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Sustainability under Change:

A Comparative Analysis of Climate Change, Agricultural Water Use and Economic Growth in Punjab and Telangana, India

University of Minnesota Institute on the Environment
Indian Institute of Technology - Hyderabad
International Water Management Institute - Delhi

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Through the University of Minnesota's Institute on the Environment *Discovery Grants*, researchers from the National Center for Earth-surface Dynamics, the University of Minnesota's Department of Applied Economics, the Indian Institute of Technology, Hyderabad, and the International Water Management Institute, Delhi are able to work in the development of academic and institutional partnerships to answer some of the most pressing questions related to the sustainability of our planet.

As partners, we would like to thank the University of Minnesota Institute on the Environment for this unique opportunity.

Punjab and Telangana Photo Credit: Diego Ponce de Leon Barido and Shashidhar Thathikonda

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Farmers preparing the paddy in central Punjab

1. Executive Summary

Water is a natural resource that is in relatively fixed supply and closely linked to the fundamental well being of people and the economy. This link is particularly important for countries such as India, and regions such as Punjab and Telangana, where a sizable proportion of the population depends on agriculture as their main source of employment, livelihood and economic activity. Punjab and Telangana's water table is deepening at an alarming rate and groundwater exploitation for irrigation purpose is a national and international concern, blamed for serious socio-economic and environmental consequences now and in the future. Furthermore, the increasing variability of monsoonal rain and extreme climate events in recent decades imposes additional stress on water availability and makes groundwater an even more reliable source of water supply. The intensive agricultural systems of the two study regions, Punjab and Telangana, depend heavily on groundwater irrigation. However, the hydrogeological systems in these regions are significantly different and provide a contrast of how these systems adapt to climate change. Increased concern for water scarcity and its potential impact on society comes from recognition that water is interlinked with the behavior of human demand within the constraints imposed by climate changes and hydrogeological systems.

Identifying and Adapting to Climate Change

The summer monsoon provides the most crucial renewable water supply for the people in India. Beginning in June, a typical monsoon lasts for four months and dumps much of its rainfall in July and August. Watching rain closely alongside, a majority of farmers in Punjab and Telangana dedicate themselves to growing rice which requires a significant amount of water. Punjab in Northwest India and Telangana in South Central India observe a changing climate and a large degree of spatial as well as temporal climate variability within each region. Evaluating daily precipitation gridded data, the present study reveals intensified and more frequent extreme precipitation events in the predominant areas of both study regions in recent decades. Many parts of the regions have experienced more variable daily monsoonal precipitation. In addition, the study examines the occurrence of dry days and dry spells in monsoon and highlights a persistent dry-days pattern change that is specific to each region. Under the onset of various climatic uncertainties, the comparative analysis of hydrogeologically-diversified regions provides important clues for understanding anthropogenic influences on the regional climate systems.

An economy's vulnerability towards climate variability and change is determined by many factors including a country's natural resource endowment. Groundwater is an indispensable resource that stabilizes agricultural production especially for regions where farmers experience a large degree of seasonal rainfall differences. Telangana is endowed with shallow bedrock aquifers and the groundwater potential is swayed significantly by monsoon rainfall. Thus, subsistence level rain-fed dependent farming in Telangana is incredibly vulnerable to climate variability and change. Punjab, on the other hand, is endowed with deep alluvial aquifers. The region has expanded the production of rice and wheat through groundwater irrigation despite the fact that Punjab's normal precipitation is inadequate for the rice-wheat growing cycle. Thus, Punjab farmers are expected to respond to unpredictable climate changes by relying on the groundwater supply in order to protect their crops and income. Of greater concern is the repercussion of over-dependence on groundwater extraction that is induced by increasing uncertainty of climate change. A large degree of climate variability and change could extend its adverse effects to the fundamental economic activities of the region and country leaving irreversible damages to the environment.

Beyond Local: An Economy Wide Concern

This project is an attempt to understand how human behavior and nature work to influence the availability of groundwater resources over time. Groundwater dynamics, in turn have a significant impact on economic and environmental issues through water availability and aquifer sustainability. In our study regions, free electricity is provided for agricultural irrigation. This administrative priority of water allocation to the farmers imposes economic stress on other sectors of the economy because of the increasing costs of electricity for pumping financed by the rest of the economy. Introducing groundwater dynamics into a general equilibrium framework, the present study evaluates the economic impact of groundwater depletion on the agricultural and non-agricultural sectors of the inter and intra-region in the economy. The simple groundwater dynamics captures the regional differences of hydrogeology and climate change. For instance, the elimination of the 'electricity for irrigation' subsidy is likely to discourage farmers from producing crops in such a water intensive manner, and likely to encourage the other sectors to use the labor, capital and energy that, at the margin, is likely to be released from agriculture. On the other hand, drought directly depletes groundwater and reduces the profit of farmers due to more irrigated water required, if available, for a given level of production. Under both cases, the resulting value of water resources is likely to be higher and together with lower profits for farmers, the agricultural sector is likely to become depressed, thus pushing some resources out of the sector. Consequently, the economy-wide GDP expands while the regional economy suffers given that the study regions are agriculturally intensive. Hence, the fundamental economic issues of groundwater and climate change requires an understanding of the direct and indirect impacts of competing resources among different sectors of the economy under the influence of changing climate and hydrogeological systems.

2. Introduction

It is clear that climate change and even natural climate variability exert their greatest impacts on the sectors which most closely rely on them. Issues related to energy, water, agriculture, food security, forestry, health, and tourism, which heavily rely on the weather and climate, are already a source of concern for many countries around the world.[1] In addition, the vulnerability and exposure to climate extremes (floods and droughts) and variability is greatest amongst the countries with the least ability to prepare for them.[2] Although many developing countries such as Brazil, Mexico, India, and China, are touted as rising industrializing economies, their wealth is relatively concentrated on a few and the large majority of their population depends on agriculture for their livelihood. As climate change is expected to increase the likelihood of extreme events, the impacts go beyond agriculture and span across the sectoral economy of a country (Figures 1 and 2). They influence population mobility and relocation, can damage infrastructure, and shift resource use across economic and productive sectors, resulting in millions of dollars of forgone productivity. Without a good understanding of the linkages that exist between natural climate variability, anthropogenic climate change, and a sectoral economy, it will be increasingly difficult to identify technical and political solutions to efficient resource management and avenues of resilience under a changing environment.

Given the need to focus on specific research questions that can later be used to understand climate-economy dynamics across the world, India, with its vast differences in hydrogeology and complicated political landscape, provides a remarkable case study for the better understanding of arid, highly agricultural, and increasingly urban developing economies. More specifically, two of its regions, the Indian Punjab (Northwest), and Telangana (Central India, Andhra Pradesh) lend themselves to the contrast of natural resource endowments (water and hydrogeology), divergent buffering capacities in the face of climate variability, and the economic externalities of natural resource depletion. Punjab, otherwise known as the breadbasket of India, has been favored not only by the deep alluvial aquifers of the Indo Gangetic Plains but also by government subsidies that provide free electricity for irrigation and price mechanisms to support the production of rice and wheat, staple foods considered essential for India’s food security. Telangana, in the northern region of Andhra Pradesh, has long been a center of political struggle searching for independence as a separate state, and has historically suffered from recurrent droughts, numerous pests, shallow hard rock wells, and poor soils.[3,4] Still, for over seventy percent of the population in Andhra Pradesh, agriculture is the main source of employment, livelihood, and economic activity.

Despite differences in natural resource endowments, both states adapt to natural climate variability, predominantly changes in precipitation, through irrigation. With a vast, yet rapidly depleting groundwater resource, Punjab exploits its deep aquifers (extractions constrained by land availability, costs, and electricity supply) and Telangana irrigates until its shallow aquifers run dry.[5,6] Here we investigate not only the environmental consequences of unconstrained natural resource depletion (which are well documented), but make a first effort at exploring the economy wide implications of adaptation to anthropogenic climate change and natural climate variability.

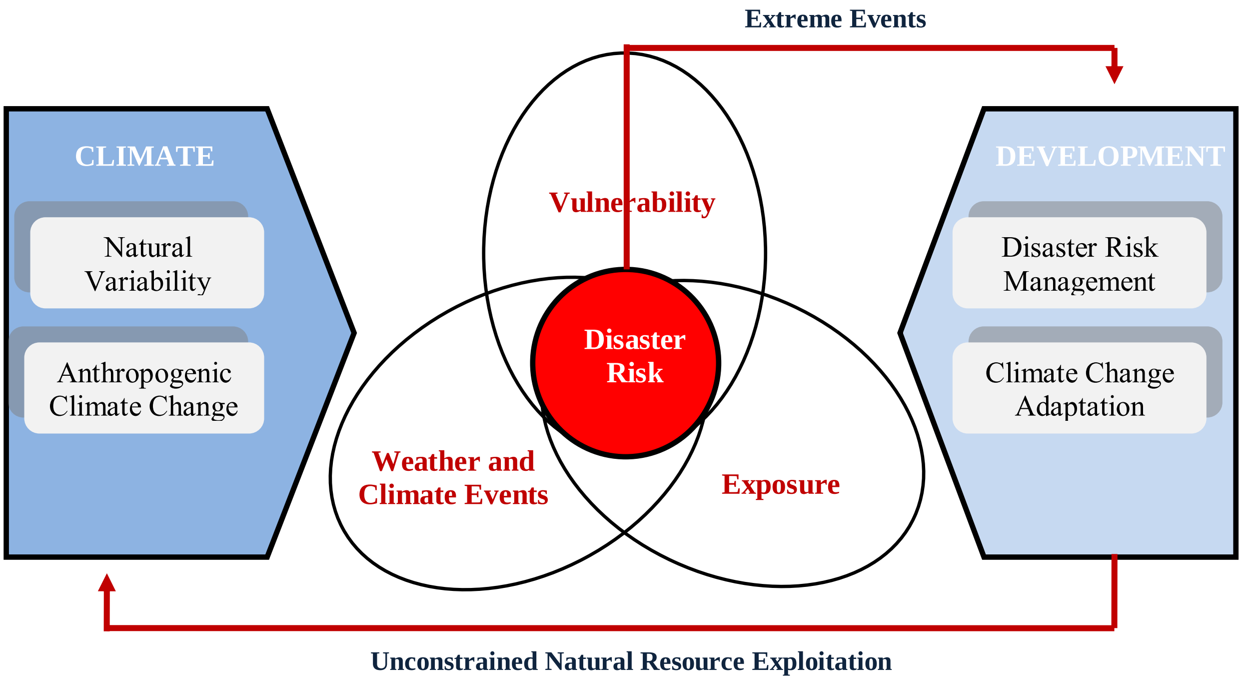


Figure 1: Climate, Disaster, Risk and Development Exposure and vulnerability to weather and climate events determine impacts and the likelihood of disasters (disaster risk). Natural climate variability and anthropogenic climate change affect climate extremes and other weather and climate events that can contribute to disasters, as well as the exposure and vulnerability of human society and natural ecosystems. Disasters and extreme events can affect a region´s development, its capability to incorporate risk management and climate change adaptation in its policy making, and likewise, unconstrained human activity (development) can affect climate and its corollaries. *Adapted from the IPCC (2011)*[1]

Several reports have begun considering the impacts of hydrology and rainfall as significant elements in economic development.[7,8] In Ethiopia, an economy-wide model used by the World Bank found that the occurrence of droughts and floods reduced economic growth by more than one third, and found that a single drought in a twelve-year period reduced economic growth by ten percent.[7] Similarly, losses in Kenya due to flooding associated with El Niño (1997-1998) and drought associated with La Niña (1998-2000) caused annual damages associated with ten to sixteen percent of the country's GDP. Researchers from the Columbia Water Center have also put forward that seasonal and inter-annual variability of rainfall is a significant factor in economic development.[9] They find that there are generally two approaches to mitigate the effects of climate variability: the hard water approach (increase water storage through investment in infrastructure) and the soft water approach (increase the efficiency of water use), with richer nations typically requiring soft water while those less developed tend to require hard water solutions.[9]

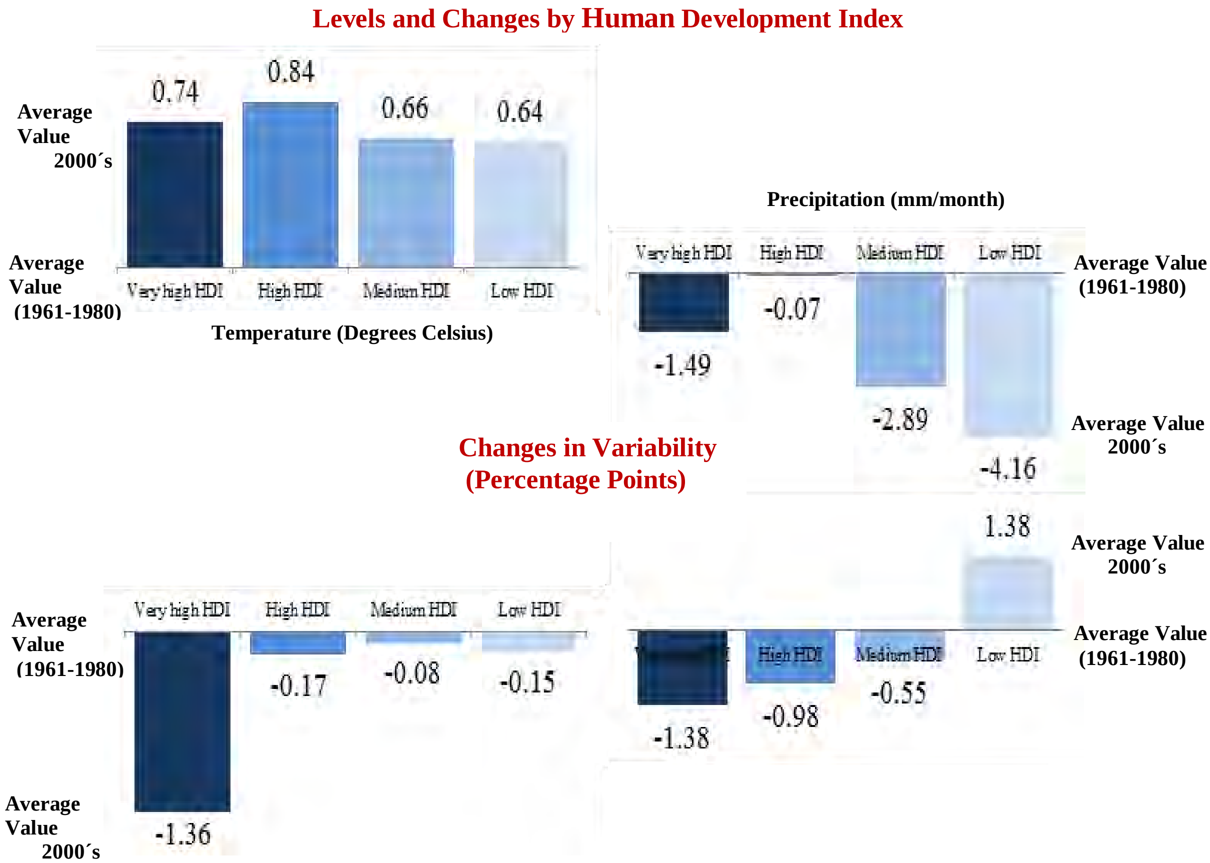


Figure 2: Increased Temperature and Reduced Rainfall by Human Development Index (HDI) Countries. In the recent decade, low HDI countries have been exposed to the largest decline of precipitation as well as the sharpest increases in precipitation variability. *Adapted from the United Nations Human Development Report 2011.*

At the zenith of the Green Revolution in India, a 1981 report by the Indian Institute of Tropical Meteorology found that years of precipitation deficiency could have a ten to fifty per cent rise in food grain prices, with agricultural production falling between five and thirty percent in the same year.[10] The impact of excess rainfall on production depend on whether the annual rain-water excess was well distributed during the year (favorable impact on production) or was concentrated in smaller periods resulting in floods (adverse impact on production). At the time, only one quarter of the gross cultivated area was irrigated and the remaining three-quarters depended entirely upon rainfall. Due to the uncertainty of rains, agriculture was considered a gamble and famine and flood in some years could considerably hamper the development activities of the country; thus, the expansion of irrigation throughout India became an important effort under the government´s rural development and Drought Prone Areas programmes.[10] Three decades later, there is no doubt that the groundwater revolution has brought immense benefits to the country, playing a major role in rural development and poverty reduction achievements.[11] At the same time, it is also now clear that the groundwater revolution has played a large role in the downfall of its own resource base, as the country now suffers severe water shortages in many of its states.[11]

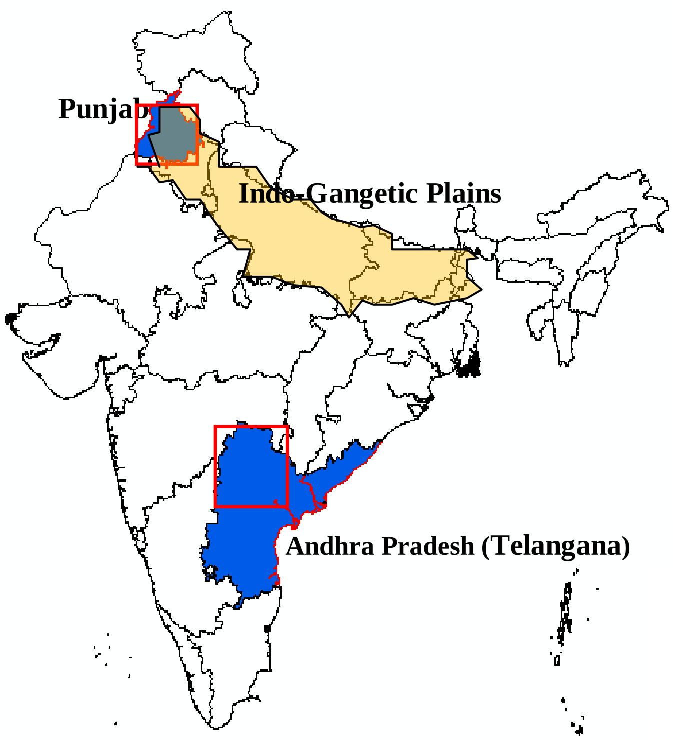
Although hard water approaches to mitigate the impacts of precipitation variability in our study regions (Punjab and Telangana) brought initial productivity and efficiency gains to agriculture, the positive effects have now been short lived, and both regions are now facing the ill unintended consequences of *adapting to* and *thriving* in an uncertain and changing environment. With India being the largest consumer of groundwater in the world, it is expected that with current extraction rates, sixty percent of its aquifers will be facing a critical condition in about twenty years.[12] In Punjab and Telangana, the electricity subsidy provided to agriculture accounts for over forty and fifty percent of the annual government budget deficits respectively, with groundwater extractions being some of the largest and costliest in the world.[11] Although groundwater irrigation indeed buffers these dry environments, the unsustainable exploitation of the resource can also result in anthropogenic climate change, groundwater scarcity and stress, a modification of the hydrologic system, a reduction in the ability to meet millennium development goals, and a divergence of benefits accrued from groundwater for small and large farmers.[12]

To date, there are few studies that have explored the widespread economic effects to *adapting* and *thriving* in an uncertain and changing environment. Hard and soft water approaches are promoted vividly in the policy arena, but little has been done to understand the dynamics and interlinkages between an uncertain climate, human activity, and the economy in which all production and activity is reflected. No good policy can come without understanding. Here, we first evaluate the hydrogeology of our two study regions, describe their socioeconomic context and finally provide a framework, through general equilibrium theory, to contextualize interlinkages, a variety of water availability scenarios, and mechanisms for policy making.

3. Hydrogeological Context

The hydrogeologies of Punjab (50,326 km^2) and Telangana (114,840 km^2) are markedly different, but their contrast and understanding could shed light into many places in the world that suffer from increasing water stress and scarcity. In these regions, as in much of India, the main determinant of agricultural productivity is water availability, and thus precipitation is fundamental in the understanding of hydrological, agricultural production, and overall economic dynamics.

