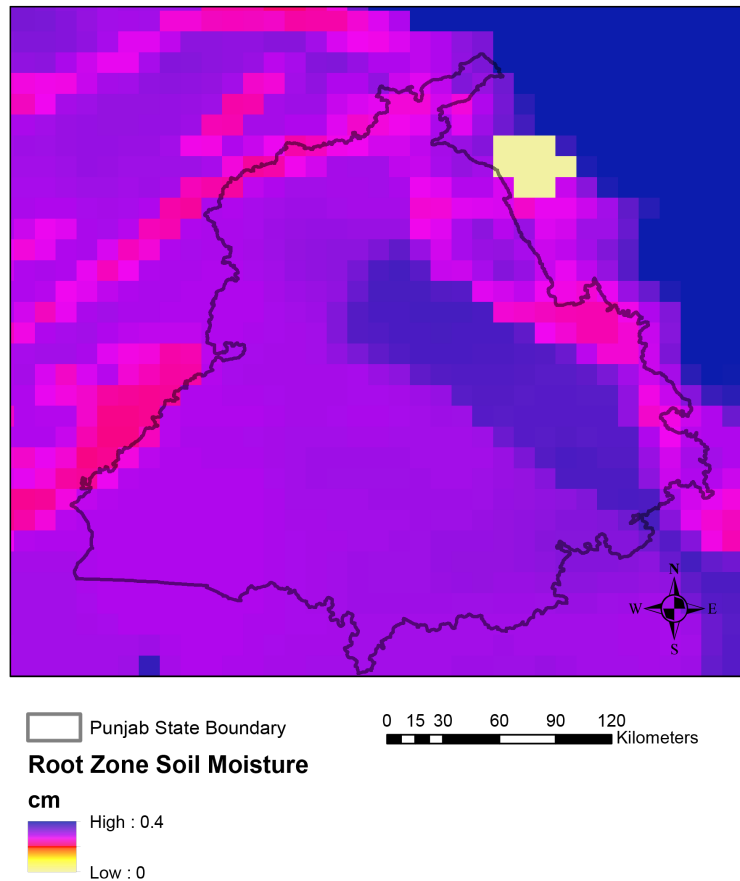


Figure 4.2: Soil moisture across Punjab, India on June 10, 2016. *Data from (NASA, 2016b).*

Root zone soil moisture is not uniform across Punjab, ranging from 0.1 to 0.3 cm out of a 1 m soil profile. Figure 4.2 depicts soil moisture in June (2016) before the intense monsoon rains of the summer.

4.2.3 Irrigated Area and Precipitation

Groundwater, precipitation, and irrigated area trends are shown in Figure 4.3. Average groundwater depth across India steadily declined (CGWB, 2013) while annual precipitation fluctuated substantially (RIHN & MRI/JMA, 2016). A steady decline in precipitation was observed from 1997 to 2003 (RIHN & MRI/JMA, 2016). Net irrigated area also increased by 1190 thousand hectares between 1970 and 2003, and irrigated rice area increased by 2250 thousand hectares between 1970 and 2003 (Vatta, 2015). Overall, groundwater declined as net irrigated area increased (Vatta, 2015) and annual precipitation decreased (RIHN & MRI/JMA, 2016), as seen in Figure 4.3.

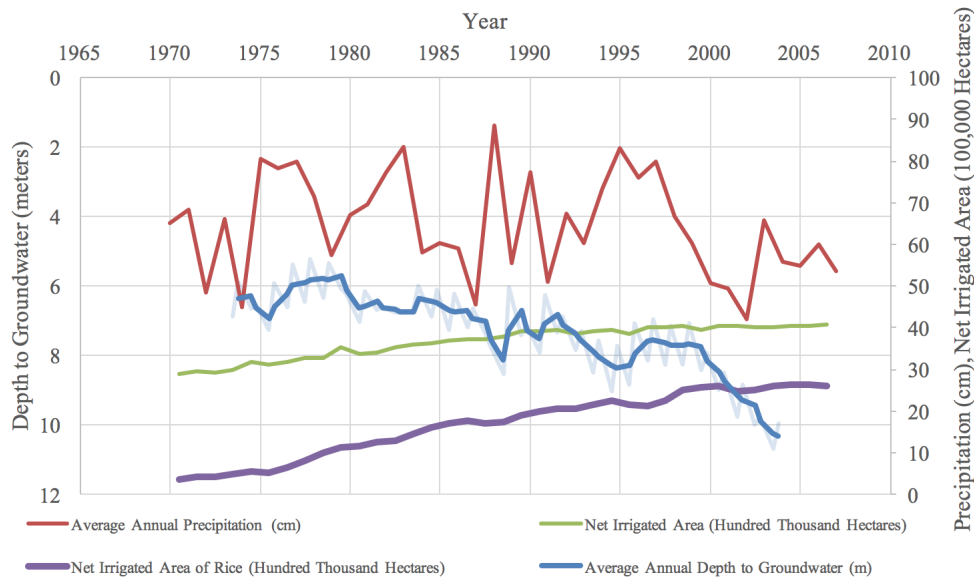


Figure 4.3: Plot of average depth to groundwater, average annual precipitation, and net irrigated area in Punjab India between 1970 and 2006. Both the depth to groundwater and net irrigated area increase over these 40 years, while precipitation decreases. *Data from (RIHN & MRI/JMA, 2016; Vatta, 2015; CGWB, 2013).*

4.3 Methods

The agriculture model calculates the water used in crop production at a given time-step. During the hydrologic model calibration, this model will calculate the water required to irrigate the crops grown over the time-step based on cropping area and yield records. With a calibrated hydrologic model, this agricultural model will calculate the water required to produce the most optimal crops under future climactic conditions. A preliminary agricultural model was creating using R to estimate the groundwater volume pumped since 1973 based on cropping information.

Inputs

- Crops Grown
- Crop Yield
- Rainfall
- Evapotranspiration or Temperature
- Soil Type
- Crop Coefficient

Variables

Table 4.1: Agricultural Model Variables

Symbol	Variable
I	Irrigation Requirement
Et_o	Evapotranspiration
T	Temperature
K_c	Cropping Coefficient
P	Rainfall
Pe	Effective Rainfall
S	Water needed to saturate the root zone
L	Rate of water lost through percolation and seepage
W	Water needed to establish water layer for flood irrigation
Y_a	Actual Crop Yield
Y_x	Max Crop Yield
K_y	Yield Response to Water

Effective Rainfall (Brouwer & Heibloem, 1986)

According to the Food and Agriculture Organization of the UN (FAO) guidelines, Pe is calculated at a monthly time-step:

$$Pe(P) = \begin{cases} .8P - 25 & P > 75mm/month \\ .6P - 10 & P < 75mm/month \end{cases}$$

Evapotranspiration

Evapotranspiration records are used when available (Russo, 2016). For model runs simulating future scenarios, evapotranspiration will be calculated using temperature:

Blaney-Criddle Formula (Brouwer & Heibloem, 1986)

$$Et_o = p(0.46T_{mean} + 8)$$

1. p = mean daily percentage of annual daytime hours

Table 4.2: Mean daily percentage of annual daytime hours at 30 degrees latitude in the Northern Hemisphere

Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
.24	.25	.27	.29	.31	.32	.31	.30	.28	.26	.24	.23

2. T_{mean} = mean daily temperature ($^{\circ}\text{C}$)

$$T_{mean} = \frac{T_{max_{average}} + T_{min_{average}}}{2}$$

Field Crop Irrigation Requirement (Brouwer & Heibloem, 1986)

At each time-step:

$$I = Et_o * K_c - Pe$$

Crop Timing

Table 4.3: Crop Timing (NFSM, n.d.)

Crop Name	Category	Growing Season
Rice	Cereal	Kharif
Wheat	Cereal	Rabi
Maize	Cereal	Rabi
Barley	Cereal	Rabi
Sorghum/Jowar	Fodder	Rabi
Bajra/Pearl Millet	Fodder	Kharif
Gram/Chickpea	Pulse	Kharif
Masur/Lentil	Pulse	Rabi
Kidney Bean	Pulse	Rabi
Mash	Pulse	Kharif
Pigeon Pea/Tur	Pulse	Kharif
Ricebean	Pulse	Kharif
Groundnut	Oilseed	Kharif
Rapeseed and Mustard Seed	Oilseed	Rabi
Linseed	Oilseed	Rabi
Soybean	Oilseed	Kharif
Sunflower	Oilseed	Kharif
Safflower	Oilseed	Rabi
Cotton	Fiber	Kharif

The Kharif season extends from April through October and is characterized by the monsoonal rains. The Rabi season extends from November through March with little rain.

Paddy Rice

Since rice is grown with flood irrigation, the crop water requirements are significantly different than other field crops.

Fixed water requirements for each planting season (Brouwer & Heibloem, 1986)

$$I_{fixed} = S + W$$

The water needed to saturate the root zone at the start of planting (S) is dependent on the soil type. The FAO recommends estimating this value at 200mm. A layer of water is required to flood irrigate the rice (W). The FAO suggests this value should be 100mm. Seepage and percolation water losses are accounted for in the variable water requirements.

Variable water requirements for each planting season (Brouwer & Heibloem, 1986)

$$I_{variable} = Et_o * K_c - Pe + L$$

The percolation and seepage losses (L) are dependent on the soil. Heavy clay soils have a loss rate of 4 mm/day. Sandy soils have a loss rate of 8mm/day. Average soils have a loss rate of 6mm/day. All of Punjab was assumed to have average soils.

Imperfect Yield

The calculations above assume the farmer is providing the crop with the water required for the crop to reach the maximum yield. However the recorded yields are consistently much lower than maximum yield. Lower yields are the result of many factors including nutrient deficiencies, poor climate, and inadequate irrigation. For this model, we assume that all yield deficits are the result of irrigation deficit. Therefore, the effective crop water use is calculated with this formula (Steduto et al., 2012):

$$(1 - \frac{Y_a}{Y_x}) = K_y(1 - \frac{ET_{actual}}{ET_{max}})$$

Round K_y to 1 for rice, wheat, pulses, and oilseeds for simplification (Steduto et al., 2012).

$$\frac{Y_a}{Y_x} = \frac{ET_{actual}}{ET_{max}}$$

$$Et_o = \frac{I + Pe}{K_c}$$

$$\frac{Y_a}{Y_x} = \frac{I_{effective} + Pe}{I_{max} + Pe}$$

To calculate volume of water used for irrigation based on historical yield data:

$$I_{effective} = \frac{Y_a}{Y_x} * (I_{max} + Pe) - Pe$$

To calculate yield based on modeled water volume:

$$Y_a = Y_x \frac{(I_{effective} + Pe)}{I_{max} + Pe}$$

Maximum Yield

Because crop varieties and agricultural techniques/technologies are constantly improving, the maximum potential yield of a given crop is not static, but increasing. This change was estimated from studies tracking the trends in maximum potential yield increases and extrapolated linearly backwards in time.

Table 4.4: Maximum Yield Values for Modeled Crops Over Time

Crop	Present Maximum Yield	Maximum Yield Growth	Maximum Yield Equation	Source
Rice	2010	7.1 t/ha	1.1%	$Y_x = 0.0639(year) - 121.51$ (T. Fischer et al., 2014)
Rabi Wheat	2011	7 t/ha	0.4%	$Y_x = 0.026(year) - 45.226$ (T. Fischer et al., 2014)
Maize	2014	6 t/ha	1.1% $Y_x = 0.0529(year) - 100.64$	(T. Fischer et al., 2014)
Jowar/Sorghum	2010	1.9 t/ha ¹	0.04% ²	$Y_x = 0.0071(year) - 12.296$ (T. Fischer et al., 2014)
Bajra/Pearl Millet	2010	1.44 t/ha ³	0% ⁴	$Y_x = 1.44$ (T. Fischer et al., 2014)
Barley	2010	3.74 t/ha ⁵	0.8% ⁶	$Y_x = 0.0259(year) - 48.248$ (T. Fischer et al., 2014)
Gram (type of Chickpea)	2010	1.86 t/ha	0.7%	$Y_x = 0.0111(year) - 20.494$ (T. Fischer et al., 2014; Bhatia et al., 2006)
Groundnut/Peanut	2006	2.54 t/ha	0% ⁷	$Y_x = 2.54$ (Bhatia et al., 2006)
Rapeseed and Mustard (Canola)	2010	1.47 t/ha ⁸	1%	$Y_x = 0.0122(year) - 23.166$ (T. Fischer et al., 2014)
Sunflower	2010	2.47 t/ha ⁹	0.7% ¹⁰	$Y_x = 0.0171(year) - 31.587$ (T. Fischer et al., 2014)
Cotton	2008	1.22 t/ha ¹¹	0% ⁷	$Y_x = 1.22$ (Bhatia et al., 2006)

¹ Estimated as twice the farmer yield, because actual farmer yield studies in Australia show maximum potential yield is roughly twice actual farmer yield. (T. Fischer et al., 2014)

² Estimated as the same rate of increase as the actual farmer yield. (T. Fischer et al., 2014)

³ Maximum actual farmer yield listed for millet. (T. Fischer et al., 2014)

⁴ No estimates on potential yield or the rate of change of potential yield. (T. Fischer et al., 2014)

⁵ World actual farmer yield for barley time the experimental yield gap in the UK. (T. Fischer et al., 2014)

⁶ Maximum potential yield gap rate of change in the UK. (T. Fischer et al., 2014)

⁷ No data.

⁸ India farmer yield multiplied by the yield gap measured in the UK. (T. Fischer et al., 2014)

⁹ World actual farmer yield times 100% average farmer yield gap. (T. Fischer et al., 2014)

¹⁰ Maximum potential yield increase in France.

¹¹ Estimated from modeled max yield in Bijapur, Karnataka, which has similar rainfall. (Bhatia et al., 2006)

Surface Water Component

Punjabi farmers irrigate with both surface water and groundwater. Reservoirs such as the Bhakra Reservoir, Ranjit Sagar Dam Lake, and the Beas River Dam store water at the head of the Sutlej, Ravi, and Beas rivers in the Himalayan foothills along the northeast boundary of the state. An extensive canal network channels water from these rivers across that state, as seen in Figure 4.4. Not much data is available for channel and river discharge, but surface water volume used for irrigation will be estimated based on available data in the final hydrologic model.

Groundwater is necessary to supplement this surface water in order to sufficiently irrigate the crops. The ratio between the area irrigated by groundwater and the total irrigated area for each crop was used to estimate the volume of irrigation water from groundwater. The dataset of area irrigated with groundwater was provided by Vatta 2015. Area listed as irrigated by groundwater was assumed to receive no surface water irrigation.

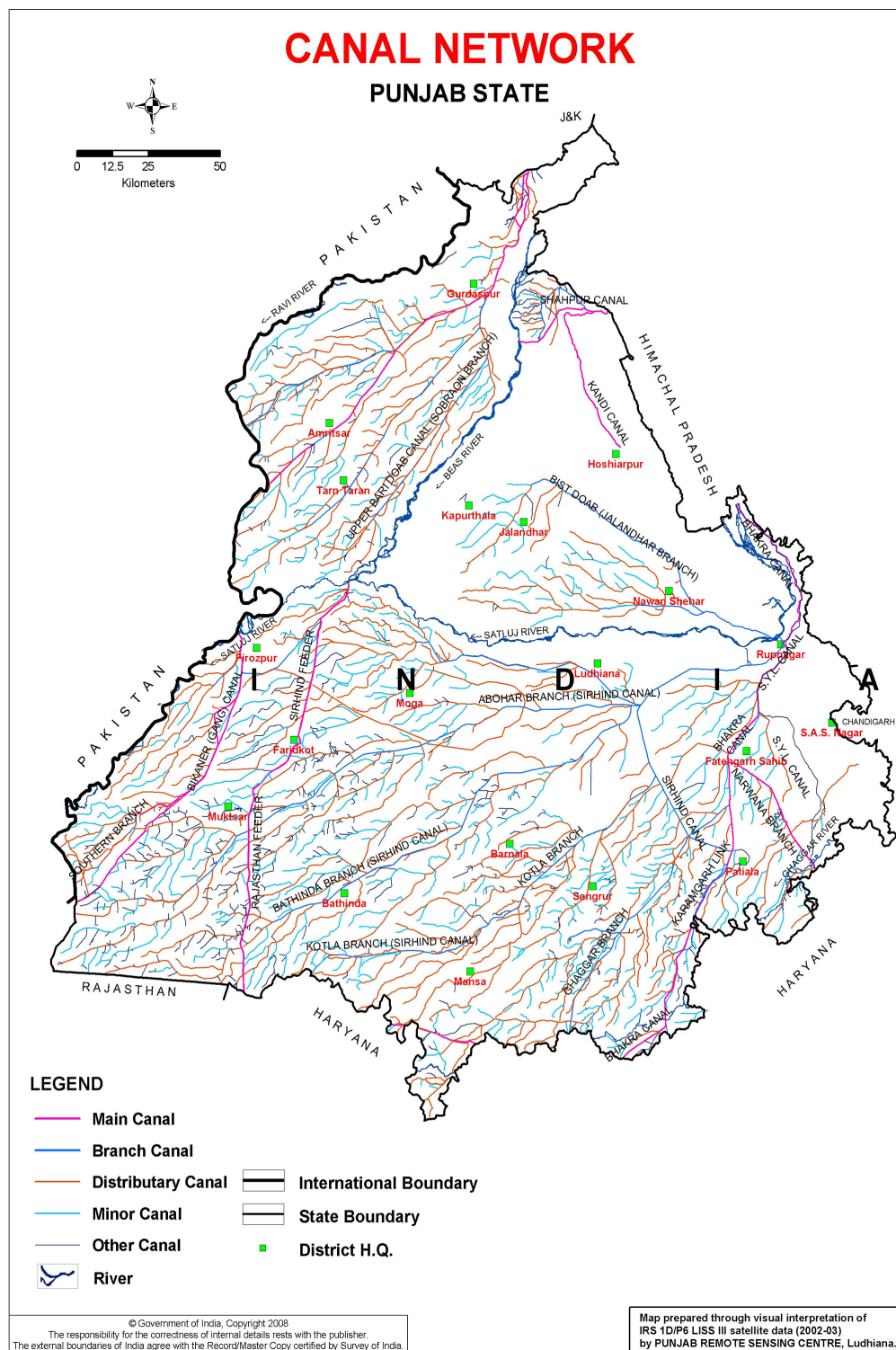


Figure 4.4: Punjab, India canal network. *Figure reproduced from (Punjab Remote Sensing Centre, 2002).*

4.4 Results

Modeled average daily water requirements for rice, wheat, and pulses are compared with average daily precipitation for Punjab in Figure 4.5. Rice requires the most water, significantly more than the average rainfall, requiring up to 7mm of irrigation water per day. Wheat needs less water than rice, but still requires irrigation when grown in Punjab in the Rabi season, requiring up to 2 mm of water per day.

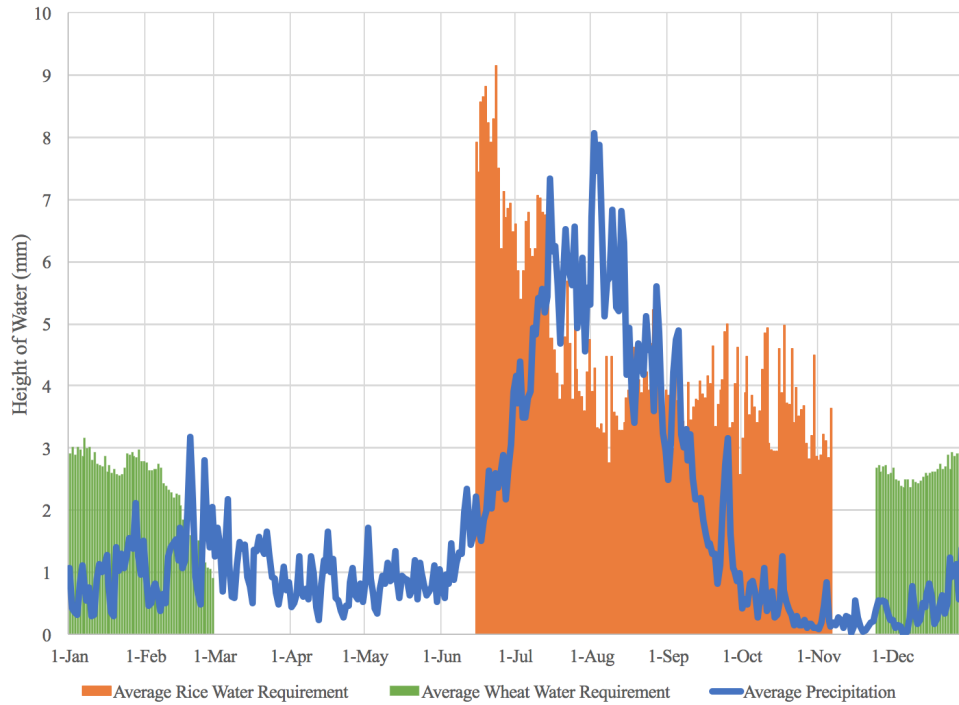


Figure 4.5: Average daily water requirements for typical rice-wheat rotation compared with average daily precipitation in Punjab, India. Precipitation data averaged from 1970 - 2004. Water requirements calculated from (Vatta, 2015) and precipitation data from (RIHN & MRI/JMA, 2016).

Other crops grown throughout Punjab, India require different amount of irrigation (Figure 4.6). This irrigation height was calculated by subtracting the daily precipitation from the water requirements for each crop, one step in the agricultural model. The precipitation used for this calculation was an average from 1973 - 2004 (RIHN & MRI/JMA, 2016). Farmers flood irrigate rice in Punjab, so it requires an initial spike in irrigation water height. The overall irrigation requirement for rice is more than double the requirement for other crops. Cereal and fodder crops grown in the Rabi season (brown to orange colors on Figure 4.6) require similar amounts of irrigation. Maize requires the least amount of irrigation followed by wheat and then barley. Pulses and oilseeds grown in the Kharif season (green and blue colors on Figure 4.6) require similar amounts of irrigation, all less than half the irrigation water required for paddy rice.

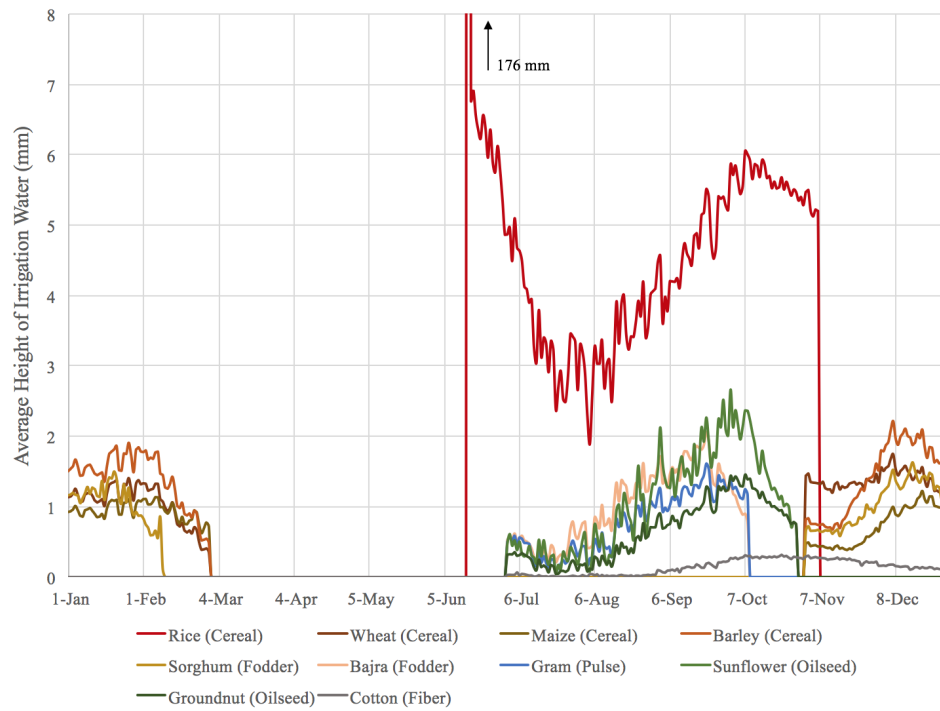


Figure 4.6: Average daily irrigation requirements for the crops in Punjab, India. *Data calculated from (Vatta, 2015).*

Based on the historical cropping data, the agricultural model predicts an increasing rate of groundwater pumping. This corresponds with the observed depth to groundwater decline, as seen in Figure 4.7. Specifically, the groundwater depth exhibits the same peaks and valleys as groundwater pumped with a lag time of 1-3 years. The most groundwater was pumped for rice, compared to any other crop.

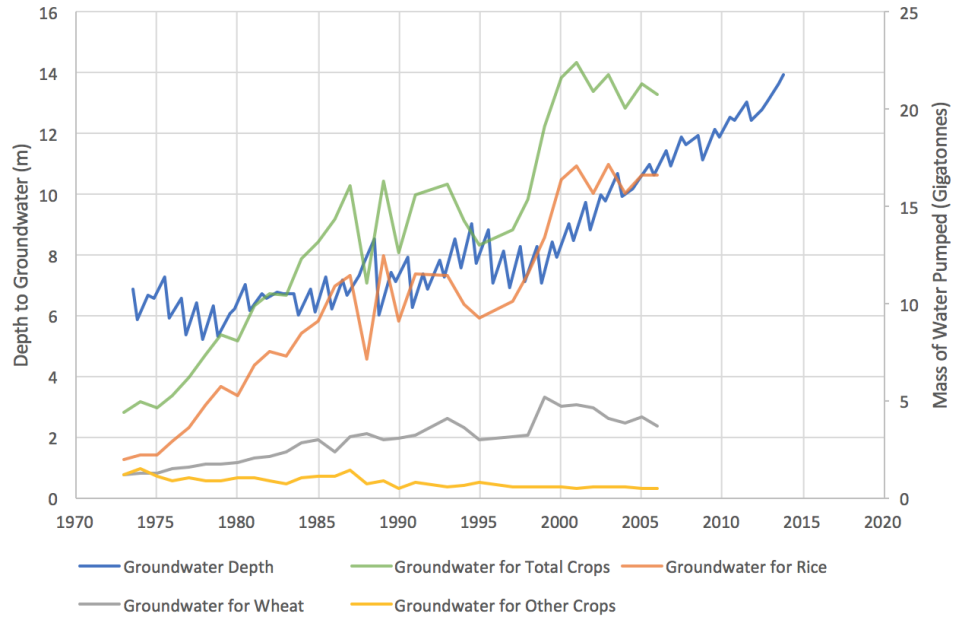


Figure 4.7: Calculated mass of groundwater pumped compared to groundwater depth.