A simple water balance to determine the dynamics of groundwater table takes into account precipitation as the main source of recharge and water extraction for agriculture irrigation, and other industrial and residential purposes as major discharges. Groundwater response to precipitation recharge depends on a number of factors including an infiltration factor and a specific yield related to geologic formations of aquifers underlying our regions. The inflow and outflow of groundwater is also related to the specific yield of the aquifers. The aquifers in Punjab are characterized by alluvial deep systems with relatively higher rainfall infiltration and specific yield while the aquifers in Telangana are characterized by shallow hardrock formations with relatively lower rainfall infiltration and specific yield. See Tables A1 and A2 in Appendix for more detailed values.



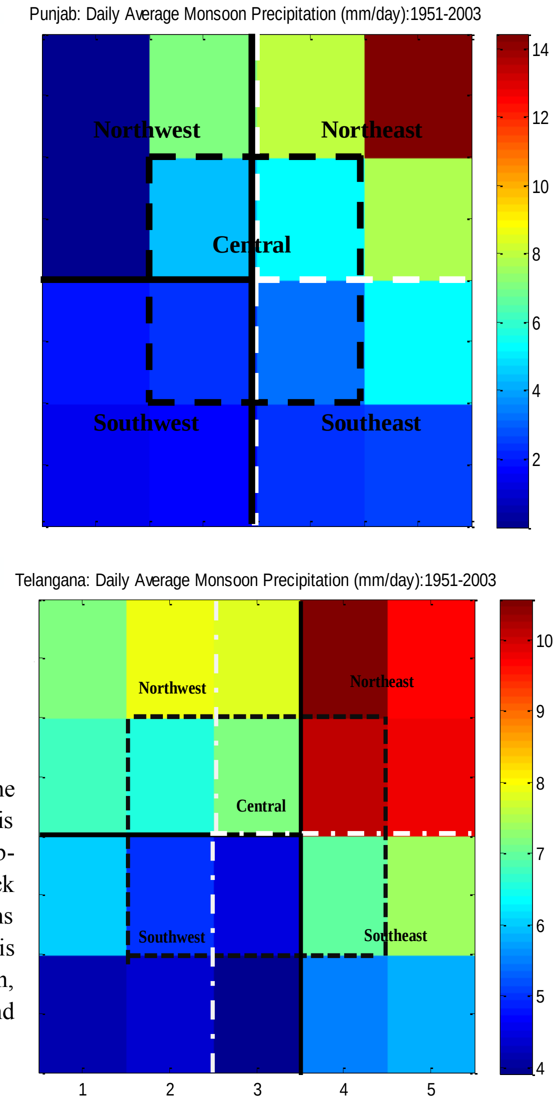


Figure 3: Precipitation Spatial Variability in Study Regions. The size of a grid is 0.5x0.5 degree (the approximate area size of a grid is 50kmx50km). In our analyses, each region was divided into five sub-sections: center (black dash), southeast (white dash), southwest (black solid), northeast (white dash), and northwest (black solid). Both regions experience a large degree of precipitation spatial variability. In this study we evaluate: total monsoon precipitation, monthly precipitation, daily precipitation, the frequency and length of dry spells, and frequency and magnitude of extreme events.

Punjab

Punjab (50,326 km^2) is located in the Northwest of India, and together with Himachal Pradesh (55,673 km^2), and Haryana (45,695 km^2) conforms the great majority of the Sub-Satluj river basin, underlain by the Indus River plain aquifer, a massive 560,000 km^2 unconfined-to-semiconfined porous alluvial formation sparsed between India and Pakistan.[13] The Satluj River (one of the main tributaries of the Indus) has its source area in the Mansarovar and Rakastal lakes in the Tibetan Plateau at an elevation of about 4,572 m.[14] After entering Indian territory, the Satluj river flows though Himachal Pradesh and Punjab, and receives runoff from snow, glaciers, and rain. The total catchment area of the Satluj river up to Bhakra Dam is about 56,874 km^2. The Indian part of the Satluj basin, covers an area of 22,305 km^2, including the whole catchment of the Spiti basin (a major tributary of the Satluj).[14]

The Indian Punjab itself is largely located in the Indo Gangetic flood Plain, a surface expression of a structural depression located immediately south of the Shiwalik Foothills of the Lower Himalayas and filled with alluvium, underlain by the Indus River Plain aquifer.[15] The hydrogeology of this massive aquifer has been amply studied, and it is well understood that the structural depression forms a deep through (>3000 m) that becomes much shallower as it extends north east from Delhi (200-1000 m).[16] The geologic formation is of marine origin, and the through is full of alluvial material deposited by the rivers from the Himalayas, with coarse to fine sediments overlaying a thick deposit of clay starting at 50 – 150 m below the surface. [17,18] Although in the north, clayey layers and medium sand and gravel deposits are intercalated, and the south is predominantly composed of silt layers, the *whole of the aquifer system can be considered as a single heterogeneous unconfined aquifer*.[15,19] The native groundwater of the Indus basin is saline (marine origin), but in their great majority, the shallow aquifers have been flushed off their salt content. Groundwater in Punjab flows from northeast to southwest with its water quality equally changing from good in the northeast (suitable for irrigation) to poor in the southwest (highly saline unsuitable for irrigation), with quality (salinity) also deteriorating (salinity increasing) with depth.[15,20] Transmissivity values from well tests range from 170 to 2600 m^2/d, and specific yield in the depth range affected by water level fluctuations is 10-15 percent.[15, 20] In essence, the groundwater resource of Punjab is rich, but as it is with every natural resource, its abundance is limited by its natural replenishment, overexploitation, and the critical depths at which it becomes saline or scarce.

Talangana

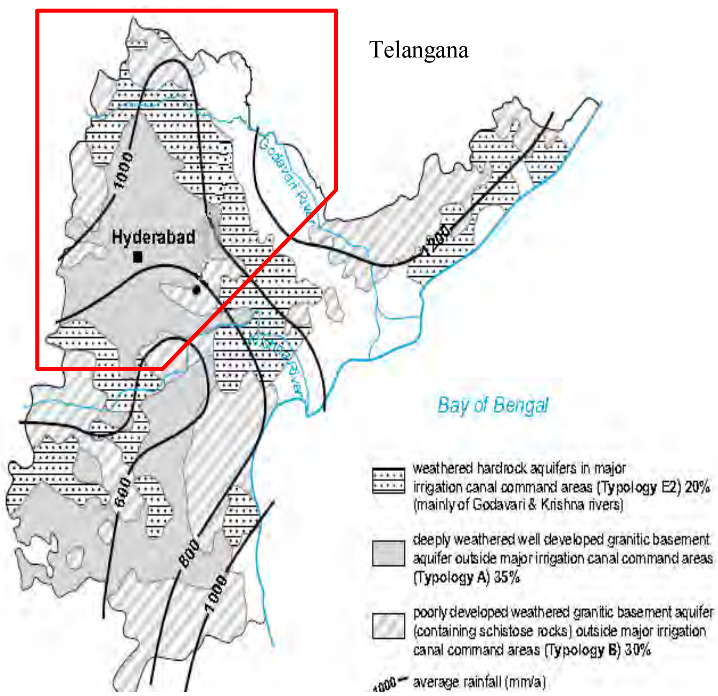


Figure 4: Hydrogeology of Telangana. Telangana is located in central India and in the northwest portion of Andhra Pradesh. There are three dominant hydrogeological typologies: A, B, and E2. Precipitation amounts decrease from north to south and more than 85 percent of total rainfall falls between June and September. Typology A suffers from intensive groundwater abstractions resulting in a continuous decrease of the groundwater table. *Adapted from the World Bank 2009*[21].

Andhra Pradesh is predominantly (85 percent) underlain by decomposed and fractured granite gneiss and granite gneiss basement rocks with negligible porosity and very limited fracturing depth.[21] Over time, these rocks have created an extensive aquifer with low storage groundwater bodies annually recharged by the monsoon. The region has three main hydrogeological typologies: (A) deeply weathered well developed granitic basement aquifers outside major irrigation canal command areas, (E2) weathered hardrock aquifers in major irrigation canal command areas, and (B), poorly developed weather granitic basement aquifer (schistose rocks) outside major irrigation canal command areas. Typologies A and E2 are predominant in Telangana of which (A) is characterized by forming more continuous groundwater bodies with greater thickness (15 – 25 m), allowing for dry season irrigation, albeit leading to groundwater scarcity and depletion due to overexploitation and/or poor monsoon season years (little recharge). (B) typologies are patchy, shallow, and thin, and are related to schistose bedrock leading to higher clay content, with groundwater storage being rapidly reduced by irrigation and dry monsoon years.[21] The command area of major irrigation canals (from the Krishna and Godavari rivers) is underlain by the E2 typology, but is little used by agriculture as most of the irrigation requirements are met by the command area irrigation provided by canal water (Figure 4).

4. Indian Monsoon

The Indian monsoon has always been a matter of life and death in India. Despite the Green and Groundwater Revolutions, precipitation is still a crucial determinant of water availability and resource use (water and electricity) for millions throughout the country. Although the deep aquifers of Punjab serve the role of a buffering system for an isolated drought, or a series of below average monsoon seasons, unrestricted groundwater extractions drop the water table further every year resulting in a myriad of environmental and economic externalities. At the same time, good monsoon seasons result in less groundwater use, recharge, and water conservation, and too much rain (in too little space and time) results in floods that can destroy an entire harvesting effort.[5] That is, even in regions with a large buffering capacity like Punjab, precipitation matters. In Telangana, precipitation is a more determinant factor for agricultural production and of sustainable livelihoods than it is in Punjab. Their dependence on large command areas and shallow aquifers means that these can provide a short lived and somewhat weak buffering mechanism. Dry seasons in Telangana can lead to food security issues, unemployment, rural to urban migration, and in the worst of scenarios, the declining height of the water table (and increase in extraction costs) can lead to farmer suicides. Here as well, precipitation matters.

As central as it is to the hydrologic system, we focus our study of precipitation on detecting trends and investigating key parameters that can explain how the system has been evolving over time: total monsoon rainfall and monthly rainfall for each of the monsoon months (June, July, August, and September), the frequency and length of dry spells (rainfall below 0.1 mm), the spatial distribution of rainfall (northeast, northwest, center, southeast, southwest), and the frequency and intensity of extreme events (Figure 3).[22,23,24,25,26] We use a 0.5x0.5 degree precipitation grid developed by the Indian Institute of Tropical Meteorology (IITM) from more than 6000 rain-gauge stations over India (1951-2003) and which uses a well-known interpolation method (Shepard's method) to interpolate the station data into regular grids of (0.5x0.5 degree) Lat x Long.[27]

Monsoon rainfall in both Punjab and Telangana comprises over 80 percent of the total rainfall that falls during an entire year. Of total monsoon rainfall, only 10 percent and 15 percent of the total falls in June in Punjab and Telangana respectively, and over 70 percent and 60 percent of the monsoon total falls in the months of July and August (*monsoon and monthly totals are daily aggregates for every year from 1951 to 2003*). There are no obvious trends in monsoon totals (Figure 5), but a closer analysis of monthly and daily events reveals that there are indeed trends in the amount and variability of rainfall in both Punjab and Telangana.

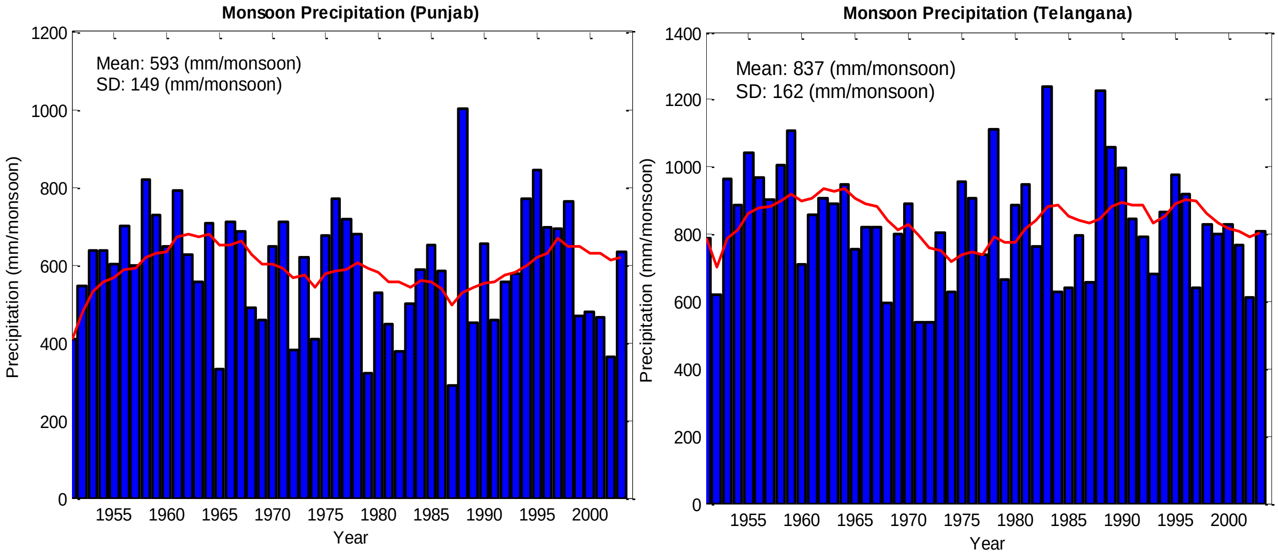


Figure 5: Total Monsoonal Precipitation. Total monsoonal precipitation was computed from daily aggregate rainfall data as developed by the Indian Institute of Tropical Meteorology (IITM). A 10 year moving average was used to detect trends in the data (red).

Punjab

In Punjab, precipitation in June has increased markedly over time, following a 10 year moving average, with monthly precipitation increasing almost by 90 percent comparing the 1951-1959 and 1990-2003 time periods (21 percent higher than the long term average). July and August, on the other hand have experienced a slight decrease over time, following a 10 year moving average, with the 1990-2003 time periods being 8 percent and 5 percent lower than the 1951-1959 time periods, respectively and 4percent and 1 percent lower than the long term average. No clear trend can be depicted for September (Figure S-1 in Supplemental Materials). In terms of daily monsoonal precipitation, mean daily precipitation has increased for June and slightly decreased for July and August. The coefficient of variation has increased steadily over time for August, and extremes at the 99th percentile have increased for June and August. As the data was divided into five time periods (1951-2003) the 99th percentile was defined for every time period (Table S-1 and Figure S-2 in Supplemental Materials).

There is also a large degree of precipitation spatial variability in Punjab. Total monsoon precipitation declines from around 1000 mm in the hilly north-east of Punjab and gradually decreases (from northeast to southwest) to around 200 mm (per monsoon season) in the southwest (Figure S-3 in Supplemental Materials). In terms of regional daily monsoonal precipitation, precipitation in the northwest daily amount has increased steadily over time as well as the variability (coefficient of variation) in both the southeast and southwest (Figure S-4 in Supplemental Materials).

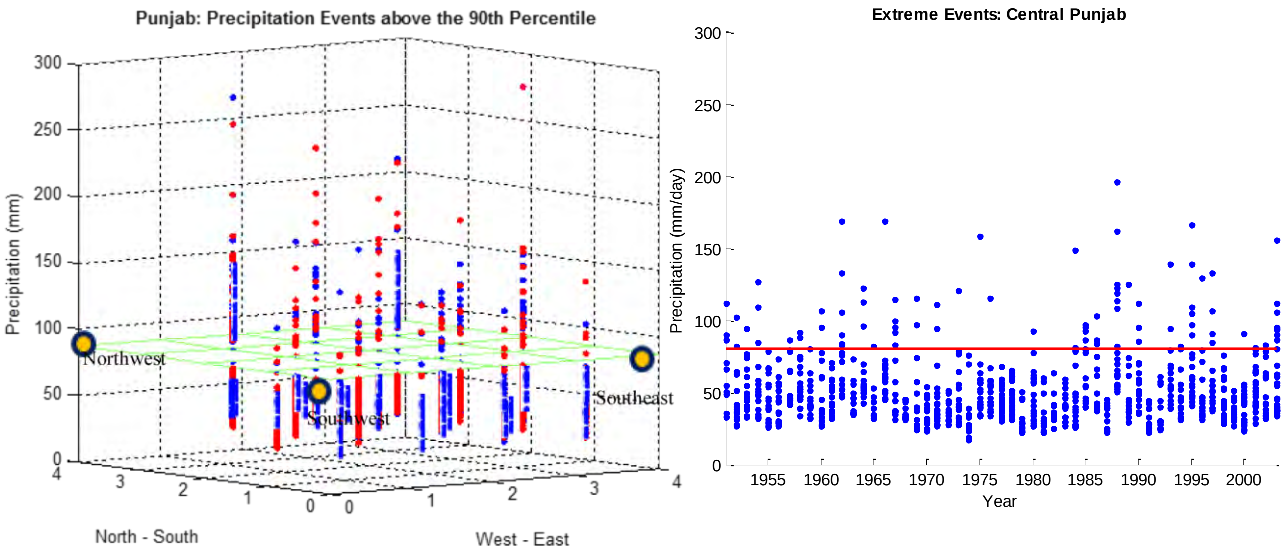


Figure 6: Punjab Magnitude and Frequency Extreme Events. Local extremes (above 90th percentiles) are compared relatively to the spatial average extreme (99th percentile of entire samples shown by green mesh) (left). The 90th percentile was computed for all values in a year over Punjab (122 monsoon days*14 grids: 1708 values per year), and the values above the 90th percentile were plotted in each grid. Blue data points are those before 1980 and red data points are those post 1980. The 99th percentile was computed for all values for all years. Notice that the largest values in most grids are shown as red indicating that the frequency and intensity of extreme events have increased since the 1980´s. No data are available for 2 grids in the Northwest section. The 90th percentile for the central Punjab each year (right) is plotted over time. (See Figure A-1 in Appendix for other regions in Punjab.)

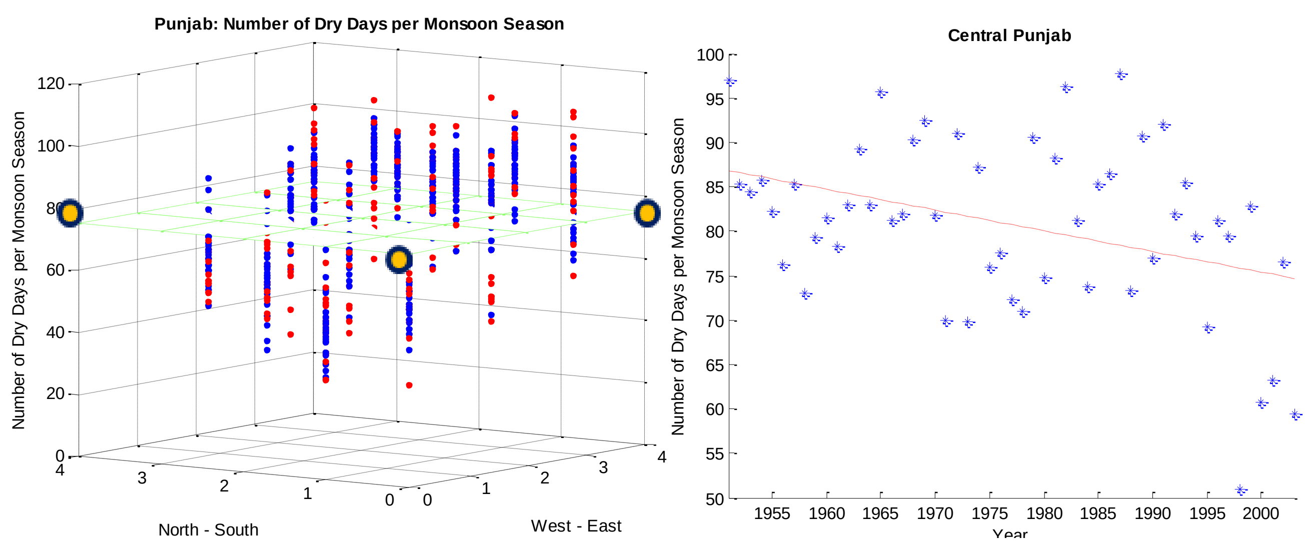


Figure 7: Punjab Magnitude and Frequency of Dry Days. Over time, and on average, the number of dry days per monsoon season has been decreasing throughout the entire region. The green mesh represents the sample mean (75 dry days per monsoon season). The blue data points are those before 1980 and red data points are those post 1980's. The number of dry days has a decreasing trend in central Punjab (right) and other regions in Punjab (See Figure A-2 in Appendix for other regions.)