Based on the model equations, the agricultural model shows groundwater consumption as inversely proportional to the precipitation, as seen in Figure 4.8.

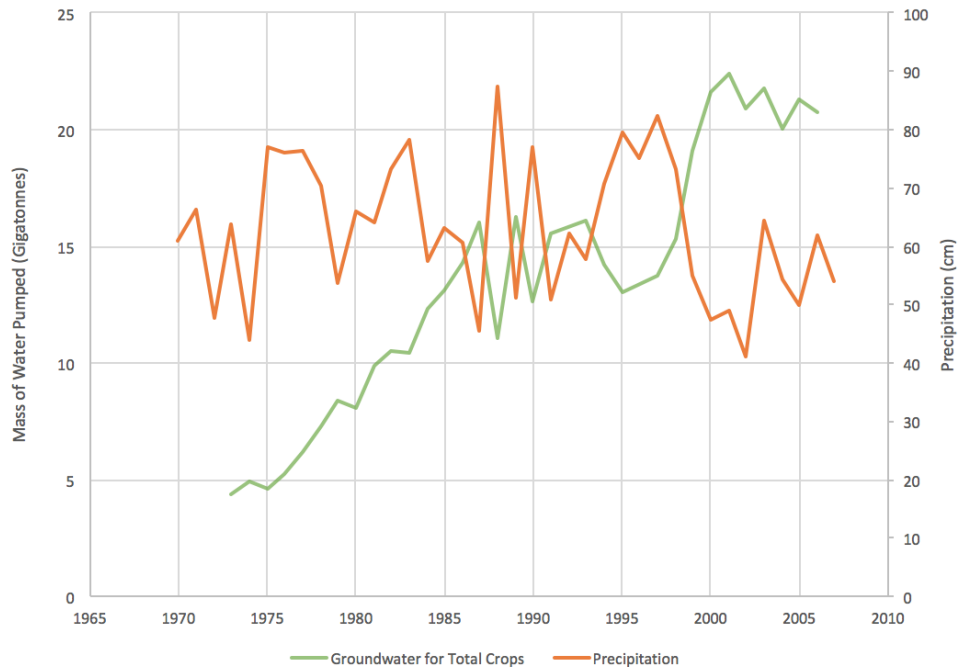


Figure 4.8: Groundwater pumped compared to annual average precipitation. *Data calculated from agricultural model and plotted from (RIHN & MRI/JMA, 2016).*

4.5 Discussion

Total groundwater loss: The agricultural model calculates a total of 430 gigatonnes of groundwater pumped out of the aquifers of Punjab from 1973 to 2006. This model calculates a bit over 20 gigatonnes of groundwater was extracted annually around 2000 - 2005, matching estimates from GRACE Satellite data that predicts 20 ± 7 gigatonnes of groundwater was extracted per year from 2003 - 2012 (Chen et al., 2014). However, Chen et al., 2014 calculates closer to 29.4 ± 8 gigatonnes of groundwater from 2003 - 2007. Therefore, this agricultural model may underestimate the mass of groundwater pumped by a few gigatonnes, but large uncertainty in the GRACE data obscure the accuracy of this model. It is likely this agriculture model does not capture the complete inefficiencies in irrigation and therefore underestimates the water pumped. For instance, this model does not account for water lost as groundwater recharge during water transport and irrigation. Future agricultural models should include these sources of water loss.

According to the basic principles of the hydrologic cycle, some of this water has recharged back into the aquifer, but the rest has left the local groundwater system through runoff, evaporation, crop transpiration, and integration into the final crop yield, as described by (Fetter, 2001). The depletion rate exceeds the recharge rate, causing a significant net decline in groundwater that has cumulated over time. This decline is compensated by increased sea level rise.

Around the world, a significant amount of groundwater used for irrigation evaporates and enters the atmospheric hydrologic cycle. A large portion of this moisture precipitates over the ocean, contributing to sea level rise. Models show anthropogenic land-use change and groundwater mining causes 0.9 ± 0.5 mm/yr of sea level rise (Gornitz, 2001) with groundwater depletion causing 0.035 ± 0.009 mm/yr sea level rise in 1900, 0.57 ± 0.09 mm/yr sea level rise in 2000, and 0.82 ± 0.13 mm/yr by 2050 (Gornitz, 2001). For comparison, the average sea level rise was 3.2mm/yr in 2013 (Jones, 2013). Therefore, freshwater stored in the Punjab aquifer is transferred to saltwater in the ocean increasing sea level and decreasing our overall freshwater supply.

Precipitation: The agricultural model explains the relationship between precipitation and groundwater observed in Figure 4.3 where peaks in groundwater levels appear 1-3 years after a peak precipitation year. The steady decline in annual precipitation between 1997 and 2003 may have contributed to the increased rate of decline around the turn of the century. The spatial variation in groundwater pumping and precipitation are not modeled since the data was averaged over the entire state. Furthermore, spatial variation in soil type and soil moisture as shown in Figure 4.2 were not accounted for due to spatial averaging in this preliminary model. Because, the groundwater volume pumped was calculated for each day from 1973 - 2006 then summed to get the annual extraction volume, daily variations in rainfall were captured in the model but are averaged in the plots. Consequently, the intricate interdependencies between rainfall, groundwater pumping, and groundwater decline are not captured in Figure 4.7. The final coupled model will consider the groundwater volume pumped, precipitation, and groundwater depth at a monthly and district level resolution to capture more fine-scale details.

This model must consider the general pattern of precipitation over time due to climate change. Annual precipitation fluctuates considerably and varies between data sources (Figure 4.3). A general decline starts in 1997 through 2006, however annual variability could explain this. Other studies show a decline in annual rainfall across Punjab (Aggarwal et al., 2009), with an increase in

frequency and magnitude of extreme rain events during the monsoon from 1951-2000 (Goswami et al., 2006). Reductions in regular precipitation can increase groundwater use and decrease aquifer recharge, further exacerbating groundwater overdraft (Famiglietti, 2014). These irregularities over time are captured within the current model because crop water requirements are calculated for each day, then totaled for the year. However, the coupled model will run on monthly time steps, so considerations must be made to include the change in high-intensity rainfall events rather than just averages.

Inefficiencies: In addition to cropping choices and climate change, inefficient water management practices cause unnecessary groundwater depletion. Water transport for irrigation results in 60 - 70% water loss (Aggarwal et al., 2009; Kaur et al., 2009) due to unlined channels and improper housing of tube-wells (Kaur et al., 2009). Agricultural water use efficiency could be improved through sprinkle or drip irrigation, zero-till practices, mulching (Aggarwal et al., 2009), dry seed rice cultivation, and precision agriculture methods (Jalota et al., 2007). In 2009, the Government of Punjab enacted The Punjab Preservation of Subsoil Water Act prohibiting farmers from planting rice during the hottest part of the year. Results from a 2016 study concluded that groundwater depletion rates significantly decreased as a result of this act (Tripathi et al., 2016). Overall, the farmer's lack of both awareness and technology is the main cause for water-use inefficiency (Kaur et al., 2009).

These technologies have the potential to reduce water consumption, but overdraft in Punjab cannot stabilize with these improvements alone (Fishman et al., 2015). To slow Punjab's aquifer decline, its government needs to consider policy changes to incentivize water conservation (Jalota et al., 2007). But, what drives cropping decisions? What economic decisions are farmers making? What policies govern this economic situation and what alternative policies could be in place to produce a different outcome?

*Humble yourself in the sight of People
You have to ask them what they know*

Chapter 5

Punjab Economics

5.1 The Environmental Economics Frame (Zipp, 2018)

Economists view the world through economic agents (people, households, firms, governments, etc.) making tradeoffs to maximize objectives. If everyone can optimize their objectives at the same time, then the world is in equilibrium where no one has an incentive to change their behavior. However, this usually cannot happen because of externalities, imperfect information, lack of private markets (e.g. public or common property goods), market distortions, etc. Environmental economists ask the questions:

- How do economic agents incorporate the environment and natural resources into their decisions?

How does the behavior of economic agents lead to environmental and resource externalities (such as pollution and over-extraction of natural resources)?

How do economic agents make tradeoffs between environmental services and market goods and thus reveal their preferences for environmental goods?

How do economic agents use common property resources differently than private property resources?

How do economic agents react to environmental policies?

- How should economic agents incorporate the environment and natural resources into their decisions?

How should environmental and resource externalities be internalized (e.g. through market solutions such as taxes or governance)?

How should public goods and common property goods be provided (e.g. through privatization or through governance)?

Before answering these questions, environmental economists need to know how environmental and resource outcomes change over time and space due to natural fluctuations, human actions, and climate change. They also need to know the institutional framework structuring the market. From this framework of interdependencies and rights, economics knowledge is discovered by observing agents' tradeoffs or asking questions about hypothetical tradeoffs. Economic models of constrained optimization (under budget and/or time constraints) are used to better understand agents' value structures. Environmental economists then judge whether or not total welfare in society is being maximized or if policies are needed to improve the efficiency of natural resource extraction or environmental pollution/consumption management. Environmental economists strive to aid and abet the efficient allocation of resources. To some this means advocating for the free market allocation of resources. Others recognize the existence of market failures and aim to design policies to correct these failures.

5.1.1 Institutional Setting

Laws of groundwater ownership: Under the 1882 Indian Easement Act, landowners have the right to collect and dispose of all water that passes on or through their land, linking land ownership

to groundwater ownership (IELRC, 1882; Suhag, 2016). Beyond this law, the Indian constitution sets groundwater under the management of each state (Cullet, 2014; Pandey, 2014; Suhag, 2016). With increased groundwater use starting in 1970, the insufficiencies of the 1882 law for equitable groundwater allocation became apparent. So, the national government proposed a Model Groundwater Bill which they periodically updated and encouraged states to replicate (Zaidi, 2007; Cullet, 2014). This model bill restricted groundwater use for new groundwater users, while allowing current groundwater use and direct ownership of the resource to continue (Cullet, 2014). Only 7 out of 29 states enacted versions of this bill due to concerns over potential declines in farmer welfare (Zaidi, 2007). Not even Punjab, the state experiencing the most severe groundwater overdraft, successfully implemented the law.

Government subsidies: Besides institutions surrounding groundwater ownership, the government instituted policies incentivizing agricultural production, which helped to spur the Green Revolution and massive groundwater overdraft (Badiani et al., 2012). The Punjab government instituted minimum support prices for rice and wheat to incentive their cultivation in order to increase the country's food security (Perveen et al., 2012). They also subsidized electricity for farmers, so they could pump groundwater with little to no cost (Jalota et al., 2007; Perveen et al., 2012).

Performance outcomes: As a result of these government subsidies and the structure of private groundwater ownership, food production, food security, and farmer incomes all increased, but groundwater resources were depleted (Badiani et al., 2012). Consequently, farmers incur higher irrigation costs to drill deeper wells and invest in new technology, skewing the system in favor of wealthier farmers (Reddy, 2005; Badiani et al., 2012; Tripathi et al., 2016). Based on the previous influence of government policies, new legislation incentivizing water conservation and water-use efficiency has ability to create a sustainable system (Jalota et al., 2007; Aeschbach-Hertig & Gleeson, 2012).

Punjab initially passed the Punjab Ground Water Control and Regulation Act in 1998 modeled after the national government's Model Groundwater Bill, only to reject it in 2003 because it imposed hardships on farmers (Parikh et al., 2007; Zaidi, 2007). But, the state government has taken action in other ways. They have looked to promote crop diversification, large scale artificial recharge, electricity supply reforms, micro-irrigation, and alterations in the cropping calendar (Parikh et al., 2007; Zaidi, 2007; Pandey, 2014). In 2009, Punjab adopted the Punjab Preservation of Sub-Soil Water Act, preventing paddy transplantation before June 10th (Bharat, 2015; Tripathi et al., 2016). Tripathi et al. 2016 showed a significant reduction in groundwater decline as a result of this act, but the continued increase tubewells caused an overall net decline in groundwater despite this law.

Changes in groundwater consumption and water-use efficiency structured through laws may help stabilize groundwater levels. Punjab faces the challenge of finding a balance among water consumption, farmer income, and food production to ensure future food security (Aeschbach-Hertig & Gleeson, 2012) (Jalota et al., 2007). Reducing the groundwater consumption today prevents the enormous negative costs of scarce freshwater resources in the future (Jalota et al., 2007).

Model Sustainable Groundwater Management Act: The national government recognized the failure of the previous institutions, so they drafted a Model Sustainable Groundwater Management

Act in 2011 that recognized the shared nature of groundwater by breaking away from the individual appropriation of this resource outlined in the 1882 Indian Easement Act (Cullet, 2014). Instead of private ownership, this act declares groundwater a public resource to be protected and preserved for all people by the government (Suhag, 2016). According to the 1991 Indian Supreme Court decision, clean water is a fundamental human right, so this model law creates binding standards for provision of water quality and quantity (Cullet, 2014; Suhag, 2016). It declares everyone has a right to sufficient, clean drinking water and that nobody can use groundwater in such a way that adversely affects any person's right to safe water for life (IELRC, 2016). Each user is responsible for ensuring their own efficient groundwater use without contamination, but the state is the public trustee of groundwater responsible for managing use to first meet "the right to water for life, followed by allocation for achieving food security, supporting sustenance agriculture, sustainable livelihoods and eco-system needs" (IELRC, 2016).

Furthermore, this act strengthens local control on the resource by creating an institutional structure of Groundwater Sub-Committees within the Village Water and Sanitations Committee with the power and function to "protect and manage groundwater resources under this Act" (IELRC, 2016). Municipality, district, and state agencies are also created to oversee the ground-up groundwater management (IELRC, 2016). This act also integrates protection, conservation, regulation, and management of both groundwater and surface water rather than separating these issues and ignoring the complex interdependencies within the hydrologic and governance systems (Cullet, 2014; IELRC, 2016).

As of 2016, 11 states have adopted and implemented parts of this groundwater legislation (Suhag, 2016), but none have enacted a comprehensive solution to the problem (Cullet, 2014). Despite serious groundwater overdraft, Punjab has not enacted this legislation (Pandey, 2014). In 2017, the Punjab Groundwater Protection, Regulation and Development Act was proposed to create Groundwater Management Plans at local levels with major stakeholders, reduce the industrial and commercial consumption of groundwater, mitigate against saline water intrusion, and increase irrigation efficiency (Hasan, 2017). The state is also considering incentives for increasing crop diversity and reforms to the agricultural power sector (Pandey, 2014).

Local rule experimentation: During the 2018 Kharif season, the Punjab government is experimenting with alternatives to subsidized electricity for agricultural use in three villages (Chaba, 2018). In this experiment, they plan to pay farmers each the averaged individual cost of the electricity subsidy upfront (Rs 48,000) and then charge the farmers the full price for electricity at the pump. This system incentivizes water conservation because farmers can keep the remaining subsidy funds unused for electricity at the end of the season (Chaba, 2018).

5.1.2 Crop Prices

Market prices of rice and wheat in Punjab have steadily increased between 2002 and 2012, with little variation in yearly price, as seen in Figure 5.1 (DIM, 2013). In comparison, potato and spinach prices in Punjab fluctuate from year to year and vary more between different markets across Punjab.

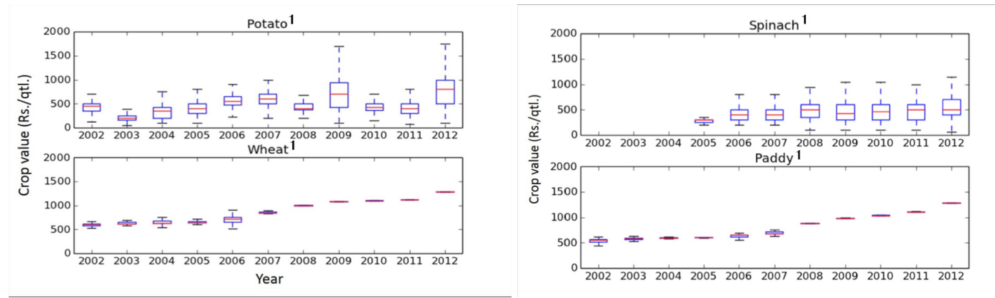


Figure 5.1: Plots of crop market prices in Punjab, India from 2002 to 2012. *Plots curtsey of T. Russo. Data from (DIM, 2013).*

In comparison, international rice and wheat prices show more fluctuation in price than rice and wheat prices in Punjab, India. Figure 5.2 shows that both international rice and wheat prices spike in 2008 in response to the global financial and economic crisis and other contributing factors (Wiggins et al., 2010). However, rice and wheat prices in Punjab experience no price spike in 2008.

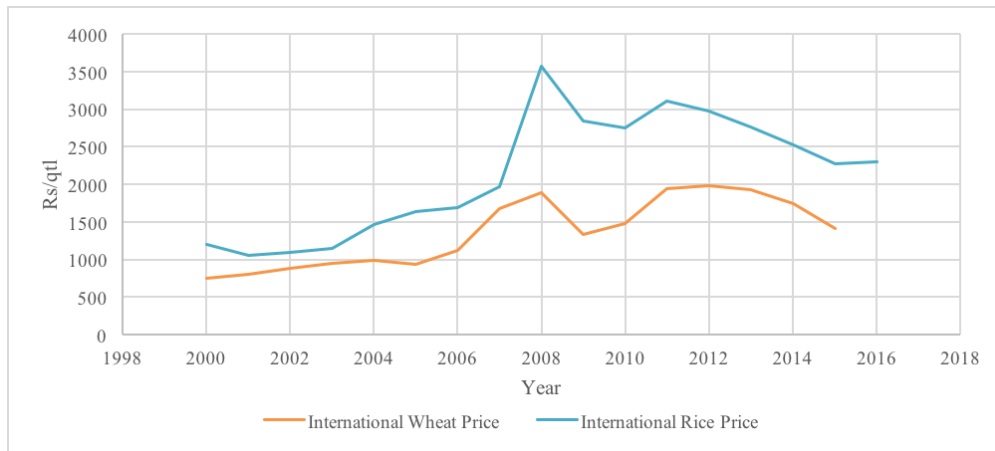


Figure 5.2: Plot of international rice and wheat prices. *Data from (FAO, 2009)*

The government uses these minimum support prices to incentivize the cultivation of rice and wheat, high-yield, yet water-intensive crops to improve the country's food security (Perveen et al., 2012). Currently, 15% of the Indian population is undernourished, lacking staple foods like rice and wheat (Kozicka et al., 2016). While support food security, these minimum support prices have reduced crop diversity (Perveen et al., 2012). Increasing crop diversity through alternative, less water-intensive crops would reduce groundwater stress (Brahmanand et al., 2013; Fishman et al., 2015; Russo et al., 2015). Farmers could even earn greater profits if they switch to oil seeds and pulses, both of which require less water (Brahmanand et al., 2013) but may not contribute to India's food security. To encourage farmers to switch, the government could consider supporting these alternative water-efficient crops instead of rice and wheat (Jalota et al., 2007). Demand for rice and wheat could still be met by the re-distribution of these crops to regions that could support their water demand (Brahmanand et al., 2013), such as eastern India (Chatterjee & Purohit, 2009). Though, political and cultural differences between regions may impose challenges to this re-distribution.

5.1.3 Electricity Prices

Electricity is used to power groundwater pumps. Farmers use diesel generators to power the groundwater pumps during electrical blackouts. The average consumer cost for electricity in Punjab, India is roughly 64% of the total unit cost of power, as seen in Figure 5.3. However, the price of electricity for agricultural use has most often been completely subsidized except for in 1995 and 2010. Agricultural consumption of electricity increased from 1996 to 2000.

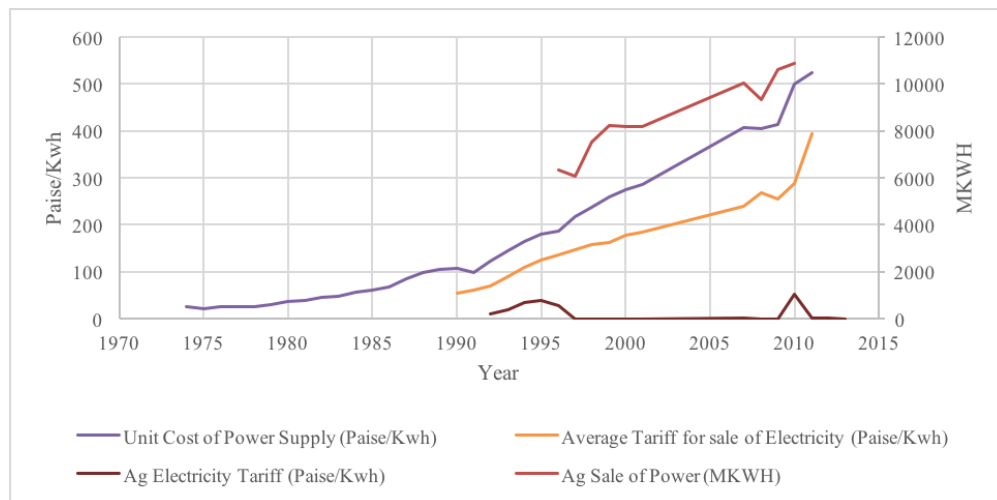


Figure 5.3: Plot of cost, price, and consumption of electricity in Punjab, India between 1973 and 2013. The average electricity cost for residents of Punjab has increased along with the unit price. However, the cost of electricity for farmers has not changed and is often free. Agricultural consumption of electricity has increased over time. *Data from (Planning Commission, 2013).*

Currently, Punjab completely subsidizes electricity for irrigation to incentivize agricultural production (Jalota et al., 2007; Perveen et al., 2012), costing the State Electrical Board \$6 billion US dollars in 2001 (Badiani et al., 2012). Since this subsidy went into effect, irrigated land has doubled, with a majority of the water sourced from groundwater (Badiani et al., 2012). Farmers feel little monetary incentive to conserve water, since they do not pay a cost per volume pumped when using electricity (Jalota et al., 2007; Perveen et al., 2012).

Poor electrical infrastructure further complicates the problem. Since electricity companies receive no revenue from rural areas, they do not invest in rural infrastructure. Consequently, electricity in rural areas is unreliable with long, inconsistent blackouts and high voltage fluctuations (Perveen et al., 2012). These blackouts trigger farmers to leave their groundwater pumps running continuously to ensure the pumping of adequate irrigation water (Perveen et al., 2012). High voltage fluctuations frequently damage groundwater pump motors, adding to the costs faced by farmers (Perveen et al., 2012). The state recognizes that farmers would be willing to pay for electricity if it was higher quality with reduced voltage fluctuations and blackouts (Planning Commission, 2013). However, no recent changes have been made (Planning Commission, 2013).

Removing the irrigation subsidies would encourage farmers to decrease groundwater use (Jalota et al., 2007; Fishman et al., 2015). Sustainable extraction rates could be achieved by taxing the electricity used for groundwater extraction at rates that reflect the true environmental and social costs of groundwater depletion (Jalota et al., 2007; Fishman et al., 2015). One study shows that

increasing electricity prices by about two-thirds would decrease agricultural output by 13% (Badiani et al., 2012). Removing irrigation subsidies would also reduce farmer's income by 50% in the summer and 20% in the winter (Jalota et al., 2007). Consequently, the government would have to institute a welfare system for the farmers to make up for these economic losses (Jalota et al., 2007). Both the predicted decrease in agriculture production and farmer income makes this solution alone difficult on political grounds (Fishman et al., 2015).

Nevertheless, Jalota's 2007 hydrologic and economic model shows reducing electricity subsidies encourages farmers to change their cropping patterns. Cotton, soybeans, and corn return higher profits than rice and wheat under un-subsidized electricity prices because they use water more efficiently. This suggests decreasing electricity subsidies will incentivize farmers to switch to less water-intensive crops, reducing the total groundwater extraction. (Badiani et al., 2012) shows that increasing electricity prices by about two-thirds would reduce ground-water extraction by 4.3%. Right now, the low effective prices for water allow farmers to ignore crop water efficiency and maximizing profits, resulting in rice and wheat production.

Who should be responsible for over-extraction? Should farmers pay the extra cost of ground-water extraction through electricity pricing or through pricing of another agricultural input? Or should consumers or the government be charged for the cost of over-extraction?

5.2 Methods

The economic model will optimize net benefits, including the shadow price of water, for a each time step constrained by potential government policies and water availability.

Inputs from Model Parameters

In order to evaluate different government policies, model parameters will be adjusted.