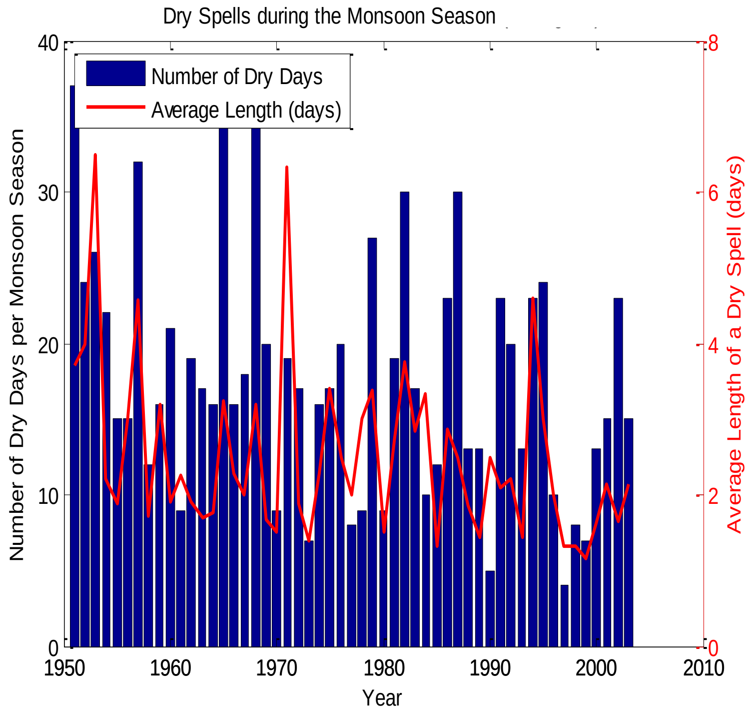


Figure 8: Punjab Dry Days and Spells. The number of dry days is computed when the entire region of Punjab was without rain. Both the number of dry days and average length of a dry spell have declined over time.

A regional analysis of Punjab depicts that the number of dry days (and the length of a dry spell) has been decreasing over time over the entire region (Figure 8) as well as each region (Figure 7), whereas the frequency and magnitude of extreme events have been increasing (Figure 6). Both Northwestern and central Punjab are the areas with the steepest decline in the number of dry days per monsoon season, dropping from 76 to 61 and from 87 to 75, respectively (Figure A-2 in Appendix). The magnitude and frequency of extreme events has increased predominantly in the central, northeast, and southeast portion of the state (Figure A-1 in Appendix). A decrease in the number of dry days does not suggest that there is more precipitation in the state, as there has not been an increase in total monsoonal precipitation. It suggests, however that there is an increase in the magnitude of extreme events on the average. This implies that more remedial measures should be put in place to alleviate some of the damage and tragedy that ensues with flooding events in the region, including crop loss.

Telangana

Telangana, overall, receives more rain than Punjab, but lacking in water infrastructure it is of little use to the agrarian economy without proper development and management.[28] Here, September is the only month for which a steep declining trend is observed using a 10 year moving average, with monthly precipitation decreasing over 20 percent comparing the 1951-1959 and 1990-2003 time periods and 14 percent lower than the long term average. No clear trend can be depicted for the other months (Figure S-5 in Supplemental Materials). In terms of daily monsoonal precipitation, mean daily precipitation and the coefficient of variation have decreased for September. On the other hand, extremes at the 99th percentile and the coefficient of variation have increased for July and August, particularly since the 1980's (Table S-2 and Figure S-6 in Supplemental Materials). Over our study region, the coefficient of variation (variability) has increased steadily since the 1970´s with large fluctuations in the standard deviation of mean daily monsoonal precipitation. See Figure 11 (left figure).

The Telangana region has also a large degree of precipitation spatial variability. Total monsoon precipitation declines from around 1100 mm in northeast Telangana and gradually decreases (from northeast to southwest) to around 500 mm (per monsoon season) in the southwest. The precipitation gradient also moves from North to South, with northeast, northwest, and central Telangana averaging 1120 mm, 880 mm, and 810 mm per monsoon season; a clear difference from the 600 mm/monsoon occurring in southern Telangana (Figure S-7 in Supplemental Materials). In terms of regional daily monsoonal precipitation, the coefficient of variation has increased steadily over time, particularly in northwest, northeast, and central Telangana (Figure S-8 in Supplemental Materials).

With the already difficult hydrogeology and shallow aquifers of Telangana, the region is currently facing two different yet serious challenges: a slow, yet steady increase in the number of dry days per monsoon season and the magnitude and frequency of extreme events. Although on average the number of dry days has only increased from 40 to 46 days per monsoon season *over the entire region* (1951 – 2003), these numbers mask some of the changes that are occurring disparately *throughout* the region. Central and northwest Telangana are close to the regional average, but the number of dry days in the northeast has increased steadily from 26 to 35 dry days per monsoon season from 1951 to 2003, almost a 35 percent increase (Figure A-4 in Appendix). Similarly, a linear trend depicts the number of days *above the regional average* to be steadily decreasing overtime. See Figure 11 (right figure). The frequency and intensity of extreme events have also been increasing over the entire region (since the 1970's), except for southwest Telangana, which is also the driest region in the state (Figure A-3 in Appendix). Without the infrastructure to store and distribute water more efficiently it is likely that the occurrence of these events will only bring harm to a region that is already plagued by economic issues related to poor water management and scarcity.

Recent research supports our findings. Satellite-based vegetation data sets have suggested that agricultural intensification and an increase in the normalized differential vegetation index (NDVI) for March-April have recently decreased July and total monsoon seasonal precipitation in Northwestern India (Punjab, Haryana, and Western Uttar Pradesh).[29,30] Here, pre-monsoon soil wetness has increased by about 300 percent between 1988 and 2002, correlating well with a rapid growth in tube well usage and with the advancement by about 4 weeks of the average rice crop cycle (cultivation to harvest). Hence, it has been suggested that the shift from monsoon based irrigation to groundwater irrigation during the replanting stage of the rice crop has increased soil moisture to the point that it has become a dominant regional forcing with the potential of altering regional circulation and precipitation patterns. Other research also confirms our results by suggesting a statistically significant increase of total precipitation in June, and a decreasing trend for July and August over Northwestern India.[31] Although the literature remains inconclusive in the events of extremes,[32] our study suggests that extreme events have been increasing both in frequency and intensity.

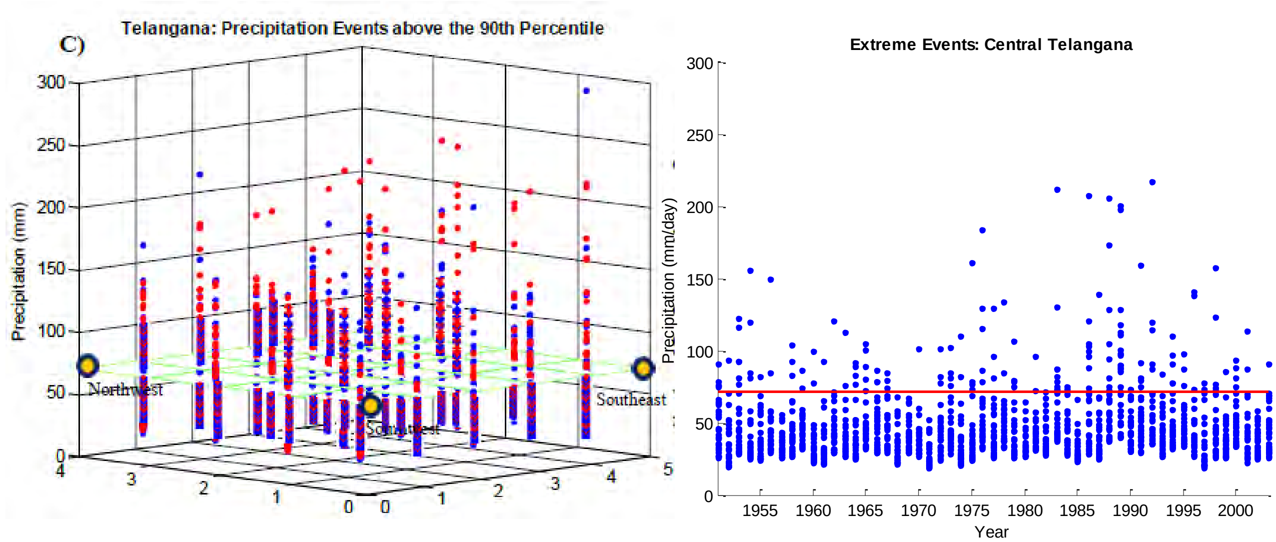


Figure 9: Telangana Magnitude and Frequency of Extreme Events. Local extremes (above 90th percentiles) in Telangana are compared relatively to the spatial average extreme (99th percentile of Telengana's entire samples shown by green mesh) (left). The 90th percentile was defined for all values in a year over Telangana (122 monsoon days*20 grids: 2440 values per year), and the values above the 90th percentile were plotted in each grid. More red data points (after 1970) are noticed as extreme events than the blue data points (before 1970). The 90th percentile as extreme events for central Telangana is plotted over time where the red line indicates the 99th percentile of the entire samples (right). For other regions in Telangana, see Figure A-3 in Appendix.

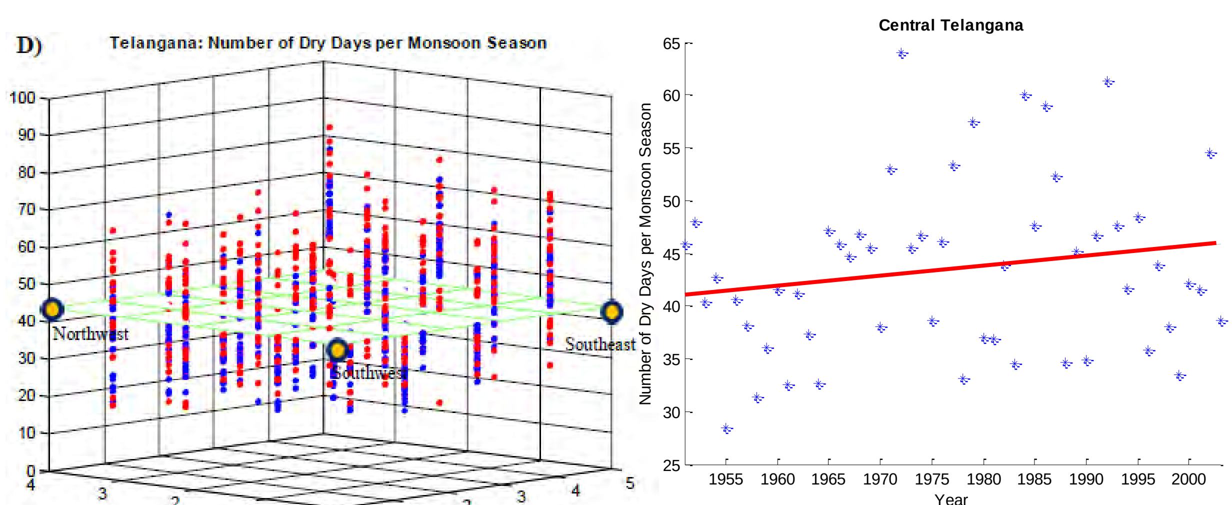


Figure 10: Telangana Magnitude and Frequency of Dry Days. The number of dry days per monsoon season has been increasing throughout the entire region. Blue data points are those before 1970 and red data points are those post 1970´s. The green mesh represents the sample mean (43 dry days per monsoon season). The number of dry days in the central Telangana shows an increasing trend over the last half century. For other regions in Telangana, see Figure A-4 in Appendix.

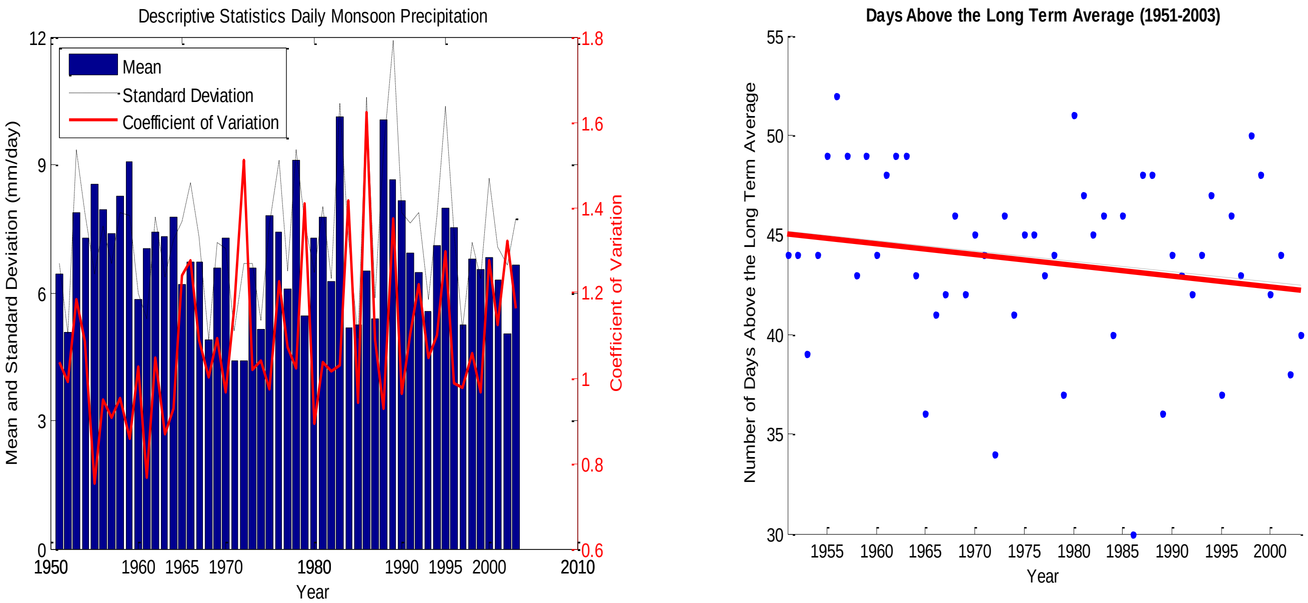


Figure 11: Telanagana Variability of Daily Precipitation and Decreasing the Number of Days. Daily monsoonal precipitation (left) has remained steady over time but there has been an increase in the coefficient of variation. The number of days above the long term mean (right) for daily monsoonal precipitation is declining over time.

5. Water Scarcity, Stress, and Adaptation

Punjab

The Indian Punjab has never been an area suitable for rice crop production. It has been estimated that the annual average crop evapotranspiration from the irrigated rice-wheat rotational system predominantly found over Punjab is of 964 mm, exceeding annual average rainfall by 128 mm.[15,33] Data also indicate that rice irrigation techniques are very inefficient, with irrigation water being applied excessively beyond rice´s theoretical requirement and with rainfall usually balancing or exceeding crop water use requirements (evapotranspiration), even after allowing for the fact that the monsoon does not start until three weeks after the crop has been transplanted and root zone has been saturated by the farmer.[15,34] Wheat on the other hand, benefits from rice irrigation´s inefficiency, as there is residual soil water available after rice and thus the annual amount of water being applied to wheat is much closer to its theoretical requirement.

Among other things, India's Green Revolution brought new high yielding and input-responsive rice and wheat varieties to Punjab, which were exploited not only by an incredible expansion of groundwater and tube well use but also by a wide variety of institutional and policy factors.[35] Farmers were provided with a high minimum support price for rice (and ensured delivery market) accompanied by cheap institutional credit and subsidies to foster investment in irrigation, including tanks, wells, pump-sets and irrigation structures.[6] Since then, energy for irrigation has been heavily subsidized, and virtually free for farmers in Punjab, encouraging activities such as over-irrigation, the use of inefficient and poor quality motors, and otherwise inefficient irrigation activities where farmers do not experience the marginal cost of electricity use, or water extraction, resulting in a wide variety of environmental and economic externalities.[6] While rice area in Punjab almost tripled (0.39 to 2.48 Mha) and wheat increased one and a half times (from 2.29 to 3.42 Mha) between 1970 and 2002, tube wells fuelled this expansion growing by a factor of twelve between 1960 and 2008 (0.1 million to 1.2 million): all these also leading to rapid declines in groundwater levels.[36,37] Over the last 20 years, the water table has declined between 5 and 15 m in 11 districts across Punjab and Haryana, and the average depth to the water table in districts of central Punjab increased between 15 and 28 meters by 2006.[38] At this rate, it is predicted that by 2020 the water table will fall below 10 m in 75 percent of Punjab, and by 2025 it is expected that 42 of 134 blocks (39 percent) will have water tables deeper than 30 meters, making it impossible to pump out groundwater using hand pumps or small submersible pumps (critical depth). Of these, the water table will fall beyond 40 meters in 30 blocks, 50 meters in 6 blocks, and 60-90 in 4 blocks.[15,38]

The results of India´s latest Central Ground Water Board report[39] were alarming. Of 138 blocks in 17 districts of Punjab 103 (74 percent) of them were exploited (extractions are 100 percent more than annual replenishment), 5 were critical, and 4 semi-critical. The stage of groundwater development was stated at 145 percent, the annual replenishable groundwater resources at 24 BCM, the net annual groundwater availability at 22 BCM, and the annual groundwater draft at 31 BCM; that is, in 2007 Punjab was overdrafting its groundwater resource by 45 percent.[39] It is stated that in central Punjab, the region with the most severe drafting problem, the water table fell 18 cm/year from 1982-1987, 42 cm/year from 1997-2002, and to 75 cm/year during 2002-2006.[6,40] A 2010 report from the International Water Management Institute (IWMI) is also alarming putting Punjab´s gross irrigated area at 97 percent with an irrigation water deficit of (-) 1.41 m ha m, with an irrigation water demand of 4.45 m ha m but only 3.04 m ha m for total water irrigation water availability (surface: 1.43 m ha m, groundwater (net draft): 1.61 m ha m).[41] It is true that skewed economic incentives and subsidies to agriculture have fostered Punjab´s groundwater depletion. However, it is also true that farmers have learned to adapt to changes in weather and climate by adjusting their groundwater resources depending on the availability of rainwater. In fact, although the cost of digging deeper wells and buying more powerful pumps increases in the everlasting chase of the receding water table and depleting groundwater resources, anecdotally farmers are equally worried of floods and pests, two catastrophes that are equally as present and catastrophic as droughts and scarcity.[42]

In recent research, Fishman found that in India five of the eight rainy season crops are all affected by total rainfall in a statistically significant manner ($p< 0.1$) and in a negative way (losses of about 3 percent to 5 percent per standard deviation in reductions of total rainfall).[26] Most crops are estimated to suffer from increased heat (degree days), but only rice yields in a statistically significant manner (at 3 percent per standard deviation decrease). In the monsoonal season, and among the intra-seasonal distributional measures, Fishman finds the frequency of rainy days to emerge as a dominant force with its statistical significance being constant across crops. In this research, all crops show a statistically significant negative response to a reduction in the number of rainy days (increase in the number of dry days), even when total rainfall is controlled for, with impact per standard deviation in the range of 4 percent to 8 percent. After controlling for irrigation coverage (no irrigation to full irrigation) the impact per standard deviation on rice yields falls from 9 percent to 1 percent. In the dry season his research finds that most crops are more affected by monsoon rainfall totals than by the frequency of rainy days. The impact on wheat, while negative, is not statistically significant ($p=0.15$) given that wheat is a highly irrigated crop (about 80 percent of the area cropped with wheat is irrigated). In the case of wheat, his only robust finding is that more irrigated districts tend to be less vulnerable to the impact or dry season degree days, both across districts and over time. In summary he finds that when irrigated water supply per unit area is uncorrelated with the same weather conditions that influence yields, irrigated yields will be higher and less sensitive to weather, and the irrigated area will respond to 'good' weather, and if the water supply is responsive to weather conditions, yields may actually be more sensitive and irrigated area may actually increase in response to 'good weather'.