1. Price of electricity for agriculture
2. Amount of electricity used for agriculture for all of Punjab
3. Fixed price for rice and wheat
4. Fixed price for oilseeds
5. Fixed price for pulses

Inputs from Hydrologic Model

1. Head values at each timestep

Inputs from Agricultural Model

1. Water requirements for each timestep

Variables

Table 5.1: Economic Model Variables

Symbol	Variable
g	Groundwater volume pumped
h	Groundwater head value
q	Depth to groundwater
e	Cell elevation
V_g	Groundwater pumping energy use
V_e	Agricultural energy use
V_d	Diesel energy used for groundwater pumping
k	Pumping Efficiency
C_g	Cost of pumping groundwater
P_e	Price of Electricity
P_d	Price of Diesel
P_c	Price of Crop
Y	Crop Yield
Y_x	Max Crop Yield
w	Irrigation Water
w_{max}	Irrigation Requirement
X	Additional costs for crop production
F_p	Farmer profit

Depth to groundwater

$$q_i = e_i - h_i$$

Energy used to pump groundwater

$$V_g = qg\left(\frac{1000kg}{m^3}\right)\left(9.8\frac{m}{s^2}\right)\left(\frac{1wh}{3600Nm}\right) = 2.72gh[wh]$$

But engines are inefficient, so pumping efficiency, k , must be considered:

$$V_g = \frac{2.72gh}{k}$$

Pumping efficiency depends on realistic pump (0.7), drive train (0.95), and electrical motor (0.9) efficiencies. Therefore, the total pumping efficiency (k) is

$$0.7 * 0.95 * 0.9 = 0.5985$$

(Foley, 2015).

Diesel energy used to pump groundwater

$$V_g = \sum_{Punjab, cells} V_g$$

$$V_d = V_g - V_e$$

Assume diesel to electricity ratio is the same for every model cell.

$$V_d = V_w \frac{V_d}{V_g}$$

$$V_e = V_w \frac{V_e}{V_g}$$

Cost of pumping groundwater

$$C_g = P_e V_e + P_d V_{di}$$

Agricultural Production Function This production function will be used for each of the four crop types: rice Y_r , wheat Y_w , oilseeds Y_o , and pulses Y_p . It approximates the yields produced (Y_i , $i = 1, \dots$, number of crops), using a standard cubic spline which interpolates the convex hull of the crop yield functions Y_i defined as

$$Y_i = f(w_i), \quad \text{where} \quad f(w) = \begin{cases} Y_x \frac{w}{w_{max}}, & w \leq w_{max} \\ Y_x, & w > w_{max}. \end{cases}$$

In such an approximation, we assume that the use of fertilizer, pesticides, and other factors affecting yield are held at constant levels resulting in maximum efficiency. As is easily seen in the definitions of Y_i given above, we consider only piece-wise linear relationships between lack of water and yield with no decrease in yield if we have excess water.

Farmer Profit Function

$$F_{pi}(t) = P_c Y(w(t)) - C_g(w(t), h(t)) - X$$

Optimization

$$\max_{w(t)} \sum_{t=0}^T \left(\left(\frac{1}{1+r} \right)^t (P_c Y(w(t)) - C_g(w(t), h(t)) - X) \right)$$

Constrained to the agricultural production function and the rate of change of groundwater head:

$$Y = f(w(t))$$

$$\frac{\partial h}{\partial t} = g(w(t))$$

Economic Model Outputs

1. Crops grown at each timestep
2. Farmer profits
3. Farmer costs
4. Government costs

5.3 Results

Statewide farmer profits were calculated for 2002 and 2003 based on available data (Table 5.2). The **Production Cost A** is the sum of value of hired human labour, value of hired bullock labour, value of owned bullock labour, value of owned machinery labour, hired machinery charges, value of seeds, value of insecticides and pesticides, value of manure and fertilizer, depreciation on implements and farm buildings, irrigation charges, land revenue, cesses, and other taxes, interest on working capital, and miscellaneous expenses. The **Production Cost B** is the sum of Production Cost A, rent paid for leased land, interest on value of owned fixed capital assets, rental value of owned land, and rent paid for leased-in land. The **Production Cost C** is the sum of Production Costs B and the imputed value of family labour. The **Production Cost D** is the sum of Production Costs C and the value of management input at 10% of total cost. The **Profit** is the **Modal Market Price** minus the **Production Costs D** all multiplied by the **State Production**.

Table 5.2: Statewide Farmer Rice and Wheat Profits

Variable	Unit	Rice 2002	Wheat 2002	Rice 2003	Wheat 2003	Source
Seed Inputs	kg/hect	80.34	104.63	79.49	105.21	(Directorate of Economics and Statistics et al., 2007)
Fertilizer Inputs	kg/hect	189.5	222.12	182.42	223.8	(Directorate of Economics and Statistics et al., 2007)
Manure Inputs	qtl/hect	29.17	15.16	26.52	11.56	(Directorate of Economics and Statistics et al., 2007)
Human Labor Inputs	man hours/hect	1019.1	216.57	974.57	184.31	(Directorate of Economics and Statistics et al., 2007)
Animal Labor Inputs	pair hours/hect	45.2	2.97	37.14	1.69	(Directorate of Economics and Statistics et al., 2007)
Irrigation Charges	Rs/hect	4149.34	615.81	28261.02	504.35	(Directorate of Economics and Statistics et al., 2007)
Rental Value of Owned Land	Rs/hect	8135.96	7693.6	7916.57	6751.25	(Directorate of Economics and Statistics et al., 2007)
Rent Paid for Leased-in-land	Rs/hect	1856.41	1571.71	3720.59	2451.38	(Directorate of Economics and Statistics et al., 2007)
Land Revenue Cesses and Taxes	Rs/hect	0	0	0	0	(Directorate of Economics and Statistics et al., 2007)
Interest on Fixed Capital	Rs/hect	1430.24	1858.47	1468.6	1950	(Directorate of Economics and Statistics et al., 2007)
Production Cost A	Rs/qtl	264.99	234.56	215.93	233.42	(Directorate of Economics and Statistics et al., 2007)
Production Cost B	Rs/qtl	458.61	473.22	415.6	484.31	(Directorate of Economics and Statistics et al., 2007)
Production Cost C	Rs/qtl	499.35	500.04	442.94	508.99	(Directorate of Economics and Statistics et al., 2007)
Production Cost D	Rs/qtl	549.28	551.04	487.23	559.89	(Directorate of Economics and Statistics et al., 2007)
State Production	qtl	88800	141750	96560	144890	(Vatta, 2015)
Modal Market Price	Rs/qtl	563.23	590.97	620.713	632.44	(DIM, 2013)
Statewide Farmer Profit	Thousand Rs	1239	5660	12889	10511	Calculated

Cost of cultivation for rice and wheat was compared to the cost of cultivation for rapeseed and mustard and cotton (Figure 5.4). Both rice and wheat have significantly lower costs of cultivation than cotton and rapeseed and mustard.

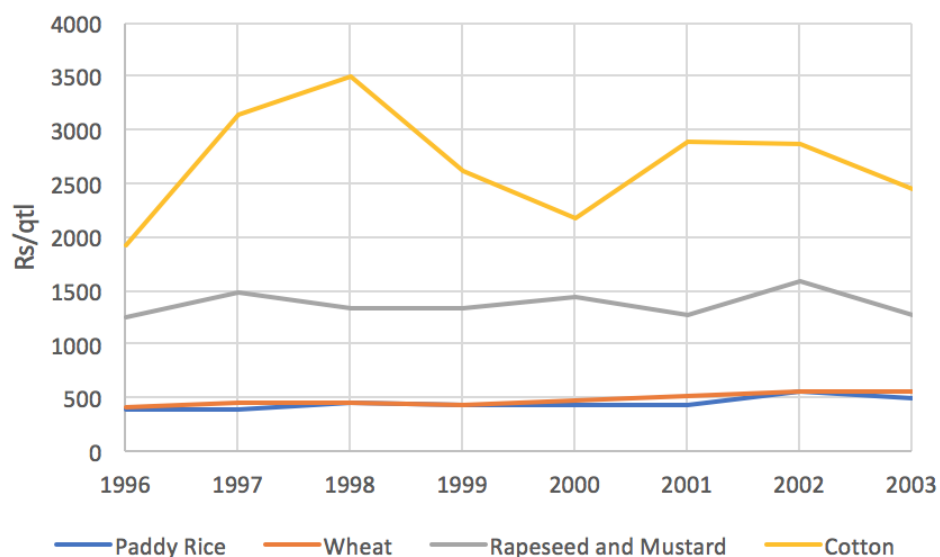


Figure 5.4: Cost of cultivation (Production Cost D) for rice, wheat, rapeseed and mustard, and cotton. Data from (Directorate of Economics and Statistics et al., 2007).

However, rice vastly exceeds irrigation charges for all three of the other crops, as seen in Figure 5.5. All irrigation charges increased in 2002, but rice experienced a disproportionately larger spike.

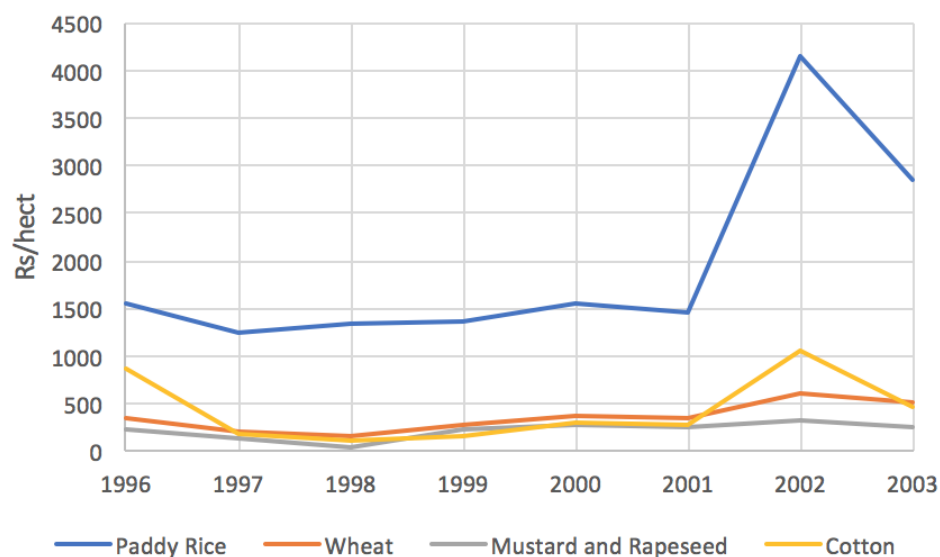


Figure 5.5: Irrigation charges for rice, wheat, rapeseed and mustard, and cotton. Data from (Directorate of Economics and Statistics et al., 2007).

The energy required to pump the groundwater consumed (as calculated in the agricultural model) was 9 - 14 times lower than the government reported agriculture consumption of electricity, as seen in Figure 5.6.

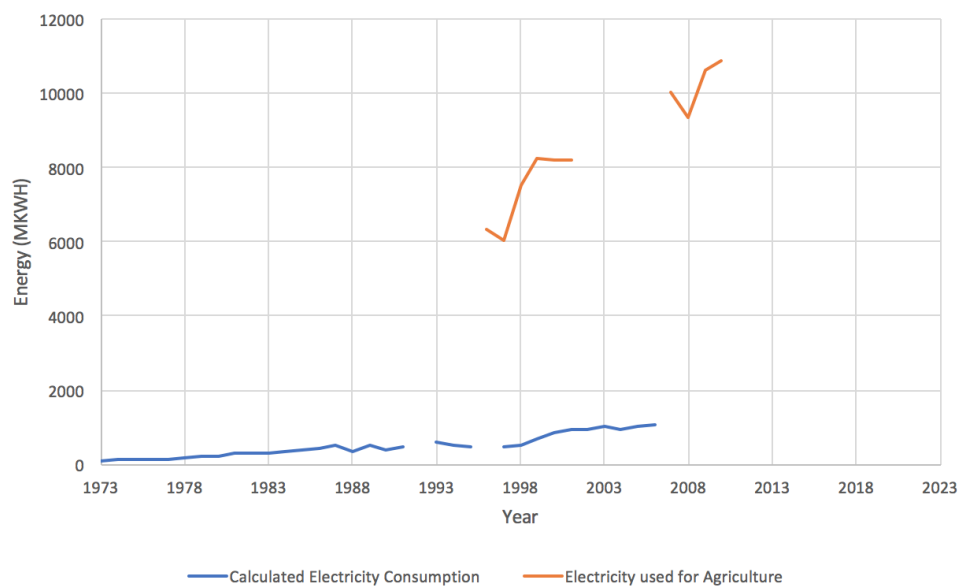


Figure 5.6: Calculated pumping energy compared to reported agricultural electricity energy use. *Agricultural electricity consumption data from (Planning Commission, 2013)*

A general negative correlation between diesel price and calculated groundwater pumped can be observed in Figure 5.7.