Our research in Punjab finds that irrigated area adjusts and increases in drought years (farmers adapt to variability through irrigation) and that extreme events (wet and dry) have a marked impact on agriculture (Figures 12 and 13, Data source: Centre for Monitoring the Indian Economy[43]). We find that despite the incredible growth of irrigation and production brought on by the groundwater evolution (time trend), isolated extreme dry years and dry year periodicities (prolonged years of below average precipitation) signal an expansion in irrigated area. The year of 1979 marked the beginning of a prolonged dry periodicity that lasted 9 years, and with it, came along one of Punjab´s longest and largest increases in irrigated area. In this time period only 1985 was a year marginally above precipitation's long term average, but irrigated area more than doubled in size (from 806 to 1,805,000 hectares), serving its role as a buffering system, protecting modest yet important increases in agricultural productivity. Year 1999 also marked the beginning of a prolonged dry periodicity, and the single largest year-to-year increase in irrigated area that Punjab has experienced: an increase of over 235,000 irrigated hectares in one year, marginally maintaining crop productivity above zero, and fueling its growth by an electrical generation increase of over 16 percent (3,000 million kWh) between 1998 and 1999 (Figures A-5 and A-6 in Appendix). The drought of 2002 however, was not buffered as electricity generation could not keep with demand, resulting in a necessary reduction in irrigated area and consequently agricultural productivity. Similarly, the devastating floods of 1988 and 1996 brought consequences to agricultural productivity in Punjab. Despite a reduction in the size of irrigated area, the floods in September of 1998 reduced crop output by almost 600,000 tonnes and the floods of 1996 reduced output even further by over 800,000 tonnes in year-to-year fluctuations.

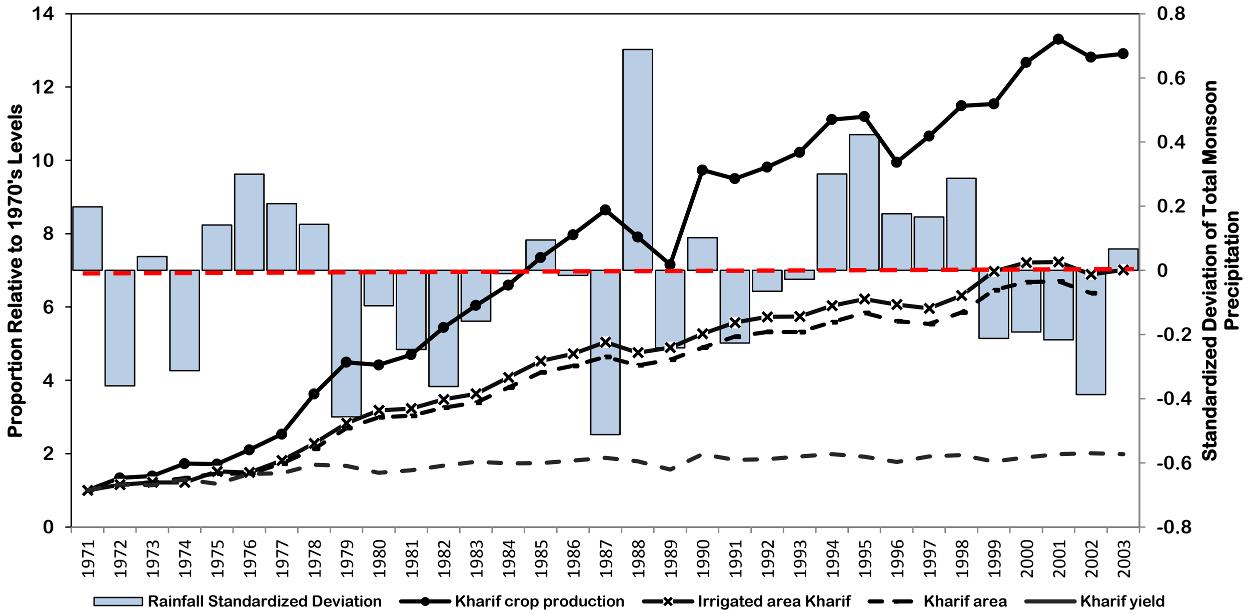


Figure 12: Punjab Rice in the Wet Season. It is remarkable that the rice production has increased by more than ten-fold since the 1970s. The irrigated and sown areas show a steady increase over time in Punjab as well. This leads to the relatively flat rice yield. The long term increase in rice production is likely to be associated with the expansion of groundwater irrigation. The irrigated area kept increasing even in the long period of drought beginning in 1979. The floods of 1988 and 1996 devastated the production of rice of the region. The changes in values are shown in Figure A-5 in Appendix. Data Source: Centre for Monitoring the Indian Economy (CMIE)

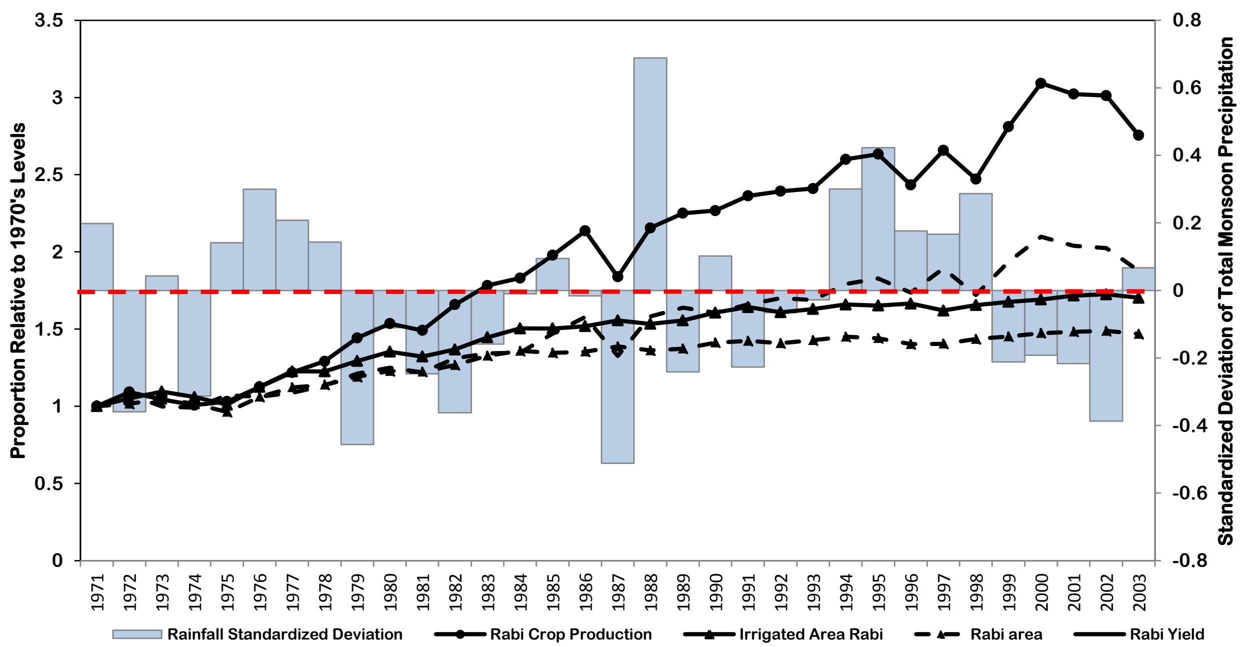


Figure 13: Punjab Wheat in Dry Season. Wheat in Punjab is also irrigated. Wheat production as well as irrigated area in the dry season have increased over time though the rate of expansion is less drastic than the case of rice. While the irrigated area in the dry season increased in the drought period of the 1980s, it has been relatively constant since the 1990s unlike the case or rice. This is consistent with the close movement of production and yield of wheat. The wheat production was less affected by the floods of 1988 and 1996. The changes in values are shown in Figure A-6 in Appendix. Data Source: CMIE

Telangana

Telangana's experience with water and agriculture has been a painful one. Long considered an agricultural backward and stagnant state, lagging behind coastal Andhra Pradesh in agricultural productivity, many political activists have blamed the lack of investment in irrigation, and the insufficiency of resources, on the variability of output that the region experiences.[44] The region began receiving international attention during the 1997-1998 drought, when hundreds of cotton farmers committed suicide due to a bad combination of below average rainfall, poor yields and cotton prices, pest, and the immiserating debt resulting from ever increasing costs of deeper wells and bigger pumps.[45] The beginning of the 1970's were crucial for Telangana, when more investments were made into increasing agricultural production, and as a result, its output within overall Andhra Pradesh agricultural production rose from around 30 per cent in 1970 to nearly 37 percent in 2001.[45] In a region with a low buffering capacity, however, growth has its limitations as it comes accompanied by an increase in rural poverty as well as significant decline in the consumption levels of both marginal peasantry and agricultural laborers during the last two decades.[46] Financially, and because groundwater irrigation needs a relatively large amount of private capital investment, small farmers have had to borrow to merely survive and remain competitive. In terms of the resource itself, the long-term sustainability of the aquifers are in peril as the districts that have sustained the highest growth rates are also the districts with the highest number of suicides amongst farmers, and with the most alarming rates of groundwater depletion.[46]

India´s latest Central Ground Water Board report[39] puts the minimum range of water availability at 1.4 meters below the ground level (mbgl) and the maximum at 29 (mbgl). It states the net annual groundwater availability at 13,000 million cubic meters (MCM), the net annual draft at 7000 (MCM) and the resource balance at 6000 (MCM) with a groundwater stage development of 60 percent. Of 448 revenue mandals (administrative districts), 247 are safe (<70 percent of net available resource), 91 are semi critical (70-90 percent), 32 are critical (90-100 percent), and 77 are over exploited (>100 percent). A 2011 report from the World Bank states that in the last 40 years the number of dug wells remained at about 0.9 million, but with an increasingly large portion falling dry or becoming 'seasonal'. In the last 25 years however, there has been incredibly rapid growth to an estimated total of about 1.74 million and groundwater irrigation doubling in size to over 3 million ha. Typology E2 (weathered granite basement) in Telangana has little demand for irrigation given that it falls within the command area of major irrigation canals that derive from the Godavari and Krishna Rivers (Figure 4), raising the cost of groundwater irrigation relative to that provided by the canal.[12] Typology A however, has experienced rapid groundwater table declines since the 1980's, and only experiencing partial and temporary recoveries in years of exceptional rainfall.[12] Pre-monsoon water-levels have experienced a net fall of 10-15 m during the 1995-2005 time period with dug wells drying-up early in the rainy season and the reduction and failure of bore well yields becoming ubiquitous as the water-table passes the critical depth of 15-25 meters.

In hydrology, and given a constant level of effort (extracting capacity of farmers), the stochastic dynamics of an aquifer converge to a steady state probability distribution that depends on the parameters of the model, and particularly, the aquifers thickness.[5] Results on the statistical analysis of water table dynamics also suggest that we expect mean extractions to decline and their variance to increase towards steady state levels, when starting by extracting a higher amount from a relatively saturated aquifer.[5] This suggests that water extractions are much more variable in Telangana than in Punjab. The Telangana aquifers is rapidly converging to a steady state while Punjab's water tables are still far away from a steady state, and its current variability is lower than its theoretical ultimate steady state value.[5] In the opposite situation as Punjab, Telangana already experiences what the latter could face in twenty years (steady state). Annual declines in water tables in Telangana are lower when the starting depth to water is deeper (after a dry year or a series of dry years), with extraction and losses both being comparable in magnitude to the aquifers storage.[5] Results suggest that years in which pre-monsoon water tables are lower by 100 mm, rice cultivated area in the wet and dry seasons tend to be lower by 8 percent and 14 percent respectively. In general, rice yields are less responsive to both water tables and precipitation than are cultivated areas, indicating that farmers respond to water scarcity by changing the size of the area cultivated *rather than the rate of water use per unit area*: a one meter decline in depth to water leads to a 4.5 percent and 13 percent reduction in irrigated areas in the dry and wet seasons respectively.[5]

Our research in Telangana, with a much lower buffering capacity than Punjab, also suggests that variability and extreme events have a more marked impact on irrigated area and agricultural productivity, particularly within-year and year-to-year fluctuations than in Punjab. Here, the inability of the hydrogeology to function as a long-term buffering system means that within-year and year-to-year variability has a marked impact on irrigated area, crop production and yields for both paddy and wheat, in both the wet and dry seasons. In other words, an extreme event and large variability this year will have a marked effect this year, and the next, although variations in the hydrologic system are more deeply felt in the dry season, as they depend on the monsoon's recharge for groundwater irrigation. Telangana also follows wet and dry periodicities, and experiences extreme events, but here irrigated area and crop productivity follow the periodicities and do not grow despite them: irrigated area will drop continuously following years of below average precipitation and will recover with those above it; and agricultural productivity will follow irrigated area but will immediately feel the beneficial impacts of an average or above average season. Take paddy and wheat in the dry season: from 1971 to 1975 Telangana's paddy experienced a dry period in which irrigated area decreased in 1971 and 1972 following the meager rains, recuperated in 1973 with average rainfall, and dropped again in 1974. Monsoon paddy depends on within-year rainfall and year-to-year recharge in years of below average precipitation. Although irrigated area can increase following years of good rainfall (e.g., 1983 and 1984), and adapts to below average years through irrigation (e.g., 1984), prolonged dry periodicities cannot be sustained, and lead to heavy losses due to the weak buffering capacity of the aquifer (e.g., 1984-1988 and 1992-1998). Although only paddy is grown in the monsoon season, paddy in the dry season heavily depend on year-to-year water table depth and within-year monsoon rains for groundwater irrigation. Dry periods will be harsher on dry-season productivity relative to the wet season, and consecutive wet years will recharge the aquifer, increasing productivity (Figures 14 and 15).

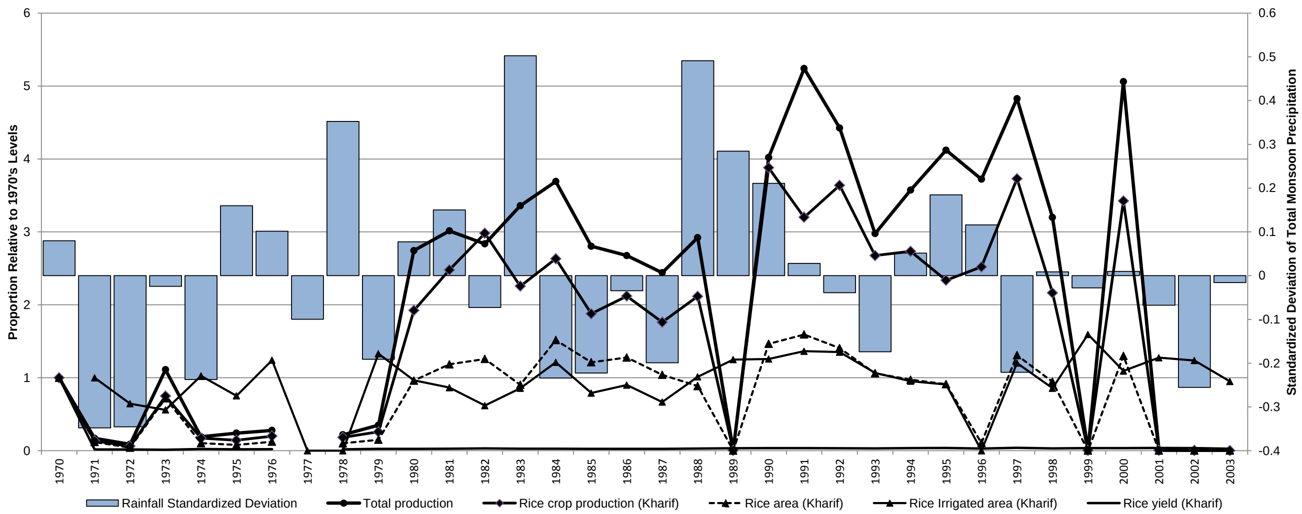


Figure 14: Telangana Rice in the Wet Season. Unlike Punjab, there is no clear long term trend of irrigated area and production of rice in the wet season in Telangana. This is consistent with the limited buffering capacity of aquifers in Telangana. In the 1980s, when the monsoon rainfall was lower for several years, the irrigated area also decreased. On the other hand, when the rainfall was greater than the average in the late 1980s, the irrigated area increased. The changes in values are shown in Figures A-7 in Appendix. Data Source: CMIE

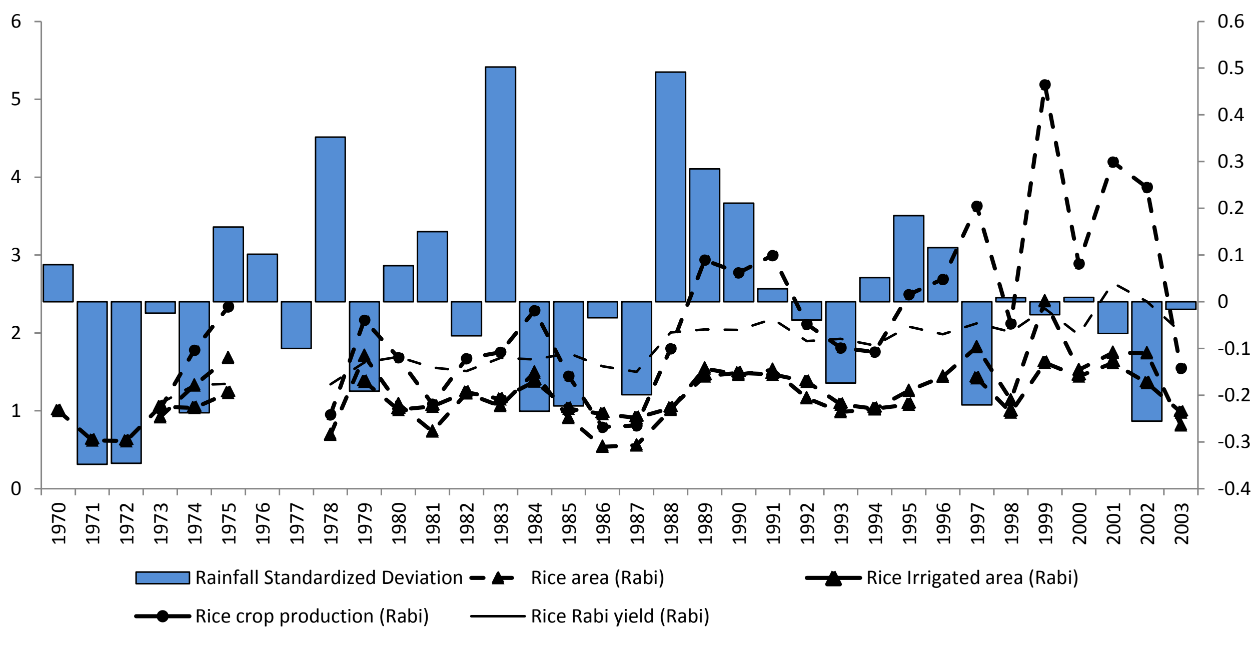


Figure 15: Telangana Rice in the Dry Season. Similar to the case of wet season, rice irrigated area tends to decline when there was a drought period and increase when there was a surplus of rainfall. The surplus of rainfall in 1978 might have reflected in the increase in the irrigated area in 1979 and the deficiency of rain in the following year may have cause the drop of the irrigated area in the next year. Similar incident can be seen in the early 1980 to the late 1990. The lagged change of the irrigated area associated with the precipitation variability is consistent with the fact that monsoon rain recharges the groundwater in the following years. The changes in values are shown in Figure A-8 in Appendix. Data Source: CMIE

An example of a transformer used for groundwater pumping that is ubiquitous over Punjab

A Punjabi farmer begins transplanting rice and flooding the rice paddy in early June. Land owners and managers are usually Sikh Punjabi´s and workers are mostly from Bihar, one of the poorest states in India. Anecdotally, land owners are reporting that costs continue to increase with time, and at a faster rate than the minimum support prices assured for rice and wheat by the Indian government. Not only do the wells have to be deeper and the pumps more powerful, but fertilizer, labor, and capital costs have all been increasing with time.