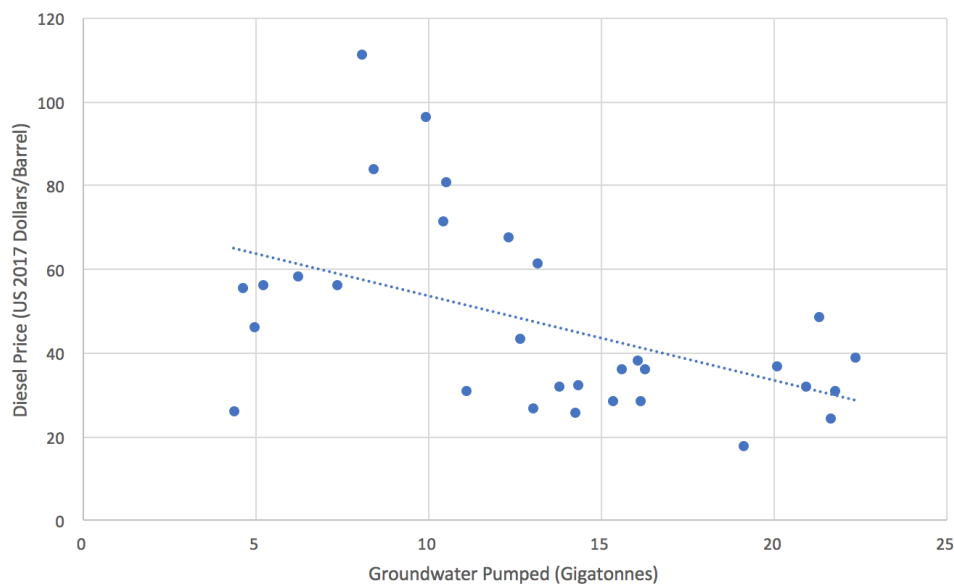


Figure 5.7: Diesel price plotted against calculated mass of groundwater pumped. *Diesel price data from (InflationData, 2017).*

5.4 Discussion

Private ownership outcomes: Given the groundwater situation, the institutional structures founded in the 1882 Indian Easement Act influenced the performance of groundwater use and the resulting overdraft. Groundwater slowly flows through the porous subsurface rocks along a pressure gradient. Therefore, pumping in one area creates a cone of depression, lowering the water table for all surrounding groundwater users. But the 1882 Indian Easement Acts and the Model Groundwater Bills ignore this interdependence and give landowners rights to all the groundwater beneath their land (Cullet, 2014). This structure allows wealthier users to pump more water at the expense of their neighbors because they can afford deeper pumps. Farmers can pump water without concern for surrounding water table decline because they own all the water below their land regardless of where it flows from. In Punjab, these groundwater institutions helped create an agricultural production system supported by 230 billion cubic meters of groundwater per year, an irrigation demand that vastly exceeds groundwater recharge (Chatterjee & Purohit, 2009). As a result, the water table declined 0.4 m/yr from 1997 - 2002 across the state (Figure 3.1).

Minimum support prices: The preliminary calculation of statewide farmer profits show the subsidies in place in 2002 and 2003 generate a profit for producing rice and wheat (Table 5.2). Profits for other crops and over time were not calculated due to lack of data at this time. The cost of cultivation for both rice and wheat between 1996 and 2003 were significantly lower than the cost of cultivation for cotton and rapeseed and mustard even though the irrigation cost for rice was much higher. Government subsidies or policies regarding other rice and wheat production costs may result in this lower total cost of cultivation. The differential cost of cultivation between crops should be further investigated along with the institutional structures that shape these production costs.

Electricity pricing: Throughout most of this study period, the Punjab government provided free electricity for farmers in order to subsidize groundwater pumping (Figure 5.1). The estimated total energy consumed by these groundwater pumps was an order of magnitude lower than the government reported agricultural sale of power (Figure 5.6). The pump efficiency was estimate to be 0.5985 (Foley, 2015), but to match the reported electricity consumed by agriculture the efficiency would have to be 0.04 - 0.07. This calculation did not account for inefficiencies in the electrical grid. In 2001, India reportedly experienced roughly a 35% loss during transmission and distribution of electricity (Aniti, 2015). Additionally, it is unclear whether the government figure for agricultural sale of power includes other domestic uses of electricity for farmers besides pumping groundwater.

However, this still does not account for the total discrepancy, especially because we predicted that the total energy consumption for pumping groundwater would exceed the electricity consumed because of the frequent blackouts that drive farmers to use diesel engines. Electricity figures are calculated based on supply from feeders and not at the point of consumption due to lack of metered tubewells, so it is unclear how much electricity the farmers are actually using (Chaba, 2018). A discrepancy of this magnitude suggests extremely inefficient electrical grids and groundwater pumps and/or over-pumping of groundwater.

Therefore, we are unable to calculate the amount of diesel used with this method. Alternatively,

we could estimate the diesel energy costs experienced by farmers from the statistic on the number of diesel compared to electric pumps across Punjab as presented in (Sarkar & Das, 2014). Over 50% of all groundwater pumps were diesel before 1980, but their use has declined through 1990 and now remain below 25-20% of groundwater pumps used across the state (Sarkar & Das, 2014).

While we were unable to calculate the exact cost of diesel per volume of water extracted, a general negative correlation was observed between diesel price and groundwater pumped (Figure 5.7). This trend possibly suggests that higher groundwater pumping prices through increased diesel prices drive lower groundwater consumption, however other factors may be at play. Groundwater demand is fairly inelasticity given that farmers make planting decisions months ahead to time, so over the timescale of fluctuation, it is likely no correlation can reasonably be concluded.

Overall, farmers are not incentivized to conserve water, since agricultural-use electricity is free. While the unit cost of power has increased between 1993 and 2012, agricultural-use electricity has remained at zero with a few fluctuations (Figure 5.1). Electricity prices are set by the state government officials (Badiani et al., 2012) (Tongia, 2003). Therefore, politicians often run on the platform of free electricity for farmers to win the rural vote. Once in office, they deliver their promise by offering completely subsidized electricity (Badiani et al., 2012) (Tongia, 2003). As a result, farmers feel no direct monetary incentive to conserve water and consequently deplete groundwater resources with inefficient practices (Jalota et al., 2007). The experiment proposed for this upcoming Kharif Season will test an alternative structure for agricultural electricity that may incentivize groundwater conservation without decreasing farmer welfare, however farmers remain skeptical of the government's intentions regarding this change (Chaba, 2018). This local-scale rule experimentation may lead to equitable, sustainable resource management, as shown in Elinor Ostrom's findings: experimentation of rules at local levels can evolve into institutions with productive outcomes whereas uniform, top-down rules stifle the institutional diversity needed for this evolution (Ostrom, 2008).

Model Sustainable Groundwater Bill: This bill invests power in communities over their local resource management and protection, a strategy Ostrom found effective in forest management in engaged community groups (Ostrom & Nagendra, 2006). It re-structures private ownership to shared ownership where groundwater is first used to fulfill everyone's right to drinking water, followed by food security, sustainable livelihood, and ecosystem needs. Communities are responsible for allocating the resource with consideration of community needs, rather than farmers owning all the water under their land. The structure also integrates groundwater management with surface water management to reflect the true interdependence of these freshwater resources. This change in institutional structure may incentivize more sustainable and equitable water management because additional stakeholders besides the landowner will be considered when making pumping decisions. And the rules collectively decided upon by the community are more likely to be followed and monitored than rules imposed by authority, according to Ostrom's work (Ostrom & Nagendra, 2006).

Furthermore, the multi-tiered structure of groundwater agencies outlined in the Model Bill allows change to take place at multiple scales, rather than just from the top down. This mirrors another institutional-change strategy described by Ostrom with regards to institutional change on climate policy. Top-down change can be slow due to the complex, high-stakes choices that often grind decision making processes to a halt. However, change can be affected at lower structural

levels where issues may be less intractable and strongly influenced with collective action (Ostrom, 2010). This local-scale rule creation and experimentation can evolve into institutions with more productive outcomes compared to outcomes from imposed, top-down rules (Ostrom, 2008).

Questions: While the groundwater overdraft continues, change is happening. According to Ostrom's work, this new model bill and ongoing local experimentation are effective strategies for generating equitable new rule structures for resource management. Will change starting from local experimentation and community-based management be fast enough to ameliorate the effects of groundwater overdraft? How can this model be created and implemented to support this experimentation process and empower communities? What is the role of experts and models in changing institutional structures?

We shall lift each other up

Chapter 6

Moving Forward

The problem of groundwater overdraft in Punjab is intractable as defined by Lewicki et al. 2003's, because it has eluded resolution since its discover, roughly forty years ago. As with all intractable problems, the case of groundwater depletion in Punjab may never reach a complete solution. However, progress can be made towards a more equitable and sustainable system through community-based resource management (Ostrom & Nagendra, 2006; Ostrom, 2010) with rule experimentation and evolution (Ostrom, 2008). This model has the potential to provide insight for this path forward, if further developed in partnership between stakeholders and experts.

6.1 Model Integration

This study shows some of the complex interdependencies between farmers, consumers, state and national government institutions, the hydrologic system, and environmental change that complicate this problem. To capture these interdependencies, the hydrology, agriculture, and economic models will be coupled to calculate groundwater availability, cropping decisions, and irrigations requirements for each timesep, as show in Figure 6.1.

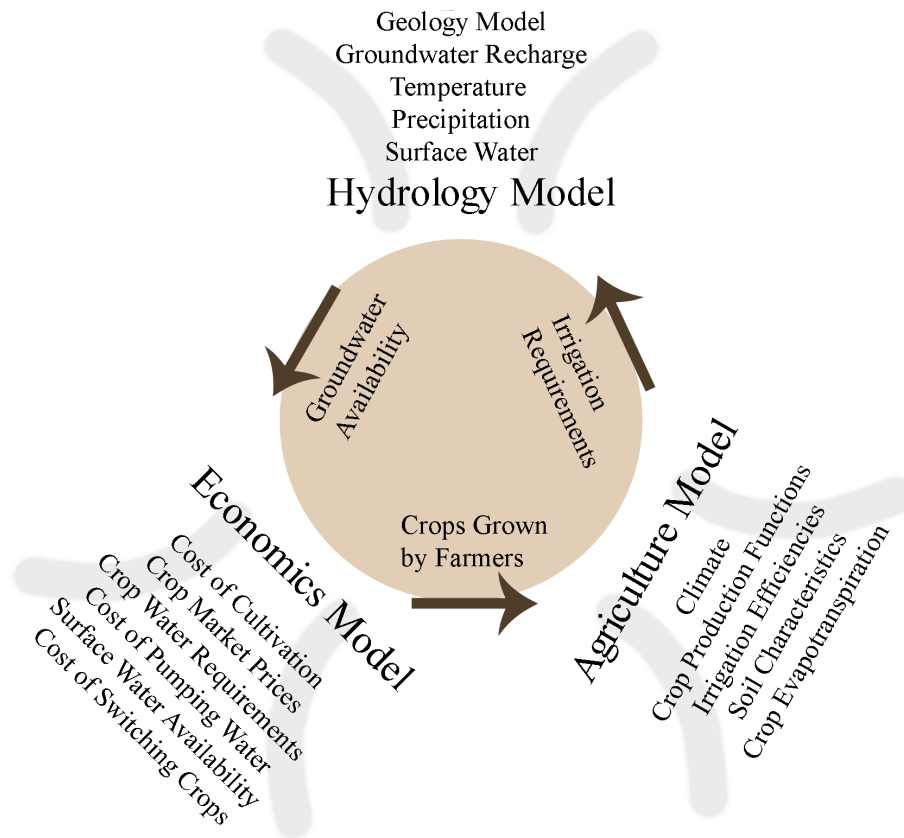


Figure 6.1: Schematic of coupled model.

The next step in model development is to run a transient hydrologic-agricultural model using

HydroLena with surface water, precipitation, and groundwater pumping. The economic model must be further developed to account for crop switching and the irrigation costs from drilling deeper wells. Once complete, the coupled model results will be compared with the same economic model coupled with a simple ‘bathtub’ hydrologic model, where the groundwater reservoir is modeled as a tub of water rather than flow through porous media. This comparison will determine if the results differ enough to justify the extended effort required to generate a more accurate hydrologic model. The Gisser-Sanchez paradox will also be evaluated for this aquifer and economic situation. The Gisser-Sanchez paradox states that little change in groundwater pumping will occur with increased groundwater costs that reflect the shadow price of groundwater (Gisser & Sanchez, 1980).

Once the individual models are constructed, they will be coupled and calibrated using groundwater head (CGWB, 2013) and cropped area and yield (Vatta, 2015) data from 1973 - 2013. Economic data on pricing of inputs and outputs will also be used to calibrate the model (DIM, 2013; Planning Commission, 2013; InflationData, 2017). This calibrated model will be run forward in time to determine the shadow price of groundwater and the projected rate of groundwater decline in the future. Alternate policies, cropping patterns, mitigation strategies, and predicted changes in climate will be tested with the coupled model to determine their effect on groundwater decline.

6.2 The Missing Component: Stakeholders

Thus far, this study fails to include stakeholders in Punjab, specifically farmers, community members, and government officials in charge of agricultural economic policy. The previous work conducted by Tess Russo (Russo et al., 2015) was a collaboration between economists at the Punjab Agricultural University and the Colombia Water Center. However, this thesis work was done without close collaboration with Punjabi colleagues due to communication difficulties. Furthermore, traveling to Punjab to build these relationships and inform the model was considered but ultimately not possible due to funding and time constraints.