6. Economic Context

Implications for long term food security. Implications for industrial development and economic growth. Agriculture and water scarcity. Irreversible ecosystem tipping points. These are phrases commonly used by the scientific community to outline the changes that might arise from natural climate change and unconstrained human activity. Research on the Indian monsoon is a popular topic in hydrology, trend identification and constraints to agriculture production are equally popular. Scientists have begun to measure the rate at which human activity depletes the resources on which agriculture depends for survival. It is usually thought that informing the general population about a specific environmental problem, and shedding light on the perils that human activity is having on an ecosystem, will bring changes at the highest levels of government and policy making. The truth is that day after day, our knowledge of the ecosystems in which we live in is getting better, but agricultural and industrial habits, the way our government makes policy, and needs of an ever increasing population have not adjusted to the fact that our world and its resources have limits. As scientists, we need to translate the implications of hydrological variability, climate change, and anthropogenic induced climate change into issues that are immediate to the people that live within an ecosystem. Indeed water depletion will bring about scarcity, food security issues, and problems related to economic growth, but what really matters is what happens to human welfare. Jobs and livelihoods are lost. Rural to urban migration accelerates poverty in rural and urban areas. Governments create policies to aid the problem with the potential of exacerbating to the point threatening depletion of the water resource, and forcing society into a delayed resource-less adaptation. Here we summarize some economic externalities of environmental degradation in Punjab and Telangana, ranging from large government deficits feeding the electricity supply of Punjab to meager government employment programs in Telangana to fight rural-urban unemployment and poverty.

Punjab

Punjab's economy has grown impressively since the 1940's, and the 1960's exemplary growth rates supported economic development models that were based on import-substitution strategies, that as of late have not brought growth to the region.[47] Economic performance across sectors in Punjab has shown substantial differences in the past with agriculture, business services, construction, mining and quarrying, and trade, showing below average performance and deceleration comparing the 1960's and 1990's time periods. At the same time, the fishing sector, banking and insurance, electricity, gas, water supply, manufacturing, transport, storage and communication, and livestock have experienced surprising growth.[47] The agricultural sector has slowed from a 5 percent growth rate in the 1980's to 2 percent in the 1990's, with deceleration being more significant after segregating crop agriculture and livestock: crop agriculture grew at 0.37 per cent and the latter at 5 percent. The share of agriculture in Punjab's state domestic product (SDP) has also decreased from 53 percent in the 1960's to 24 percent in the 1990's. On the other hand, livestock has grown with its share of SDP increasing from 11 percent in the 1960's to 17 percent in the 1990's, with manufacturing (8 percent vs. 21 per cent), electricity and construction (2.2 percent increase), and banking and insurance (5 percent increase) all growing in the same time period.[47] These growth rates suggest changes in the economic structure of the state economy and depict a systematic change from an agrarian economy to a more diversified industrial and tertiary one, although Punjab remains an economy that is predominantly defined as of slow growth and agrarian in nature.

Of all sectors however, electricity has played a pivotal, if not the most important role in the economic development of the state. It has helped in the production of consumer durables and the provision of services for human wants and provided solutions to pressing issues related to poverty, agricultural production, and industrial development that the region demands.[48] Coalmines, natural gas, wind power and oil are not available in the region, and thus, coal is imported to produce thermal power, which together with hydropower is the main producer of the state's electricity. Although Punjab's total area comprises merely a 2 percent of India's total land mass, it produces a large portion of rice and wheat requirements for the country's food security programs and has the highest per capita consumption of electricity amongst all Indian states.[48,49] From a modest capacity of 62 megawatts (MW) in 1948, Punjab's State Electricity Board (PSEB) has now grown to a capacity of 6356 MW, serving close to 6 million people and employing more than 80,000 workers.[49] However, despite this remarkable growth, PSEB faces numerous issues which are directly related to the subsidized/free supply of electricity to the agricultural sector.[49] The 1970's and the agricultural and groundwater revolution brought about a massive rural electrification program that was accompanied by a massive tubewell expansion fully subsidized by the state. Today there are more than 1 million pump sets in the state. Free electricity has led to large inefficiencies in production and distribution of the power sector: in just the 1990's the electricity subsidy to agriculture increased from 687 crores (1 crore is 10 million Rupees Rs.) to 2339 crore in 2002. Because of the ever increasing demand for electricity for agriculture in Punjab, together with its growing industry and booming urban populations, the state has been forced to purchase electricity from outside the state, partially fulfilling the requirements of agriculture. Electricity generation has increased over time, but only because it has been bought from outside the state. The sector itself is plagued by inefficiencies and issues that go from transmission and distribution losses, to the theft of electricity, overemployment, political interference and lack of accountability, to a constant delay in the construction projects.[49] In past years, agricultural demand for subsidized electricity accounts for over 40 percent of the state's deficit.

Anecdotally however, the inefficiencies in the state's distribution of electricity, water-energy policies, and groundwater extractions do more than affect the government deficit. Power outages are ubiquitous over the state with households, universities, and industrial production units all being affected by electricity use in agriculture. Year after year, as the water table recedes more energy is required to draw water from a shallower water table bringing more energy issues to an already crippled sector.[42] At the macro-scale, these inefficiencies affect the production of goods and services as the rest of the Punjab economy can be left without electricity for hours on end, labor goes unused, capital is not employed, and the production of goods and services are reduced. In essence the inefficient use of productive resources leads to wider inefficiencies and distortions across an economy; precisely the sort of issues that can be studied via a general equilibrium framework. At the micro level, evidence suggests that the reduction in the quantity and quality of power supplied, the rising capital costs of acquiring new electricity connections for tube wells, and an eight-fold increase in the nominal price of diesel (1990-2007), have caused distortions in the region's groundwater economy.[50] A study by the International Water Management Institute found that in Punjab, summer paddy fields are now on the decline (primarily due to soaring diesel prices) and that it produces less of a surplus for a farmer who views the activity as an economic enterprise. Soaring diesel prices affect smallholder farming not only through the costs of pump irrigation, but also through the cost of other machine services such as ploughing and threshing, which small landowners do not own but usually rent. In Punjab's agrarian economy only large farmers with economies of scale can afford to run generator sets (gensets), while the rest have to resort to rain-fed crops or quit farming altogether. As a result, small landowners lease their land to workers from the poor states of Bihar and Madhya Pradesh, while they themselves get off farm jobs, and their tenants are sufficed with full-employment wage rates, using their muscle power for the intensive cultivation of high-value crops. As the agrarian economy stands, it is the small land owners that suffer from an energy squeeze, as they fail to make themselves productive and are usually unemployed in cities.[50]

Telangana

The economic consequences of overexploitation in Telangana are similar to those in Punjab, although here the electricity subsidy accounts for over 50 percent of the government deficit, and includes externalities that are all related to groundwater availability and hydrological variability: increased drilling depths and costs are required for a shallower groundwater table and inequality increases as richer farmers can finance the deepening of their wells but poorer farmers are unable to do so, often selling their land at a reduced price to cover debt that comes as a result of borrowing to adapt to a changing and drier environment.[12,51] Decreasing well yields in Telangana also distort the groundwater economy as there is less water available for informal 'water markets', this being the livelihood for many people in the region.[12] First, farmer income reductions resulting from crop losses and reduced irrigated area are obvious as the system loses its ability to buffer dry seasons and adversity, and second, a reduction in income has spiraling consequences across an economy as farmers can default on loan payments for pumps and other machinery, discrediting them socially and at the same time increasing the risk of exposure across rural development banks.[12] The loss of income has a much wider impact that goes beyond defaulting loans, as the purchasing power of an entire agrarian economy is reduced and unemployment, affecting not only banks but also the producers of goods and services.

Anecdotally however, the impact goes beyond the externalities that arise because of groundwater depletion. Economic sectors within Telangana compete for both water and energy resources, and scarcity has resulted in conflict with neighboring states as 90 per cent of the water is captured in Telangana but it is unequally distributed among the states. In addition, dry periodicities not only bring with them drought and reductions in the buffering capacity of the aquifer but also labor movements as laborers move to the nearest urban conglomerations seeking employment and a livelihood.[52,44] According to several reports, monsoon failure leads people from North Telangana to Maharashtra, from South to Hyderabad, and from West to Karnataka.[44,52] Mahabubnagar, the poorest and driest of the districts in Telangana sees during any year and because the recurrent dry periodicities a mass migration of over five hundred thousand laborers move throughout India in the search of livelihoods and employment, and in years such as 1997, when the monsoon failed, over 1 million laborers migrated to urban areas with the hope of making themselves productive. Over India they are known as "Palamur labor", and have worked in all major construction projects throughout the country but always returning to Telangana, with the hope of working once again as agricultural laborers.[44,52] Recently however, this labor has become unproductive in some cities of Telangana, such as Hyderabad, as India's Mahatma Ghandi's Rural Employment program has created all the wrong incentives for farmers to move to the city, or participate in water resource projects that have remained intact since 2006, remaining essentially unemployed, yet receiving a paycheck, and further sending Punjab and the India's government into debt.[53]

The economic impacts mentioned here however, obviously have to do with the great reduction that has occurred in the buffering capacity of both ecosystems in Punjab and in Telangana, but hydrological variability, periodicities, and extreme events further aggravate this issue in a situation where governments have failed to mediate remedial policies with political support. Here we suggest that the periodicities and extreme events (wet and dry) that both regions experience, will continue and also aggravate, reducing both the buffering capacity of the ecosystem and a population's ability to adapt to them. In the next section we provide a framework from which hydrological variability (via periodicities and extreme events) can be linked to the sectoral economy of a country, as it is here where the linkages begin. An extreme event or a periodicity arrives, or continues, and sets forth several mechanisms of adaptation that in the short run buffer variability, but at the same time degrade the system by overexploiting the aquifer (the buffer), and in the process set in motion a chain reaction involving a wide variety of environmental and economic externalities that have been mentioned above.

7. General Equilibrium Framework

India's groundwater resources are depleting at an alarming rate and unsustainable consumption of groundwater for irrigation uses are blamed for serious socio-economic consequences. The Punjab and Telangana are agriculture intensive regions that rely heavily on groundwater, the extraction of which is causing a steady decline in the region's water tables. The share of agriculture and allied sectors in the total gross state domestic product is 30 percent for Punjab, 24 percent for Andhra Pradesh (AP) and 16 percent for all India in 2009-2010. For the same period, the share of rice production to all India is 13 percent for Punjab (ranked 2nd) and 12 percent for AP (ranked 4th).[54] The gross irrigated area is 98 percent of gross cropped area for Punjab, 49 percent for AP and 45 percent for all India in 2008-9.[55] Groundwater as a source of irrigation accounts for 72 percent and 50 percent of total irrigation in Punjab and AP, respectively, in the period of 2007-08.[56] The share of consumption of electric power for agriculture use is 32 percent for Punjab, 31 percent for AP and 20 percent for all India for the period 2008-2009.[57] Furthermore, financing the increasing costs of electricity for irrigation pumping puts pressure on the electrical grid and leads to the unstable supply of electricity for other sectors in the economy.[6] Thus, the administrative priority of water allocation to the farmers imposes an extensive economic stress on other sectors of the economy and consequently, the process of the industrial growth and economic development is adversely affected. The serious consequence of rapid groundwater depletion is clearly an economy-wide concern. Withdrawing groundwater at rates that threaten to deplete the aquifer in the Punjab and Telangana region not only affects the livelihood of farmers, but also the regional economy as well as the broader economy as food staples (rice and wheat) produced in these regions are currently "over supplied." The over supply unnecessarily causes the country to be reliant on staple food supplies from regions of the country that are not sustainable in the longer run. As the Punjab and Telangana aquifers become depleted, rather massive economic adjustments in both the regional and national economy are likely. From the regional Punjab-Telangana economy perspective, the unsustainable extraction of groundwater encourages the employment of agricultural labor and other farm inputs at levels in excess of those that would be employed if groundwater was extracted at rates that sustain the capacity of the aquifer. Thus, the depletion of an aquifer is likely to cause a decline in farm employment and a sharp fall in returns to land that serves as a main source of farm profits.

Beyond the farm, the production of food staples at unsustainable levels tends to maintain a regional economy of food marketing, food processing and ancillary economic activities, all of which are likely to face large contractions with employment declines and migration of workers out of the region when groundwater is depleted. In recent years, India has been an exporter of wheat and rice, the foreign exchange earnings of which have been used to pay for the imports of machinery and other industrial goods. These goods help the economy to increase the productivity of labor and foster growth in per capita income. The decline in wheat and rice production as the aquifers in the Punjab and Telangana region are depleted will cause the country to risk the loss of this source of foreign exchange earnings. Moreover, the loss of this production of staple crops will likely force the economy to allocate more resources toward staple food production in other regions of the country and, unfortunately, away from other sectors of the economy. This reallocation will almost surely decrease, at the margin, the production of industrial and service sector goods thus causing a slow down in economic growth at the national level.

Some studies have focused on water as an economy-wide resource and extend the resource management of water to a general equilibrium setup. Both Diao et al.[58] and Hassan et al.[59] analyze impacts of groundwater on the agricultural and non-agricultural sectors using a detailed general equilibrium framework. They show that allowing markets to play a more significant role in the allocation of water to its most productive alternatives leads to an increase in gross domestic product of three to four percent in the case of Morocco and South Africa. This efficiency gain at the national level is large when irrigated agriculture only accounts for five to ten percent of the economy. Although their quantitative simulations have an important implication of water regulation in the macroeconomic perspective, the analysis focuses on a static approach so that questions regarding the effects of economic growth and sustainability of water supplies are not addressed. No studies to our knowledge have focused on water as an economy-wide resource in the context of economic growth and the transition of an economy over time. Moreover, as we note below, no studies of an economy-wide nature have incorporated into the analysis the equations of motion, linking the key features of hydrology to water extraction and precipitation.

As shown in Tsur et al.[60], the economic literature on groundwater resources is predominantly a partial equilibrium type. For instance, Knapp et al.[61] evaluate the efficiency/inefficiency of different types of water resource management, recognizing an important effect of groundwater dynamics on the value of water. In their model structure, the demand for irrigated water is determined by the price of water resources whereas other elements including the prices of energy and factor prices of water production are exogenously given. Consequently, the indirect economic interaction among sectors and the rest of the economy is overlooked. Although their implication of efficiency gains from establishing water markets is a shared view with our approach as well as many others, their partial equilibrium analysis may lead to an incorrect conclusion when the total effects of groundwater related policies are evaluated. With a similar approach, Krulce et al.[62] model groundwater dynamics that link to the cost of desalination of water. The saline groundwater has become a serious issue in many parts of our study regions and thus, the deterioration of groundwater quality should be addressed when the critical depth of water tables is considered. There are also studies that focus on India's regional models in order to examine the specific issues in the context of local and microeconomic aspects such as Diwakara et al[63] and Reddy[51].

Both studies evaluate the costs of alternative recharge mechanisms such as water shed development programs and irrigation and percolation tanks in order to reduce the external environmental costs caused by the exploitation of groundwater. Overall, these studies provide important insights into the effects of water scarcity on individual farmers, the choice of crops and production techniques, but they provide no insight into the broader regional and economy wide effects mentioned above. Thus, they tend to grossly underestimate the consequences of policies to sustain/deplete ground water supplies. Moreover, the effects of water policy on the regional and national economy feedback to farmers in terms of changes in labor wage, capital costs and food prices. These indirect effects can exceed the direct effects measured by partial equilibrium analysis including the literature mentioned above. The present study constructs a dynamic, multisector-multiregion, general equilibrium model to evaluate the direct and indirect economic impact of groundwater depletion on the agricultural and non-agricultural sectors in the Punjab and Telangana, taking regional hydrologic differences into account.

The Modeled Economy

In this section, we sketch out briefly the key features of the dynamic general equilibrium model that we propose to use in order to measure empirically the effects of water policy in the Punjab and Telangana region on their and the broader economy of India. In addition to the primary factors of production (e.g., labor, capital and land), the agriculture sectors are interconnected by groundwater resources and in turn, the irrigation activity of groundwater links to the manufacturing sector through the competition for energy. Disaggregation of the agriculture sector into paddy as the most water consuming crop and other resource competing crops (e.g. wheat) is a key to characterize the farm environment of the study regions. Each sector in agriculture as well as other sectors of the economy is specified by the production technology employed and factors of production. Beyond the general agriculture activities, specification of the irrigation technology including energy use is unique to the present problem, and to our knowledge, has not be incorporated into an economic model of the nature proposed here. The hydrology component of the model captures the economic incentives leading to the extraction of groundwater causing the depth of the water table to increase in the Punjab, and the depletion of groundwater in the Telangana region. Also affecting the properties of the aquifer is water infiltration from rainfall, which is periodical. To understand the basic characteristics of the economic environment of the Punjab and Telangana region, a general equilibrium framework needs to answer questions such as (1) whether the electrical grid of the study regions is part of the country's over all grid so that electric consumption in the region competes with the rest of India, (2) whether the production of goods and services in the study regions is similar and could be a close substitute for the goods and services produced in the rest of India, (3) whether labor moves, to some degree, in and out of the region in response to wage differentials in other parts of India and (4) whether the groundwater resources are shared significantly with others including domestic and industrial uses.

We introduce groundwater dynamics into the general equilibrium model and attempt to understand how human behavior and nature combine to influence groundwater table levels over time. It is our interest to project how changes in the groundwater table in each of the Punjab and Telangana region impact agriculture and other parts of the economy. The water dynamics show the contrasting structures of aquifers in two study regions, taking into account the rainfall infiltration factor and specific yield related to geologic formations. We adopt a simple equation for hydraulic power to capture the behavior of increasing electricity consumption for pumping per unit of irrigated water as the depth to a water table increases. The dynamic features of this system depict levels of water extraction and water infiltration (due to rainfall and irrigation), that can lead to various levels of "aquifer sustainability." The level of sustainability can become a policy objective, albeit at the short-run cost of likely pushing some resources out of irrigated agriculture, relative to their current level of employment. The level of sustainability of water stocks in the aquifer will depend upon energy costs, and risk considerations associated with the probabilities of drought.

Modeling Approach

Here we attempt to model an aggregate economy in a descriptive and tractable manner so that the investigation of the behavior of models' endogenous variables is relatively straight forward. We begin by identifying the main features of the Punjab and the Telangana economy, and then cast these regional economies into the context of the broader Indian economy. In this way, our analysis captures the effects within the regional economy of water policy, and the spillovers from the regional economy to the national economy. The next step involves organizing the data on resource allocation to various crop production and non-farm production activities within the regional and national economy, as well as goods consumed, level of savings and other features of these economies. The data are cast into a social accounting matrix or SAM. This is the typical method used by economists engaged in applied general equilibrium analyses. The SAM is a double-entry accounting system that shows the major economic transactions among agents of an economy over a given period of time, usually one year. It organizes the data based on economic identities such that flows of payments to remunerate resources balance with the value of the goods and services produced in an economy. Returns to resource are distributed to households, governments and foreigners in terms of international trade flows. The data in the SAM, as well as time series data linking rice and other crop production to levels of labor, capital, fertilizer and water use, are used to estimate the production functions and consumption functions in an economy.

The behavioral relationships, such as determinants of quantities supplied of crops, industrial production, and consumer demand, are based on the traditional economic assumptions such as the optimizing behaviors of economic agents, firms and households. Imposing a mathematical economic structure on these data, we identify the endogenous variables in the model by each entry of the SAM. When the model is solved, a solution of the model reproduces the base data in the SAM for the initial period. This process leads to a system of equations, some of which describe the behavior of the economy for a single year, and a system of equations that depict how the economy "moves" through time. The model is "solved" backward and forward in time. The backward in time analysis is used to validate the model with economic history and to provide an economic explanation for the temporal decline in the water table and the various economic linkages and feedback mentioned above. Solving forward in time, on the other hand, we seek to explain the impact that both economic policy and water resource level shocks have on water availability and aquifer sustainability.