By working closely with stakeholders, we could have obtained more data and meta data to inform the model, specifically local knowledge of how the hydrologic, agricultural, and economic system works. We also would have gained insight on what economic policies were more favorable to different stakeholders, creative solutions we had not considered, and other interdependencies and value systems not observable in the data. Most importantly, we could have learned what questions stakeholders wanted answered and then designed our model to provide the desired information. This stakeholder engagement would have been best if conducted through community-science based model from the start with the guidance of social scientists as described in Pandya 2014 and Lang et al. 2012 . Without connections with stakeholders, the effectiveness and relevance of this model is greatly reduced. An important next step is therefore traveling to India to develop relationships with stakeholders to co-create a useful, usable model.

6.3 The Big Questions

Safe yield: The question of ‘safe yield’ or sustainable groundwater consumption is not straightforward. Safe yield is often assumed to be equal to aquifer recharge, but this assumes the aquifer

discharge elsewhere is negligible or not-important (Fetter, 2001). By pumping exactly the recharge rate, the aquifer will experience no net recharge. However, it still discharges elsewhere into surface water or aquifers across political boundaries. Therefore, pumping the exact recharge rate is not sustainable and the 'safe yield' is an arbitrary concept defined based on system requirements set by people. Therefore, safe yield for Punjab must be defined by what the groundwater stakeholders want from groundwater in the future.

1. How much groundwater does Punjab need and want in the future? How will climate change affect the demand and the quantity of water resources globally?
2. How much freshwater do 11 billion humans need in the future?
3. How does desalinization technology influence freshwater requirements of the future?

Sustainability: Furthermore, this study of groundwater overdraft in Punjab, India brings to light several major questions about sustainability. By subsidizing electricity and supporting rice and wheat prices, the Indian government incentivize maximum food production today in order to meet the growing demand of food for its current population. However, the food is produced using groundwater at an un-sustainable rate, decreasing the availability and increasing the cost of groundwater in the future. Therefore, the food production today is encouraged at the expense of food production in the future. The choice of sustainability is truly a choice between maximizing food security today and maximizing food security of the future. This choice is based on the ethical considerations of the government policy-makers and their worldview prediction of what the future holds.

1. How much do we value freshwater, food, and human life in the future?
2. Is the future going to be better than today?
3. Based on our belief of the future, at what rate should we discount the future when relating future costs to present day value?
4. Who is responsible for creating a sustainable system? Who should pay the costs today for ensuring water in the future?

Modeling the unknown: When thinking into the future, the uncertainty of climate change and other unknown unknowns makes forecasting difficult and possibly inconsequential (Taleb, 2007). We are leaving the relatively stable ice-house climate of the Holocene and entering into a different climatic system with higher atmospheric CO₂ concentrations (Hansen et al., 2008). Models solving for steady state equilibriums and sustainable solutions are ignoring the swiftly changing climate and the unpredictable consequences. Sustainability is therefore not a steady state optimum, but an adaptive strategy to maintain the ethical standard of society. What this means for decision support models.

1. With future known unknowns and unknown unknowns both with extreme consequences, how do we make useful models?

2. How should policies be made given this uncertainty? How should we design our institutions?
3. How do we make institutional and policy change? Who decides?
4. What is the role of a hydrologist in creating a more sustainable, equitable world?

Chapter 7

Process Reflection

I have not come to any concrete answers to my questions. If anything, I have just come up with bigger questions. Overall, my experience has lead me to the understanding that hydrology, mathematics, agricultural sciences, and economics are necessary for making progress towards equitable sustainability, but not sufficient. Local knowledge from farmers and government officials, and community development knowledge from social scientists is also necessary, but also not sufficient alone. Progress will come from strong collaboration between all dimensions of these intractable problems. Interdisciplinary research is a start, but not the solution or end.

7.1 Interdisciplinary Research

7.1.1 Building a team

The questions surrounding real-world sustainability problems are fundamentally interdisciplinary (Dockry et al., 2016) requiring a diverse, collaborative team of scientists, practitioners, and stakeholders (Lang et al., 2012). For this project, I started out with the consequential real-life problem of groundwater depletion in Punjab, India. I was exposed to the problem by Tess Russo, who framed the issue from an hydrology perspective: groundwater is declining because of irrigation. Upon further exploration, I uncovered the interdependent system (spanning many areas of expertise) responsible for the unsustainable and concerning problem of groundwater overdraft.

Successful interdisciplinary research starts from initial collaboration across disciplines during the research question formation (Campbell, 2005), though researchers are often added on as more complexity is revealed requiring researchers with different areas of expertise (Lang et al., 2012). During my exploration of the Punjab problem, the complexity grew in every dimension, so I decided to pursue an interdisciplinary approach combining mathematics, natural resource economics, and hydrology.

7.1.2 Bridging worldviews

The over-arching challenge of interdisciplinary research is working between the differing worldviews of each academic discipline (Benda et al., 2002; Campbell, 2005). Researchers in different disciplines are trained to question and analyze the world with different frameworks: different theories of knowledge, different spatial and temporal scales, different precision and accuracy of variables, and different discipline historical/socioeconomic/political context (Benda et al., 2002; Boulton et al., 2005). While these discrepancies can lead to conflicts and challenges (Benda et al., 2002; Lang et al., 2012), they can be overcome through explicit conversations between researchers (Benda et al., 2002; Boulton et al., 2005; Campbell, 2005; Strauss, 2017).

Communication: The first step to bridging worldviews is establishing good communication (Daily & Ehrlich, 1999; Benda et al., 2002; Strauss, 2017). The specialization of academia has resulted in discipline-specific jargon that must be discussed in order to develop a common language (Lang et al., 2012). I learned the technical language of each of the disciplines by taking classes in each of the fields and always asking questions. By taking the time to learn the basics of each field, I was able make connections across each field and develop a framework for an interdisciplinary model.

Friendships: Long-term friendships between researchers of different fields are critical for successful interdisciplinary research because they grow a mutual understanding and respect (Daily & Ehrlich, 1999). Tess, Kate, Ludmil and I had family dinners together to grow our friendship. By spending time together engaged in conversation, we built relationships based on trust, respect, mutual understanding, as Daily et al. 1999 and Castleden et al. 2012 emphasize in their analysis of interdisciplinary work. The interpersonal respect and trust carried over into our work, breaking down power dynamics that could have created barriers to genuine collaboration. Academic power differentials stem from difference in career stages, team organization, and discipline hierarchies (Campbell, 2005). However, despite being an undergraduate, I was not afraid to ask questions, take risks, or mess up within this team because I knew I was respected and valued in my relationships with my advisors. I was therefore able to learn more effectively and think creatively about the problem.

Outlining frameworks: Once these relationships were established, I began outlining the framework each discipline worldview. Each chapter of the thesis begins with an overview of the discipline framework including their theory of knowledge, research methods, and knowledge structure as suggested by Boulton et al. 2005. The framework could have been more fleshed out to include usual spatial and temporal scales, standard precision and accuracy, and the historical, socioeconomic, and political context of each discipline as suggested by (Benda et al., 2002). This explicit documentation of the framework and integration of the disciplines helps everyone stay on the same page and allows new members to easily join the team (Boulton et al., 2005).

By laying out all the disciplines and exploring the previous work in each area, I was able to uncover the missing integrated perspective and build my project to fill that niche. Spanning this intersection demanded and fostered creativity as we each tried to understand other dimensions of the problem, ask questions, and propose methods to generate answers. Ludmil mentioned that he found interesting, complex mathematical problems from our hydrologic and economic questions that he would have never thought of without our collaboration. The same can be said from all perspectives. From my experience, interdisciplinary research generates questions that are both intellectually stimulating and relevant by the nature of working at the intersection of thought.

Including stakeholders: This intersection of thought should have been expanded to include stakeholders. In order to make the model useful and usable, it should have been built in partnership with stakeholders from the beginning, as explained by (Benda et al., 2002; Lang et al., 2012; Pandya, 2014). The process of this community-science would be similar to the process of interdisciplinary research: engaged, knowledgeable team members would have to build relationships through effective communication to build mutual understandings and respect across differing worldviews (Lang et al., 2012; Pandya, 2014). While this process is slow (Boulton et al., 2005; Campbell, 2005), the stakeholder perspective would have fostered more creative, useful work at this true intersection of knowledge and worldviews.

7.1.3 Defining the Research Question

After bridging worldviews and building respect, the following step is to construct solvable questions by rejecting and/or modifying the initial problems of the interdisciplinary project (Benda

et al., 2002; Campbell, 2005). Collaboratively framing the problem is a continually recursive process between all the experts and stakeholders relevant to the complex system (Lang et al., 2012; Dockry et al., 2016). Together, the research team must agree upon objectives and societally relevant questions and then develop a conceptual method framework (Lang et al., 2012). This collaborative process then must continue as researchers and stakeholders co-produce solution-oriented and transferable knowledge that will be applied in both scientific and societal practices (Lang et al., 2012).

Managing Complexity: In a dynamic system where variables are interdependent and largely unknown such as future climate and unknown groundwater pumping, how do we make a useful, usable model? The standard method for academic studies is to break up the problem into discipline-specific questions and simplify each question into an easily-defined problem solvable with an equation. However, systems are dynamic and interdependent (Dockry et al., 2016): changes in one variable studied by one discipline effect the outcomes of another variable studied by a different discipline. To simplify, economics models often assume groundwater hydrology is equivalent to a bathtub and hydrologist speculate about agricultural changes without evaluating the economic effects such as in (Russo et al., 2015). But, the system is infinitely complex and therefore decisions must be made regarding which variables and what interdependencies to include. Some suggest using bayesian statistical analysis of relationships to eliminate several disciplines and degrees of complexity (Benda et al., 2002; Russo et al., 2015), but this may overlook important known physical relationships. Additionally, the precision and accuracy of each input variable and the sensitivity to each assumption must be considered when evaluating the certainty and usefulness of the model result. The research question must be refined given these constraints.

1. What complexities do we ignore to simplify the model?
2. What useful question can we answer given our limitations of data and complexity?

We are still at the stage of co-creating a model and refining the research questions. It is not a linear process, but continually iterative. As we begin to develop one part of the model, we circle back to another, dive into a new complexity and try to reframe and simply the problem to fit within our technical ability and timeframe. The challenge is how to model complexity based with little data to provide useful insights into the system dynamics to inform decision.

7.1.4 Outcomes

While the project has not produced useful policy information thus far, the overall work has created numerous valuable outcomes. The entire process of completing truly interdisciplinary research, as outlined above, has in itself cultivated relationships between all of the people involved. These relationships have carried over into other projects such as environmental economics modeling of invasive species. If we had pursued the end result without taking time to understand each other and our respective disciplines, we may have generated more publishable material, but it would have captured and accounted for less of the true complexity of the situation and therefore been less useful. Furthermore, we would not have developed the invaluable relationships that improve work within and outside of this project. The process of conducting interdisciplinary research matters tremendously, even more than a perfect final outcome.

7.2 Reflection on Academia

The traditional academic path conflicts with the interdisciplinary community-based science method discussed above. Academia's siloed culture drives specialized progress (Daily & Ehrlich, 1999), valuing the individual expertise over other ways of knowing, particularly the local knowledge necessary for informing research questions, methods, and place-based and community-specific knowledge in effective decision support models. This culminates in a trend of scientists studying and advocating for global mitigation policies over local adaptation (Stehr, 2015), even though local adaptation can lead to more productive outcomes than top-down rules (Ostrom, 2008)

The influence of socioeconomic status: Those who are not privileged enough to become experts (or are not lucky or powerful enough to be considered by experts) are not involved in studies used to create policy: their voices are not heard or respected, so their knowledge is not utilized and their rights likely ignored (F. Fischer, 2002). Vulnerable populations around the world are already suffering disproportionately from global climate adaptation policies because they are left out of global policy decisions, so their needs are ignored (Marino & Ribot, 2012). And wealthy interests have an outsized voice with their ability to fund specific scientific pursuits in efforts to prove predetermined outcomes that influence or justify policy (F. Fischer, 2002) or simply study interdependencies that effect their livelihoods and capital. Because of the influence of socioeconomic status on science, the body of knowledge produced from science is far from unbiased and instead produces knowledge that reflects the dominant worldview at the expense of vulnerable communities.

Creativity at the intersection: The innovation and creativity required to move society forward will happen at the intersection of different fields of knowledge (Horton & Freire, 1990; Dockry et al., 2016), just as we found innovative research questions in this interdisciplinary project. The academic system of competitive, individual research within discrete disciplines does not encourage this intersectional work (Daily & Ehrlich, 1999; Boyte, 2004; Anonymous, 2013). Furthermore, the publish-or-perish demands of academia struggles to accommodate the slow process of true interdisciplinary, community-based research (Boulton et al., 2005; Campbell, 2005) that leads to innovation.

Process matters: The interdisciplinary community-based pursuit towards sustainability is further hindered by academia's traditional emphasis on solutions, answers, and outcomes over process. Students are heavily graded based on final products and professors are awarded for their findings showcased in published papers that hide the human process of science. Specifically, method sections communicate the steps taken in passive voice, distancing the researcher from the experiment and ignoring the interpersonal lessons learned through the process (Boulton et al., 2005). Yet evaluating and learning from different processes is critical as we search for better ways to conduct interdisciplinary research with partners outside of academia to solve the world's complex problems.

No complete solutions: Additionally, academia's value of outcomes over process conceals the real truth of forward progress on these complex issues: there are no complete solutions. These

wicked, intractable problems surrounding water management as well as other areas are dynamic and complex (Dockry et al., 2016) and not entirely solvable (Allen & Gould, 1986; Lewicki et al., 2003). They are problems we must continually work at. We must recognize our small efforts are important and consequential but not fix-all solutions. Therefore, our success of our sustainable water management efforts is found within the process of our work, not in the outcomes. Did we build meaningful relationships of respect and mutual understanding that moved the issue forward? Did we gather lessons about making change which we can apply to other problems? However, this processed-base success is not traditionally publishable, awarded, or valued in academia.

The importance of stories: The human story of the scientific pursuit, a story of curiosity and awe, is also lost through this traditional outcome-focused academic culture. In the keynote address at the 2017 AGU Fall meeting, Dan Rather explained sharing these human stories of science allows people of all backgrounds to relate emotionally to the pursuit of science. This connection can drive a deeper understanding and respect for the scientific work and knowledge while breaking down the preconceived boundaries between experts and everyday citizens (Rather, 2017). Nicole Brunozzi, a Penn State senior once said to me “I learn more science from reading a scientist’s autobiography than a textbook.” Stories are powerful, yet we write science as the last page of the book without ever sharing the novel that precedes it. On the quest for an informed public who will push for science-based policy, we need to tell our stories (Rather, 2017) because educating through facts does not change minds, especially at this time of anti-science sentiment (Anonymous, 2016).

But we cannot just focus on our stories as scientists. Respect is built through the reciprocal action of sharing and listening. Everyone has a story worth listening to and everyone brings knowledge essential for creating a sustainable future. Science is just one way of knowing that cannot solve complex environmental problems alone (F. Fischer, 2002). But science in the academic world makes little if any room for other ways of knowing and other stories (F. Fischer, 2002; Pierotti, 2011).

Academia as a leader: I have hope. Higher education has the potential to become an agent of change by disseminating information in a way that develops citizen agency to co-create our democracy (Boyte, 2004) and co-create policies around the world on a path towards an equitable sustainable future. This requires higher education to empower citizens (Boyte, 2004). Harry Boyte in his book *Everyday Politics* explains:

It means building extensive relationships across silo cultures. It means turning hidden, privately felt discontents into objects for public discussion. It means developing public leadership through experiences of public work, cooperative, successful effort with others. It means learning to share credit and public recognition. It means creating space for reflection and collective evaluation. Yet all these steps go directly against the grain of free-wheeling individual entrepreneurship, disciplinary turf wars, argument culture, hierarchies, and competitiveness that both structure and fragment academia. (Boyte, 2004)

Academia has the potential to help lead our country and our world towards sustainability for all people.

I cannot walk the established academic path. Simply becoming a neutral hydrologist would mean surrendering to the strongest forces of the larger system, forces that will not guide our society towards equitable sustainability because they often ignore or exploit vulnerable communities. Therefore, I want my life's work to follow a path outside of the conventional frameworks and instead guided by my own values and goals.

Chapter 8

Philosophy of Professional Practice

My philosophy of professional practice is a living document designed to guide my work going forward and evolve as I grow through more life experiences. This philosophy reflects who I will strive to be both personally and professionally.

8.1 Humility

Humble yourself in the sight of the Earth

Earth is a dynamic complex system of life. I am merely one observer with one perspective, one life experience, and one mind. I am an important part of the the ever-evolving structure and outcomes, but I am only one actor among this interdependent community. My community extends to all earth processes, life forms, and human beings. I only exist for a short time and therefore, I must be humble for there is power much greater than me, life much older than my mind and my species, and knowledge far outside of my comprehension. I must act on this humility with curiosity.

8.2 Curiosity

You have to ask her what she knows

I must explore everything from and between earth, eco-, and human systems. I must ask questions of nature and of people, including myself, to grow an understanding of differing worldviews and value systems. I must read books and read the natural landscape around me, listen to stories of all forms, question my own knowledge and assumptions, learn through continuous exploration, and value local knowledge and what others bring. To serve others, my work must be grounded in what they know and I must be humble enough to listen.

8.3 Open Mind and Heart

Humble yourself in the sight of the Earth

To be humble is to open my mind and my heart. I must open my mind to the knowledge of my explorations. Nature (including the human-constructed world) is not bounded by the neat categories of academic disciplines, the worldview I have been taught, or even words in the English language. Nature (and life) is messy with fuzzy borders, so I will not let society's barriers impede my process of weaving together knowledge along a path towards equity and sustainability. I must also open my emotions to the experiences of others and learn through empathy. My heart must break open to hold the existential tensions of differing worldview and complex interdependencies in ways that bring life.

8.4 Reflection

You have to know what she knows

I must take time to reflect on and with myself and my community. We must learn together from reflections on our experiences because everyone has something to teach me. Personal reflection is necessary for myself to develop a personal voice and agency born from what I know and ever-evolving with what I learn. Reflection allows me to evaluate and subsequently re-align my behavior in order to be my true self and act upon my values. Reflecting with my community means taking what I learned (whether professionally or personally) and sharing it with others in meaningful ways beyond academic or government publications. I must pass on knowledge to young people, for they will soon be here to join me and take my place.

8.5 Relationships

We shall lift each other up

My bounded rationality limits my ability to hold knowledge, but I will forever be able to learn and access more knowledge through my relationships with others. I must take the time to build genuine relationships of trust and respect between people and all members of a community in order to produce meaningful collaboration, deep reflection and learning between perspectives. While solutions are not possible, the path forward is built from our relationships with one and other. Power must be shared, not hoarded, to empower everyone and to build a strong and resilient community. I must make people feel welcome by valuing them for their true self.

8.6 Equality

Higher and higher

I cannot say for certain the arc of history bends towards justice, but I will do everything in my power to bend the institutions I am a part of. I will always question equity: *who benefits and who loses? who is making the rules? what stakeholders are missing based on the nature of the interdependencies?* As I work with and stand by vulnerable communities in my professional practice, I must seek out all stakeholders and invite them into the decision-making process with equal information and respect. Science is inherently biased because it is conducted by humans with biases and funded by human institutions with agendas. Therefore, it is my job to serve vulnerable communities ignored or exploited by science and policies. This work must be done by co-creating science with communities, truly developing projects with stakeholders and using my expertise as a service for others.

8.7 Gratitude

We shall lift each other up

I must be grateful for my community and for all the relationships that lift us up. The complex interdependent system of Earth has brought me here today. I must be grateful for the mere existence of life and my species *Homo sapiens* and for my ecological and human community that sustains my life. I am grateful for all that lifts me up. And from the gratitude grows respect and awe. I am forever humbled. I am here to give what I can from my love for the Earth.

“Never give up until you have released your unused capacities for service and shared your gifts with others. One enkindled spirit can set hundreds on fire.”

– William H. Danforth.

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- Zikatanov, L. (2018, February). *Mathematics Worldview*.
- Zipp, K. (2018, February). *Environmental Economics Worldview*.
- Zull, J. (2011). *The Art of Changing the Brain: Enriching the Practice of Teaching by Exploring the Biology of Learning*. Stylus Publishing.

Madeline Nyblade

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EDUCATION

2014 – 2018 B.S. Geoscience, The Pennsylvania State University, Schreyer Honors College with honors in Geoscience, Mathematics, and CED (Community, Environment and Development)
Thesis: Numerical Modeling of the Hydrologic-Agricultural-Economic System in Punjab, India: An Analysis and Reflection on Interdisciplinary Modeling for Sustainability
Advisors: T. Russo, K. Zipp, L. Zikatanov, Penn State

WORK EXPERIENCE

2016 – 2018 Computational Math, Hydrology, and Economic Research Assistant at Penn State for T. Russo, K. Zipp, L. Zikatanov
2016 Research Assistant in the Human Environmental Dynamics Lab at Penn State for R. Bird and D. Bird
2011 – Professional Ski Patroller at Tussey Mountain
2014 – 2015 Youth Development Professional at Merrowvista Summer Camp

GRANTS RECEIVED

2017 Erickson Discovery Grant for undergraduate summer research
2017 Best Student Abstract Award, MODFLOW and More Conference

HONORS AND AWARDS

2018 Earth and Mineral Sciences College Science Honor Marshal
2018 EMSAGE Laureate, Earth and Mineral Science College
2018 GEMS Diamond Award Honorable Mention
2018 Dean Edward Steidle Memorial Scholar Award
2017 Eastern Division Outstanding Patroller, National Ski Patrol
2017 Western Appalachian Region Outstanding Patroller, National Ski Patrol
2017 Tussey Mountain Patroller of the Year
2017 Sustainability Tree Award for outstanding sustainability leadership at PSU
2017 Best Student Poster Award, MODFLOW and More Conference
2017 Third Best Physical Sciences Poster, Penn State Undergraduate Poster Competition
2016 Best Course-Based Poster, Penn State Undergraduate Poster Competition
2014 PEO Star Scholarship
2013 Bruce E. Knox Community Service Award, Youth Service Bureau
2013 Hans Hyson Young Adult Patroller Award, National Ski Patrol

PROFESSIONAL MEMBERSHIPS

2016 – Geological Society of America
2017 – American Geophysical Union

PUBLICATIONS

Nyblade, M. (2017, March 20). Student activism needs community support. *The Underground*.
Nyblade, M. (2017, February 27). Freshman matter in student activism. *The Underground*.
Nyblade, M. (2018, February 13). How to get more women in math. *The Underground*.
Nyblade, M. (2018, January 30). The sustainability movement needs community. *The Underground*.
Nyblade, M. (2018, January 16). Diversity should be the top priority of the sustainability movement. *The Underground*.
Nyblade, M. (2017, October 31). THON, let's talk about health care. *The Underground*.
Nyblade, M. (2017, April 28). Change starts here. *Centre Daily Times*.

FIELD RESEARCH

2017 *Water Sampling of Beech Creek, Pennsylvania*

2017 *Penn State Geoscience Field Camp (Utah, Wyoming, Montana, Idaho)*
Measuring stratigraphic columns in Price, Utah
Mapping the structural geology of Elk Basin, Wyoming
Mapping the geomorphology of the Tetons, Wyoming
Mapping the structural geology of Wildhorse, Idaho
Mapping the structural geology of the Alta Overthrust, Utah
Mapping metamorphic isograds of the Alta Stock, Utah

ORAL PRESENTATIONS

Nyblade, M. (2017, October). *A Fight for Clean Water: Acid Mine Drainage in the Beech Creek Watershed*. Presented at the Rural Studies Student Conference, Penn State.

POSTER PRESENTATIONS

Nyblade, M. (2017, December). *Numerical Modeling of the Agricultural-Hydrologic System in Punjab, India*. Presented at the AGU Fall Meeting, New Orleans.
Nyblade, M. (2017, November). *Numerical Modeling of the Agricultural-Hydrologic System in Punjab, India*. Presented at the EMS Undergraduate Poster Competition, Penn State.
Nyblade, M. (2017, May). *Numerical Modeling of the Agricultural-Hydrologic System in Punjab, India*. Presented at the MODFLOW and More, Colorado School of Mines.
Nyblade, M. (2017, April). *Numerical Modeling of the Agricultural-Hydrologic System in Punjab, India*. Presented at the All In Conference, Penn State.

Nyblade, M. (2017, April). *Numerical Modeling of the Agricultural-Hydrologic System in Punjab, India*. Presented at the Undergraduate Poster Competition, Penn State.

Nyblade, M. (2016, August). *Numerical Modeling of the Agricultural-Hydrologic System in Punjab, India*. Presented at the CHUASI Biannual Meeting.

Nyblade, M., Ulmer, K., & Sarkawi, G. (2016, April). *Spring Creek Water Quality Analysis*. Presented at the Undergraduate Poster Competition, Penn State.

TEACHING EXPERIENCE

2016	Central Pennsylvania Geology	Shaver's Creek Summer Camp
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COMMUNITY SERVICE

2016 –	Big sister in the Youth Service Bureau's Big Brothers Big Sisters program
2014 –	Volunteer young adult ski patrol advisor
2011 –	Volunteer ski patroller at Tussey Mountain

INTERNATIONAL EDUCATION

May 2016	Following the footsteps of the Irish potato famine, Penn State embedded study-abroad spring class with a trip to Ireland in May
Fall 2015	Himalayan Ecology semester abroad in Bhutan, School for Field Studies
May 2015	Biology of Eco-Health, Penn State study abroad course in Tanzania
Nov 2015	International Agriculture, Penn State freshman seminar with embedded travel to Belize over Thanksgiving Break