A very relevant policy shock is a reduction in the power subsidy for irrigation. The elimination of the subsidy whether it is partial or complete is likely to discourage farmers from pumping water from aquifers at historic levels, thus reducing crop production, lowering farm income and the purchasing power of farm households. While the local economy may be adversely affected by the decline in farm household purchasing power, the impact to the broader economy can be different from this change of policy. At this point, we can speculate that more resources including electric power, labor and capital are likely to move into the manufacturing sector from the agricultural sectors. The magnitude of resource movement depends on the relative importance in production of labor, capital and water (i.e., factor intensities) of each sector. The value (i.e., the implicit price) of water is likely to be higher compared to the case with the complete subsidized irrigation. This increase in value signals the need to ration this scarce resource, relative to past use, and discourages the over exploitation of the aquifer, thus preserving this resource for future generations. Consequently, the economy-wide GDP expands while the regional economy suffers, as mentioned above, given that the study regions are agriculture intensive.

A natural shock is implemented by imposing different patterns of the precipitation projection. The decline of precipitation directly affects the depression of the water table for a given irrigation behavior. The lower level of precipitation also reduces the profit of farmers due to more irrigated water required in order to maintain crop production. The resulting value of water resources is likely to be higher and together with lower profits, the agriculture sectors are depressed and resources tend to move out of the sectors. These results are expected and obtained from testing a preliminary computer code. As we expect the groundwater dynamics to have economy-wide implications, the relative magnitude of resource and product behavior is carefully evaluated in order to understand the role of hydrogeology of groundwater resources. We could also evaluate the effects of farmers adopting more efficient water allocation technologies, or their effects of producing less water consuming crops. This analysis provides a sound basis to formulate water policy, which typically, is not a once and for all change in policy instruments but instead a phasing in over time to achieve specific targets, such as a level of water sustainability in an aquifer.

The structure of aquifers is crucial in the economic context because aquifers can serve as buffer storage especially during the periods of water shortage, thus stabilizing the uncertainty of the other water sources. The long run depth of water table is reached when the irrigated demand of ground water equals the long run precipitation recharge. Questions addressed include the following. Given current policy (such as the subsidization of electrical power to farmers) will the aquifer in the Punjab reach a level of sustainability that is conducive to farmers following current practices? The expected answer is almost surely negative, but the point in time when exploitation leads to non-sustainability or sustainability at historically low levels of water extraction is unknown and to be estimated by our analysis. The analysis will also trace the direct and indirect economic effects on the regional and national economy of this situation over time. What other policies are likely to decrease groundwater extraction to rates that lead to a "higher" level of aquifer sustainability, and at what rate should these policies be phased in over time? Since, as noted above, resources are likely to be pushed out of irrigated agriculture, once and for all policy changes can be socially disruptive and lead to policy reversals.

We will evaluate whether a policy or no policy is an economically feasible concept for the sustainability of aquifers. For example, suppose a water user right contract is provided to each farmer. The contract endows the farmer with the right to withdraw a given amount of groundwater. This amount would likely be less than the amount of water the farmer has historically withdrawn. This limitation would be required to sustain the aquifer. However, the farmer could "rent out" all or part of his contract to other farmers. That is, those farmers who are more efficient are willing to pay the price to rent the contract. In this way, water is allocated to its highest marginal product, and the less efficient farmer is appropriately compensated, thus lessening resistance to a policy that seeks to sustain open access to the aquifer. Other questions that can be addressed are: Are aquifers sustainable even though the cost of extracting groundwater exceeds the value of irrigated water? What about the relationship between quality of water and sustainability? These are questions to be carefully examined when the different structures of aquifers are considered in our economic analysis. The fundamental economic issues of groundwater use require developing a deep understanding of the direct and indirect impacts of competing resources including water and energy use and transactions among sectors.

Rice is grown in a nursery before flooding the paddy and transplanting the rice.

Water is not only an economic resource, flooding and irrigating the paddy year after year in Punjab, but it is also a source of life and joy for many people in the region. Here, children from a nearby farm play close to a water pump while workers from Bihar, one of the poorest states in India, look on.

8. Appendix

Table A-1: Rainfall Infiltration Factor

A) **For Alluvial Terrain**

Sl. No.	Geographic location	Rainfall infiltration factor as a fraction		
		Recommended value	Maximum value	Minimum value
1	Indo - Gangetic plains and inland areas	0.22	0.25	0.20
2	East coast	0.16	0.18	0.14
3	West coast	0.10	0.12	0.08

B) **For Hardrock Terrain**

Sl. No.	Rock type	Rainfall infiltration factor as a fraction		
		Recommended value	Maximum value	Minimum value
1	Vesicular and Jointed Basalt	0.13	0.14	0.12
2	Semi-consolidated Sandstone	0.12	0.14	0.10
3	Weathered Granite, Gneiss and Schist with Low Clay Content	0.11	0.12	0.10
4	Weathered Granite, Gneiss and Schist with Significant Clay Content	0.08	0.09	0.05
5	Weathered Basalt	0.07	0.08	0.06
6	Laterite	0.07	0.08	0.06
7	Consolidated Sandstone, Quartzite, Non-cavernous Limestone	0.06	0.07	0.05
8	Granulite Facies like Charnockite etc.	0.05	0.06	0.04
9	Phyllites, Shales	0.04	0.05	0.03
10	Massive Poorly Fractured Rock	0.01	0.03	0.01

Note :

1) The recommended value of the 'Rainfall Infiltration Factor' alone as given above is to be adopted unless, results from documented field studies indicate that a value different from the recommended value can be used. Even in the latter case, the 'Rainfall Infiltration Factor' which is adopted has to be within the range of the maximum and minimum values as specified above.

2) The 'Rainfall Infiltration Factor' obtained on the basis of the norms as given above has to be increased by 0.02 for those sub-units in which watershed development with associated soil and water conservation measures are implemented.

Table A-2: Specific Yield

A) For Alluvial Terrain

Sl. No.	Type of alluvium	Specific yield as a fraction		
		Recommended value	Maximum value	Minimum value
1	Sandy	0.16	0.20	0.12
2	Silty	0.10	0.12	0.08
3	Clayey	0.06	0.08	0.04

B) For Hardrock Terrain

Sl. No.	Rock type	Specific yield as a fraction		
		Recommended value	Maximum value	Minimum value
1	Karstified Limestone	0.08	0.15	0.05
2	Sandstone	0.03	0.05	0.01
3	Weathered Granite, Gneiss and Schist with Low Clay Content	0.03	0.04	0.02
4	Laterite	0.025	0.03	0.02
5	Limestone	0.02	0.03	0.01
6	Weathered or Vesicular Jointed Basalt	0.02	0.03	0.01
7	Weathered Granite, Gneiss and Schist with Significant Clay Content	0.015	0.02	0.01
8	Quartzite	0.015	0.02	0.01
9	Phyllites, Shales	0.015	0.02	0.01
10	Massive Poorly Fractured Rock	0.003	0.005	0.002

Note :

1) The recommended value of the 'Specific Yield' alone as given above is to be adopted, unles results from pump tests indicate that a value different from the recommended value can be usec Even in the latter case, the 'Specific Yield' which is adopted has to be within the range of th maximum and minimum values as specified above.

2) The 'Specific Yield' can be also adopted on the basis of 'Dry Season Ground Water Balanc Method'. This method can be however used, only for non - command area in hardrock terrain.

Data Source: Central Ground Water Board, Ministry of Water Resources, Government of India, 2009[64]

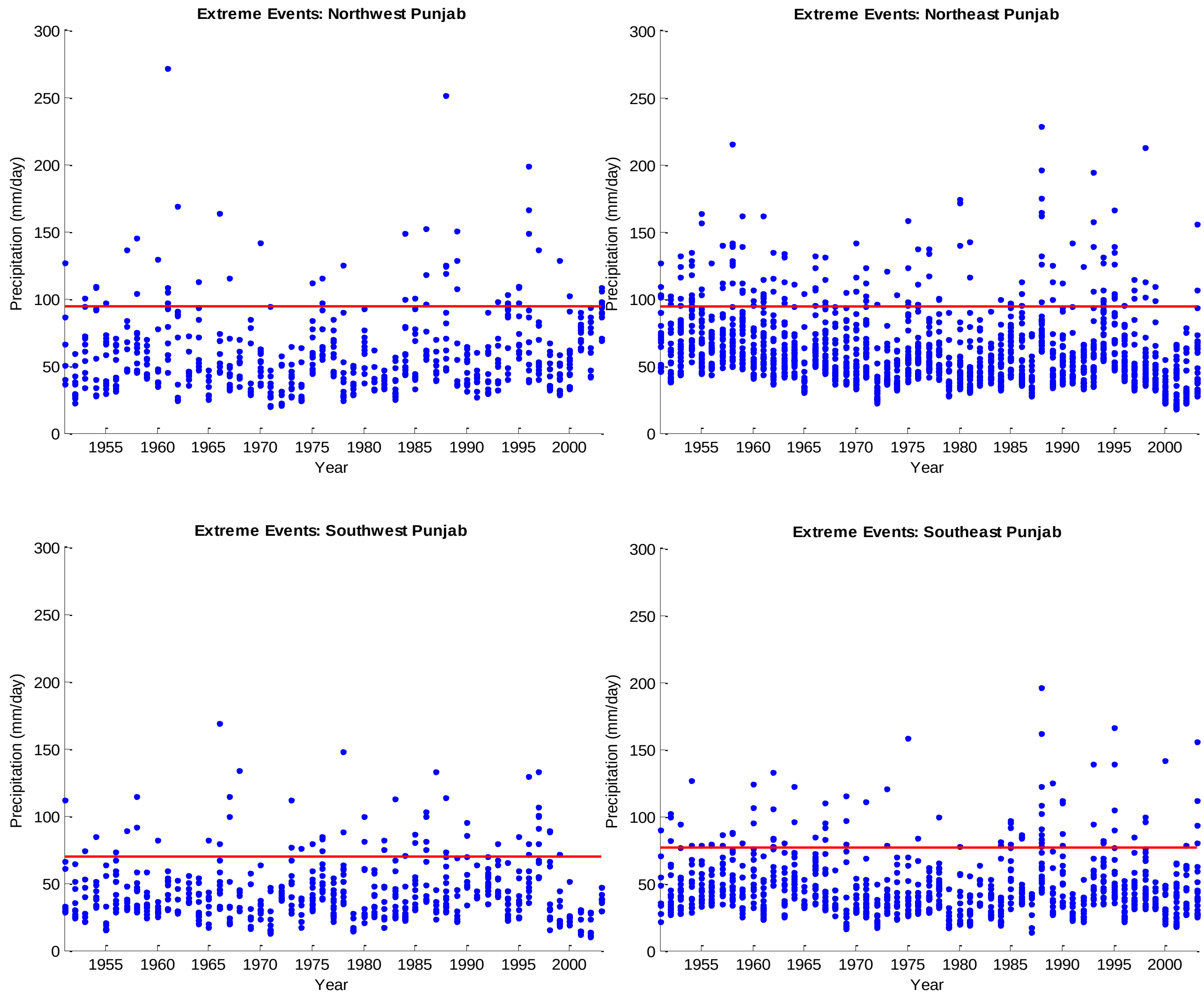


Figure A-1: Punjab Regional Extreme Events. The 90th percentile was defined for all daily precipitation events per year over each region (122 monsoon days*4 grids: 488 values per year; 2 grids for the Northwest Punjab). The scatter plot depicts events above the 90th percentile for every year in a region from 1951-2003 by year (the red line is the entire samples' 99th percentile). The magnitude and intensity of extreme events above the 99th percentile have been increasing over time for Northeast, Northwest, and Southeast Punjab.

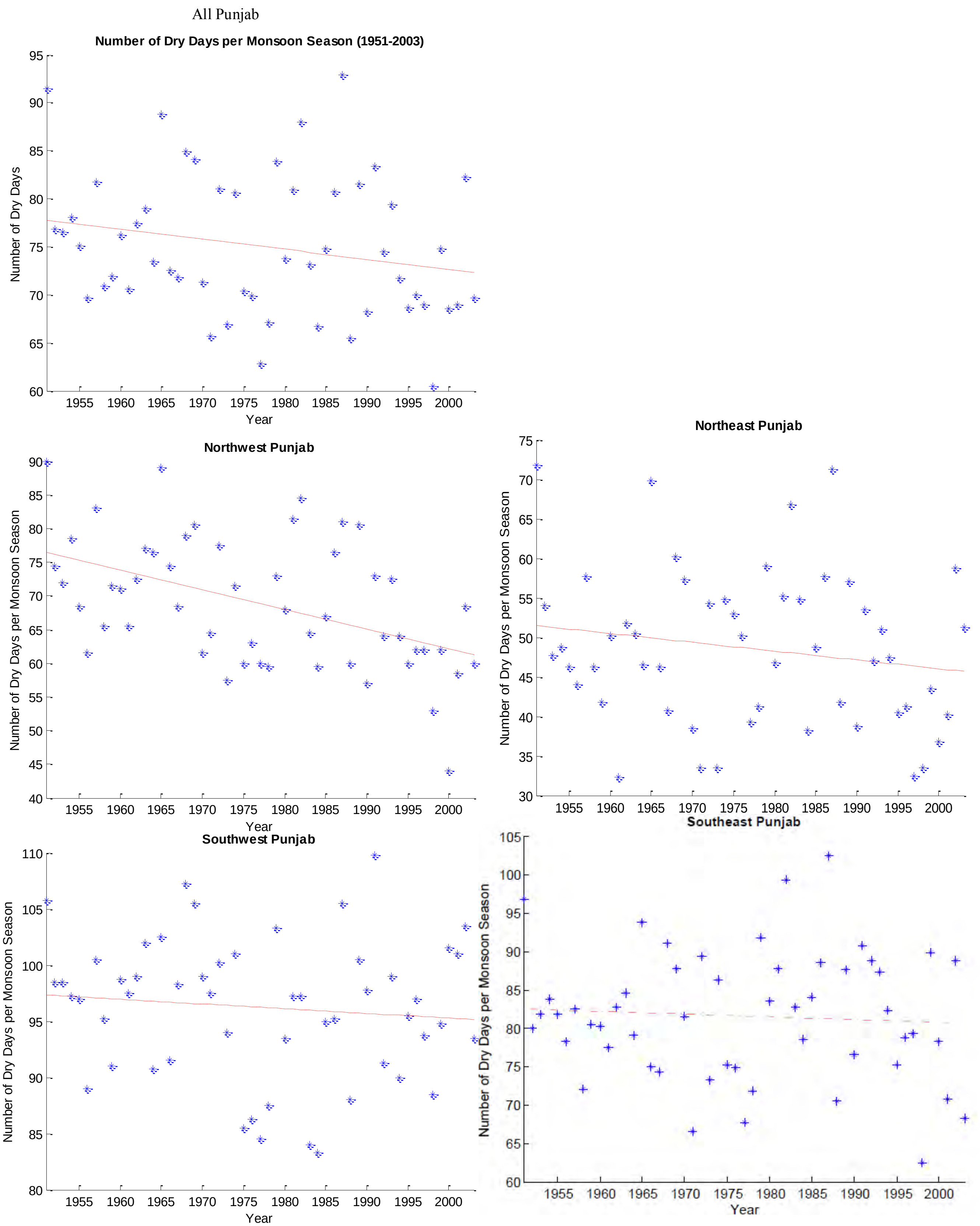


Figure A-2: Punjab Average and Regional Dry Days per Monsoon Season. The spatial average number of dry days per monsoon season (top left) shows a declining trend over time. The number of dry days per grid was calculated and then a spatial average was taken per year; a linear trend (red line) over the data depicts a steady decrease from 1951 – 2003. Each region of Punjab has observed a steady decrease in the number of dry days per monsoon season.

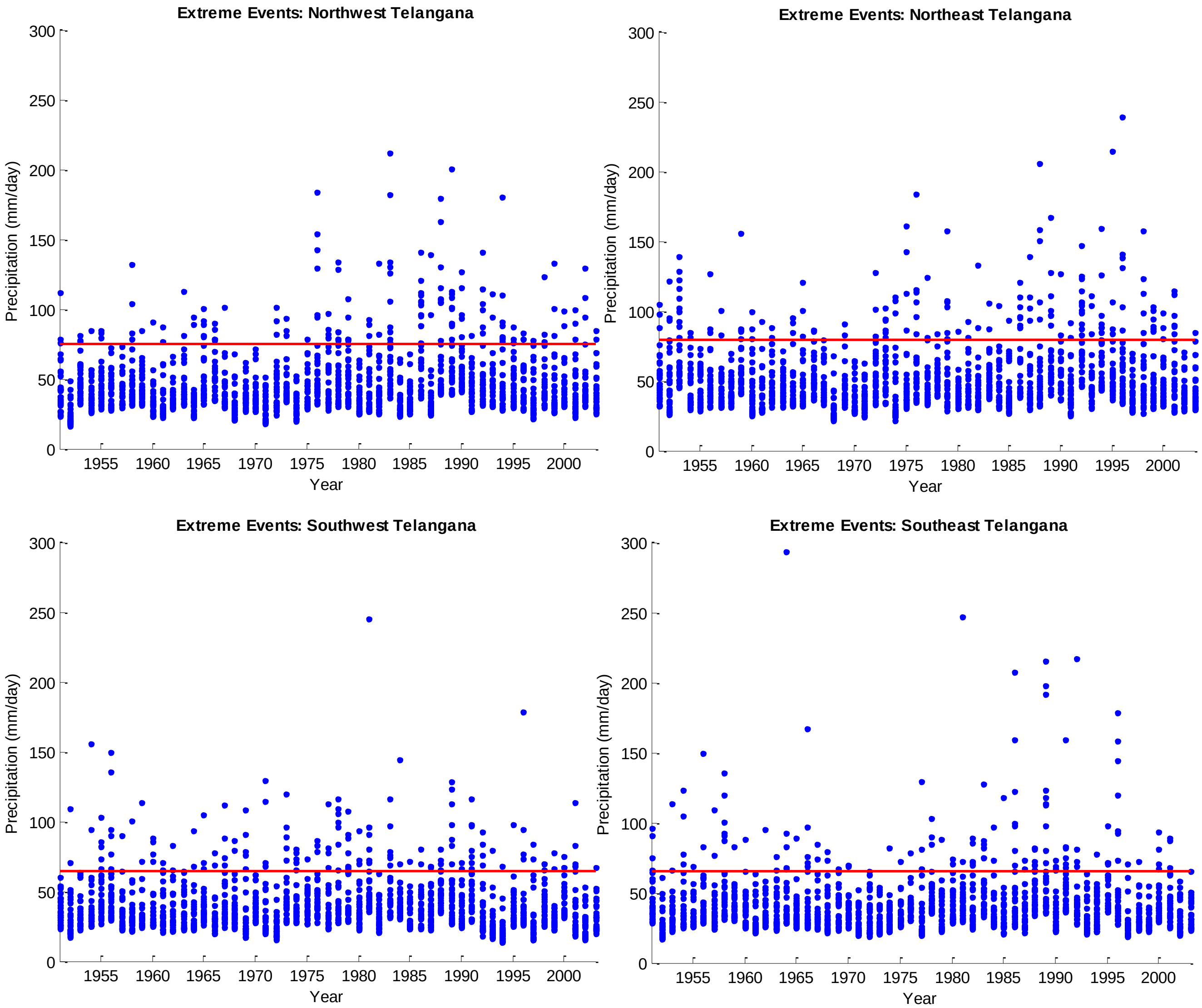


Figure A-3: Telangana Regional Extreme Events. The 90th percentile was defined for all daily precipitation events per year over each region of Telangana (122 monsoon days*6 grids: 732 values per year). The scatter plot depicts events above the 90th percentile for every year in Telangana from 1951-2003 by year (the red line is the entire samples' 99th percentile). The magnitude and intensity of extreme events above the 99th percentile have been increasing in time for Northeast, Northwest, Southeast and Central Telangana.

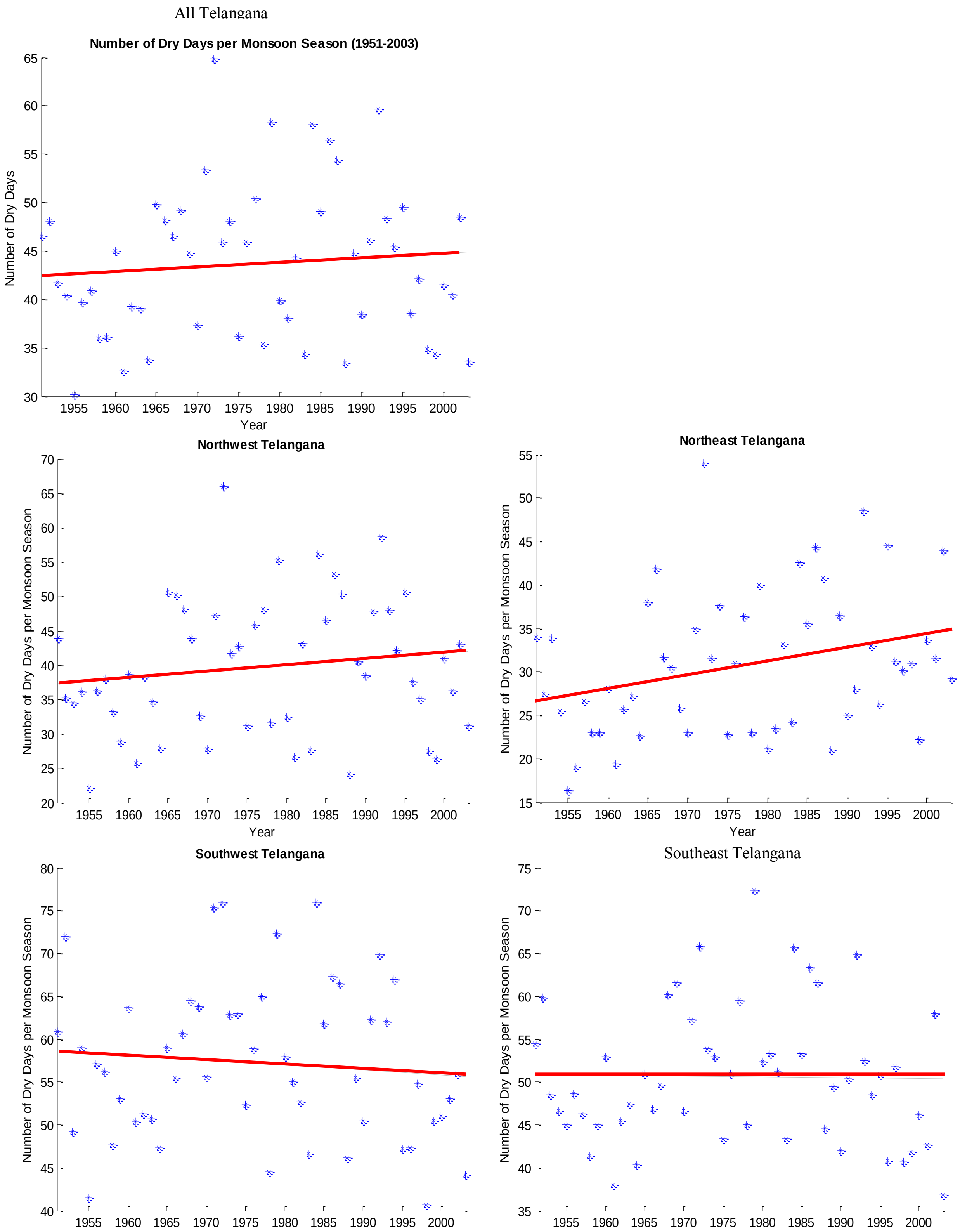


Figure A-4: Telangana Average and Regional Dry Days per Monsoon Season. The spatial average number of dry days per monsoon season (top left) shows an increasing trend over time. The number of dry days per grid was calculated and then a spatial average was taken per year. A linear trend is shown by red line. Northeast and Northwest regions show an increasing trend while Southwest shows a decreasing trend. Note that the command (surface irrigated) area of Telangana is primarily in its center, traveling from the region's Northwest to the Southeast.

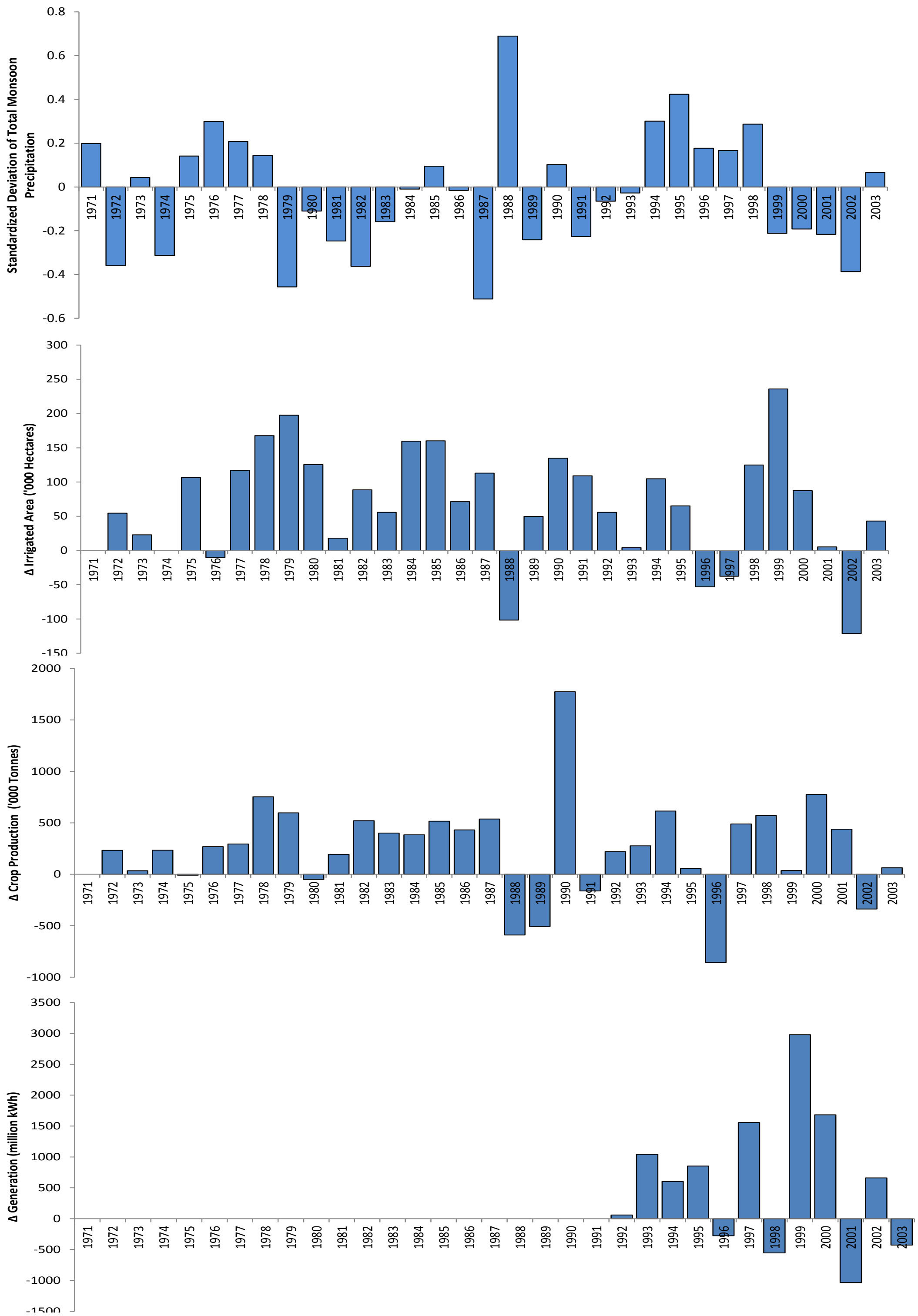


Figure A-5: Punjab Rice in Wet Season. In the prolonged dry period after 1979, exception of the flood in1988, the irrigated area increased. The reduction of irrigated area in 1988 might have been due to the flood of the same year. The crop production also grew at a positive rate for most of the time. This is consistent with the fact that Punjab doesn't directly rely on monsoon rainfall for their rice production. The expansion of irrigation is likely to have contributed to the increase of the rice production over time.

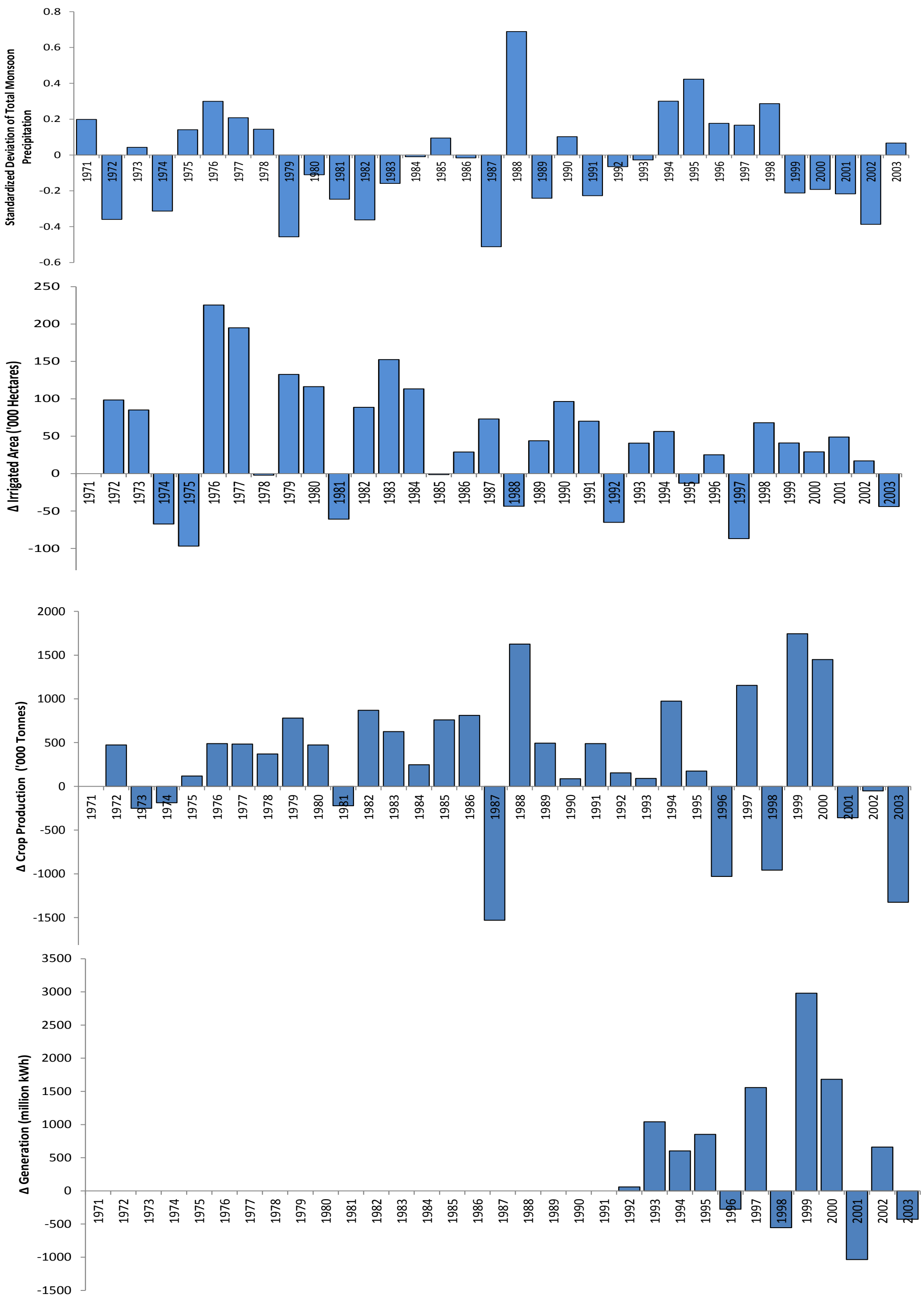


Figure A-6: Punjab Wheat in Dry Season. Similar to the case of rice in the wet season, the irrigated area for wheat has increased in the dry period in the following decade after 1979. The irrigated area has increased in the positive rate at most years. However, the rate of increase of irrigated area has decreased. The changes in crop production and the changes in electricity generation have a positive relationship. A low generation of electricity may have hindered the crop production in 1996, 1999, 2001 and 2003.

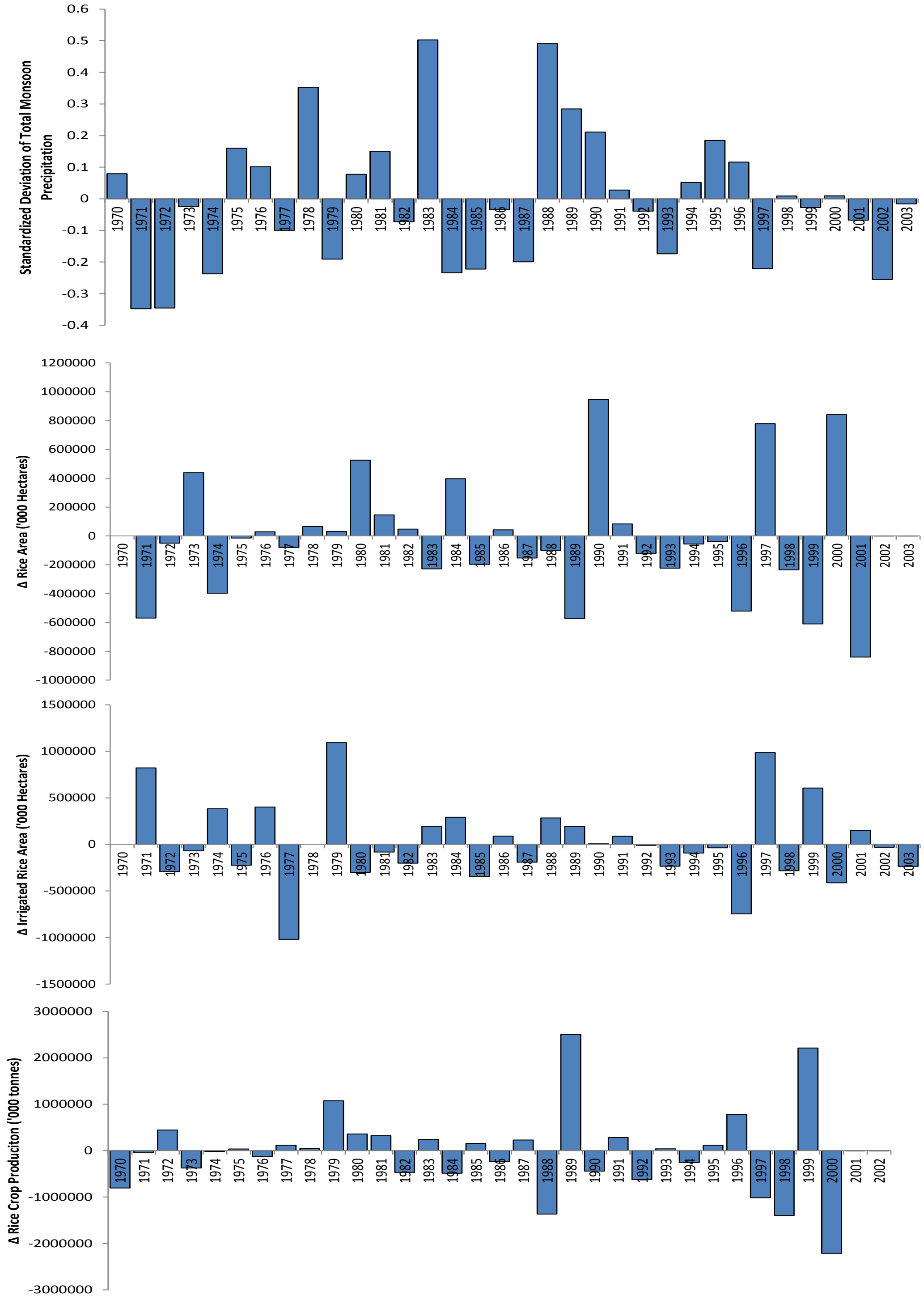


Figure A-7: Telangana Rice in Wet Season. The level of the irrigated area was stable from the 1980s to the mid-1990. In the late 1980s and the early 1990s when wet years lasted for 4 years, irrigated area increased. The previous 4 years suffered from drought and the irrigated area show some positive and negative changes. The rice production was also stable except for the period of 1988 and 1989. The drop of production in 1988 might have been due to the flood.

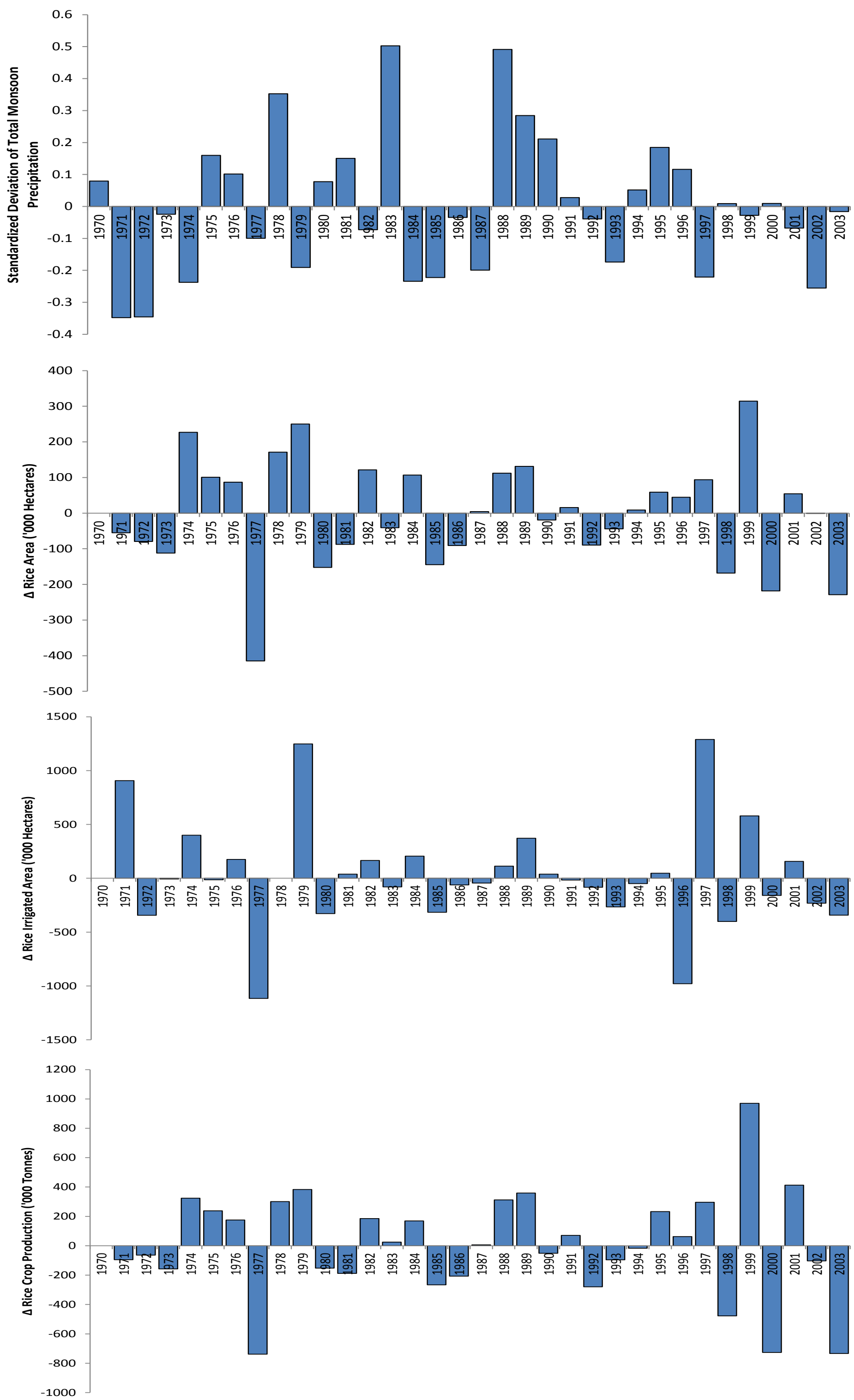
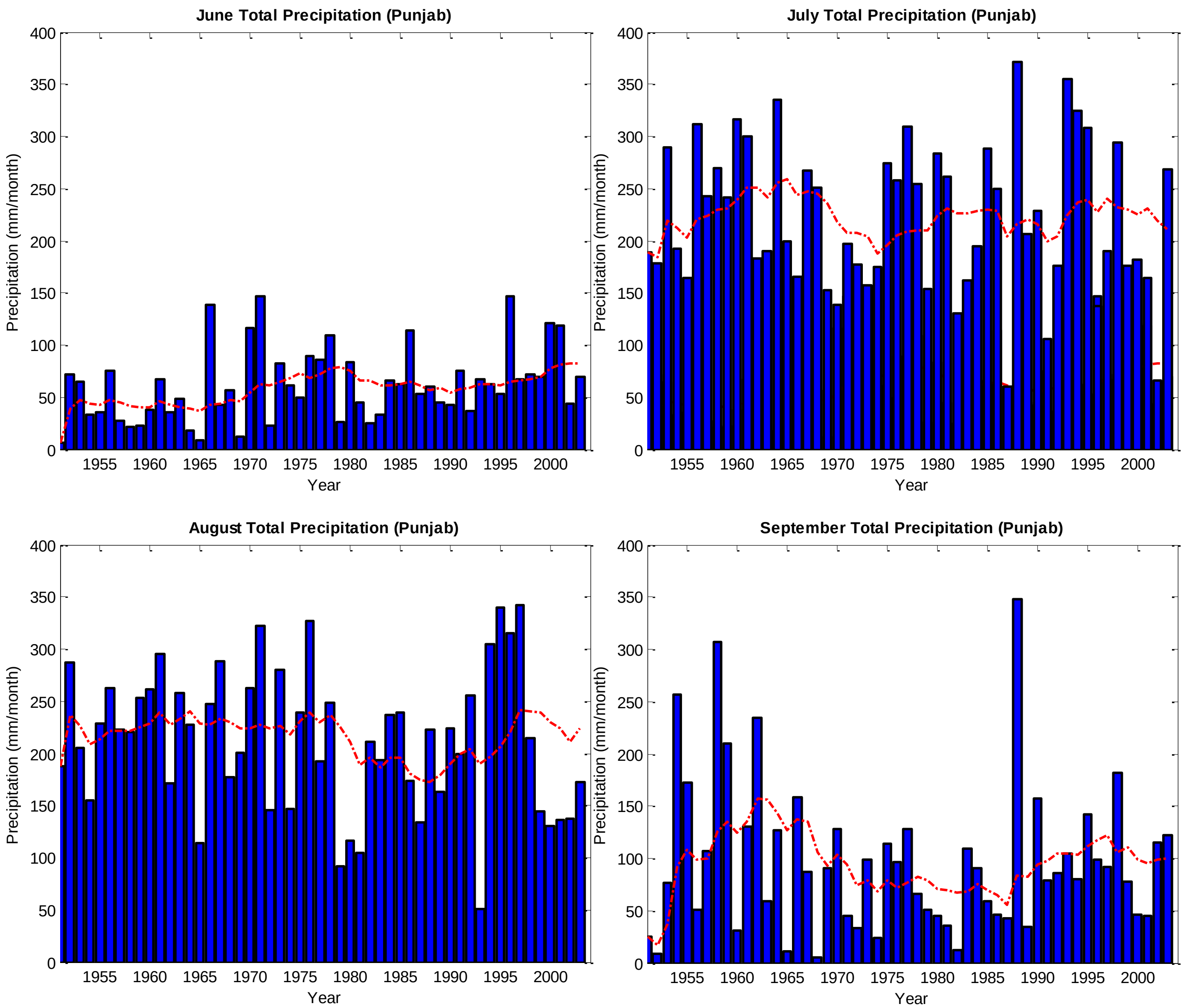


Figure A-8: Telangana Rice in Dry Season. In the 1970s and 1980s, many incidents of deficit of rain were followed by the reduction of irrigated area and incidents of surplus of rain were followed by increase of irrigated area. For example, the wet year of 1978 was followed by increase of irrigated area in 1979 while the dry year of 1979 was followed by the decrease of irrigated area in 1980. The change in the irrigated area, in turn tends to correlate to the rice production of the year. This amounts to s a stable rice yield over time.

9. Supplemental Materials



Decadal Changes in Monthly Precipitation

	June					July				
	1951-1959	**1960-1969**	**1970-1979**	**1980-1989**	**1990-2003**	**1951-1959**	**1960-1969**	**1970-1979**	**1980-1989**	**1990-2003**
Mean (mm/month)	39.97	46.67	79.04	58.72	74.79	230.93	235.92	209.72	220.88	212.59
Standard Deviation (mm/month)	24.74	37.50	39.55	25.60	32.04	52.51	66.23	59.55	89.62	86.39
Coefficient of Variation	0.62	0.80	0.50	0.44	0.43	0.23	0.28	0.28	0.41	0.41
	August					**September**				
Mean (mm/month)	224.66	224.17	225.57	179.47	212.04	135.10	93.52	78.56	82.38	102.05
Standard Deviation (mm/month)	39.81	57.46	78.96	49.40	89.77	106.36	71.79	39.55	97.38	39.34
Coefficient of Variation	0.18	0.26	0.35	0.28	0.42	0.79	0.77	0.50	1.18	0.39

Figure S-1: Punjab Monthly Precipitation. A simple (no weights) 10 year moving average is used to visually inspect changes in total monthly monsoon precipitation. Daily gridded data was aggregated over the region of Punjab to analyze monthly precipitation and decadal changes from 1951-2003. Mean monthly precipitation increased significantly in June and decreased slightly in July and August.

Table S-1: Punjab Daily Precipitation Descriptive Statistics

		1951-1959	1960-1969	1970-1979	1980-1989	1990-2003
June	Mean*	1.33	1.56	2.63	1.96	2.49
	Standard Deviation*	2.61	3.03	4.07	3.72	3.96
	Coefficient of Variation	1.96	1.95	1.54	1.90	1.59
	90th Percentile*	6.64	5.93	9.74	5.98	8.87
	95th Percentile*	9.00	9.58	12.70	10.19	10.73
	99th Percentile*	13.02	17.53	21.54	19.22	22.34
July	Mean*	7.45	7.61	6.77	7.13	6.86
	Standard Deviation*	8.13	8.18	6.77	7.51	8.00
	Coefficient of Variation	1.09	1.08	1.00	1.05	1.17
	90th Percentile*	18.40	17.23	14.35	16.59	15.48
	95th Percentile*	23.96	23.36	19.36	21.55	22.16
	99th Percentile*	39.54	43.56	36.14	37.26	36.37
August	Mean*	7.25	7.23	7.28	5.79	6.84
	Standard Deviation*	6.30	6.30	7.17	6.34	7.48
	Coefficient of Variation	0.87	0.87	0.99	1.09	1.09
	90th Percentile*	16.08	16.89	16.28	13.81	16.30
	95th Percentile*	19.24	20.51	22.86	18.04	20.56
	99th Percentile*	26.37	26.26	35.19	34.02	36.11
September	Mean*	4.50	3.12	2.62	2.75	3.40
	Standard Deviation*	7.71	6.85	3.72	8.61	6.02
	Coefficient of Variation	1.71	2.20	1.42	3.14	1.77
	90th Percentile*	14.60	11.38	8.15	7.52	9.75
	95th Percentile*	22.93	17.37	11.38	10.44	13.00
	99th Percentile*	44.19	49.82	19.41	71.00	34.76

* mm/day   increase   decrease

Mean daily monsoonal precipitation increased in June and slightly decreased in July and August. The coefficient of variation increased in August. The extremes at the 99th percentile increased in June and August.

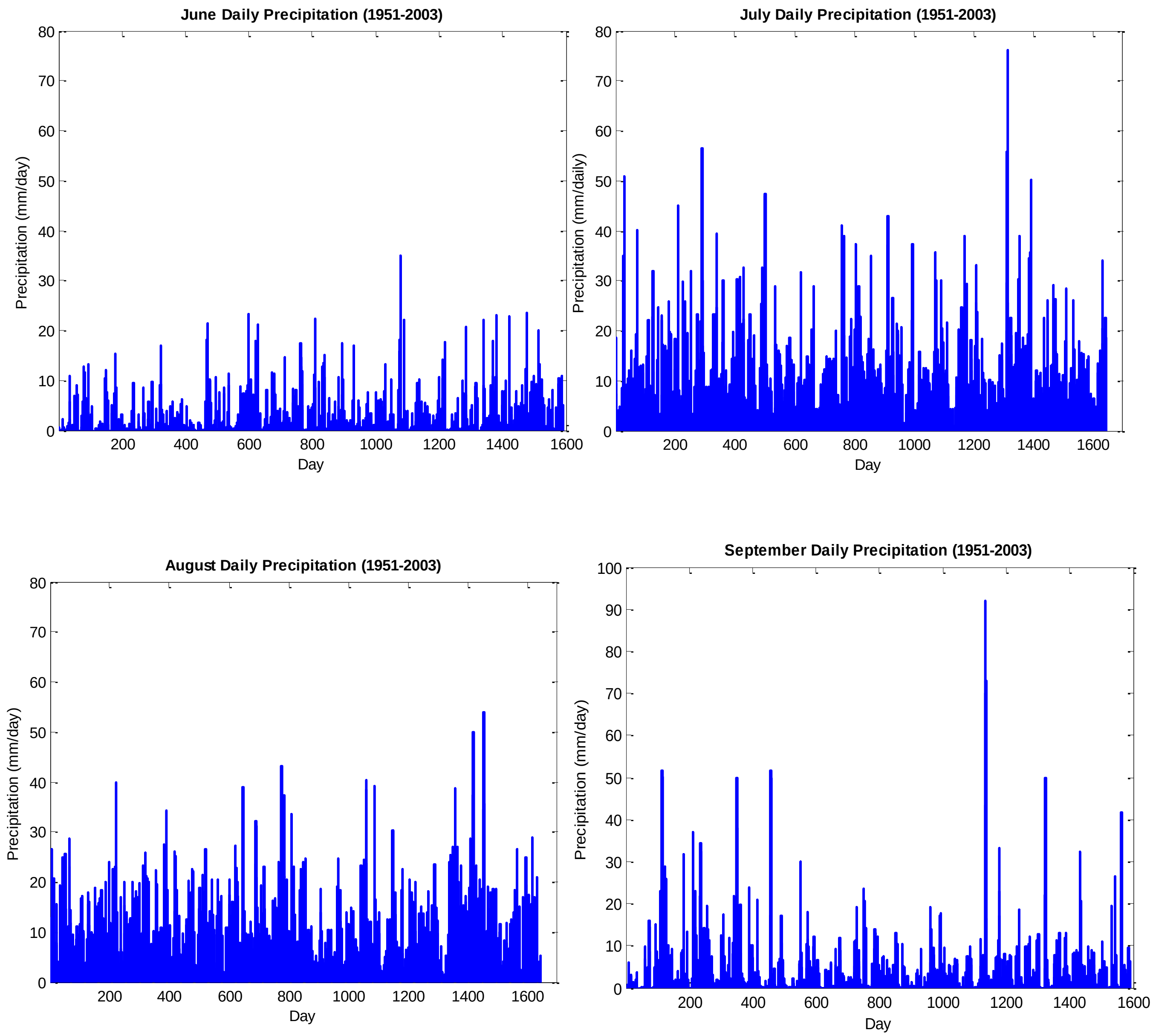


Figure S-2: Punjab Daily Precipitation. Daily precipitation over time for the months of June, July, August, and September (1951 – 2003) is shown. Daily monsoonal precipitation increased in June and decreased in July and August.

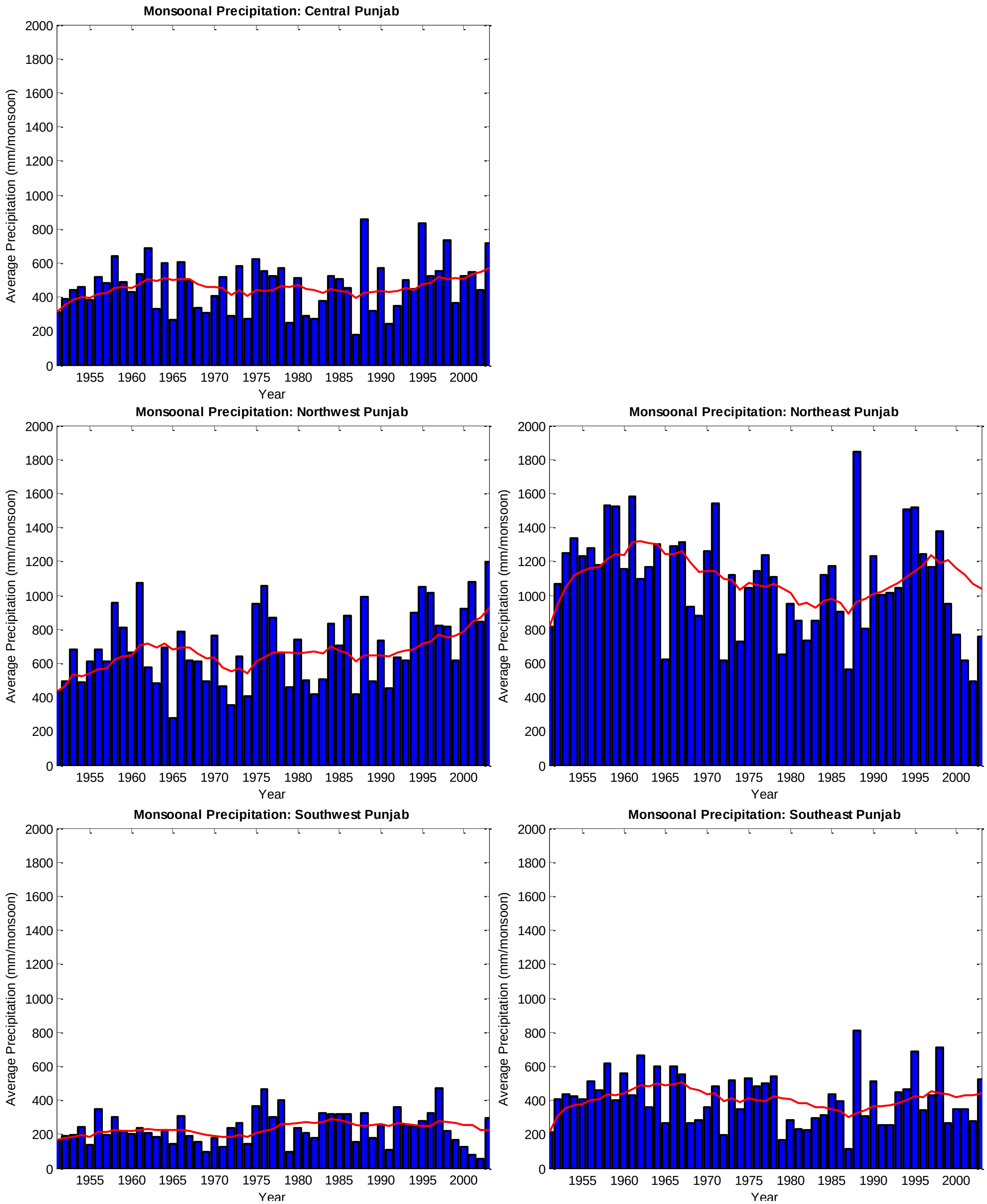


Figure S-3: Punjab Regional Monsoonal Precipitation. A 10 year moving average is used to inspect changes in total monsoon precipitation for monsoon precipitation over northeast, northwest, southeast, and southwest Punjab (1951 – 2003). On average, north Punjab receives more rain than the centre and south with the northwest experiencing an increase in total monsoonal precipitation (1951-2003).

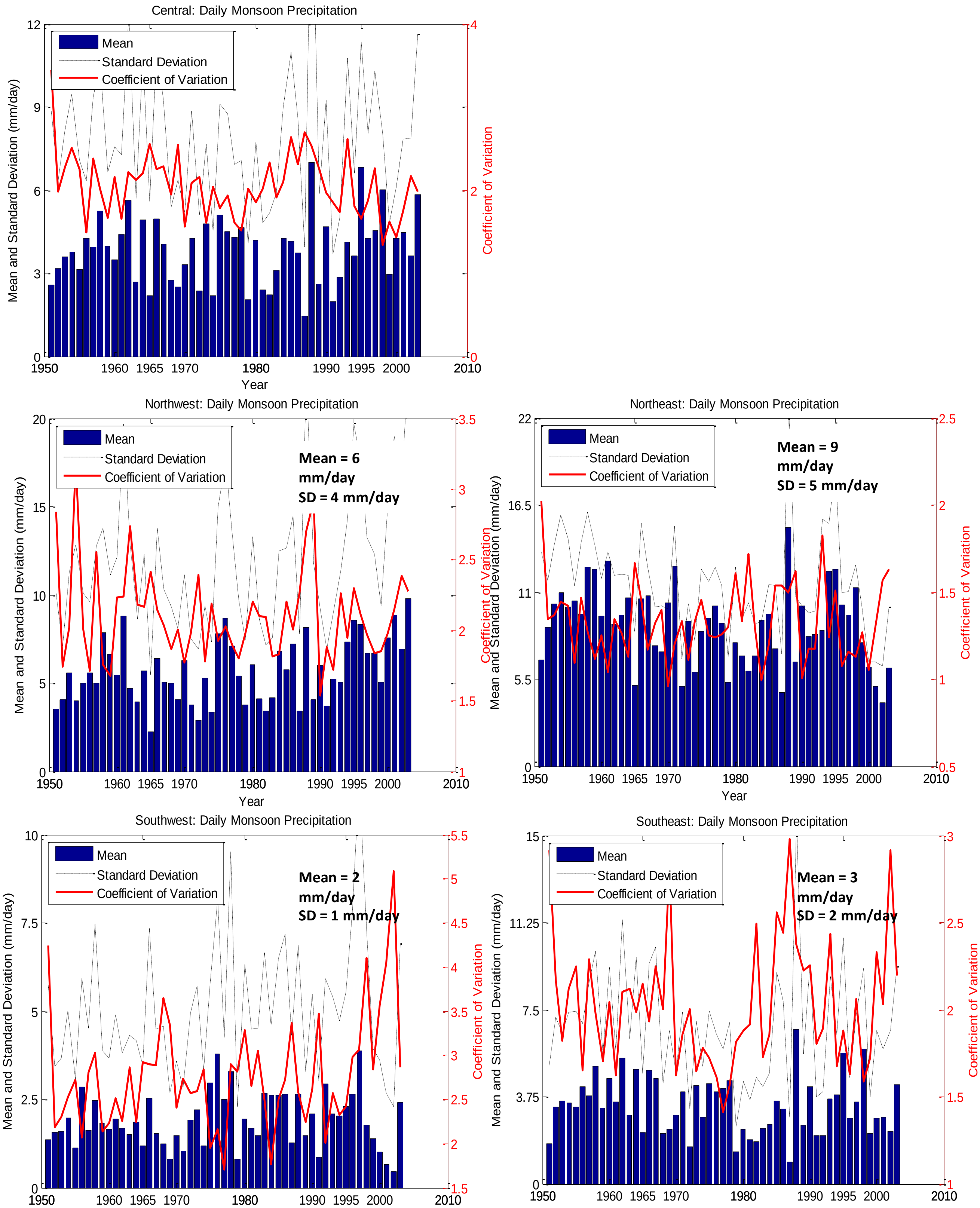
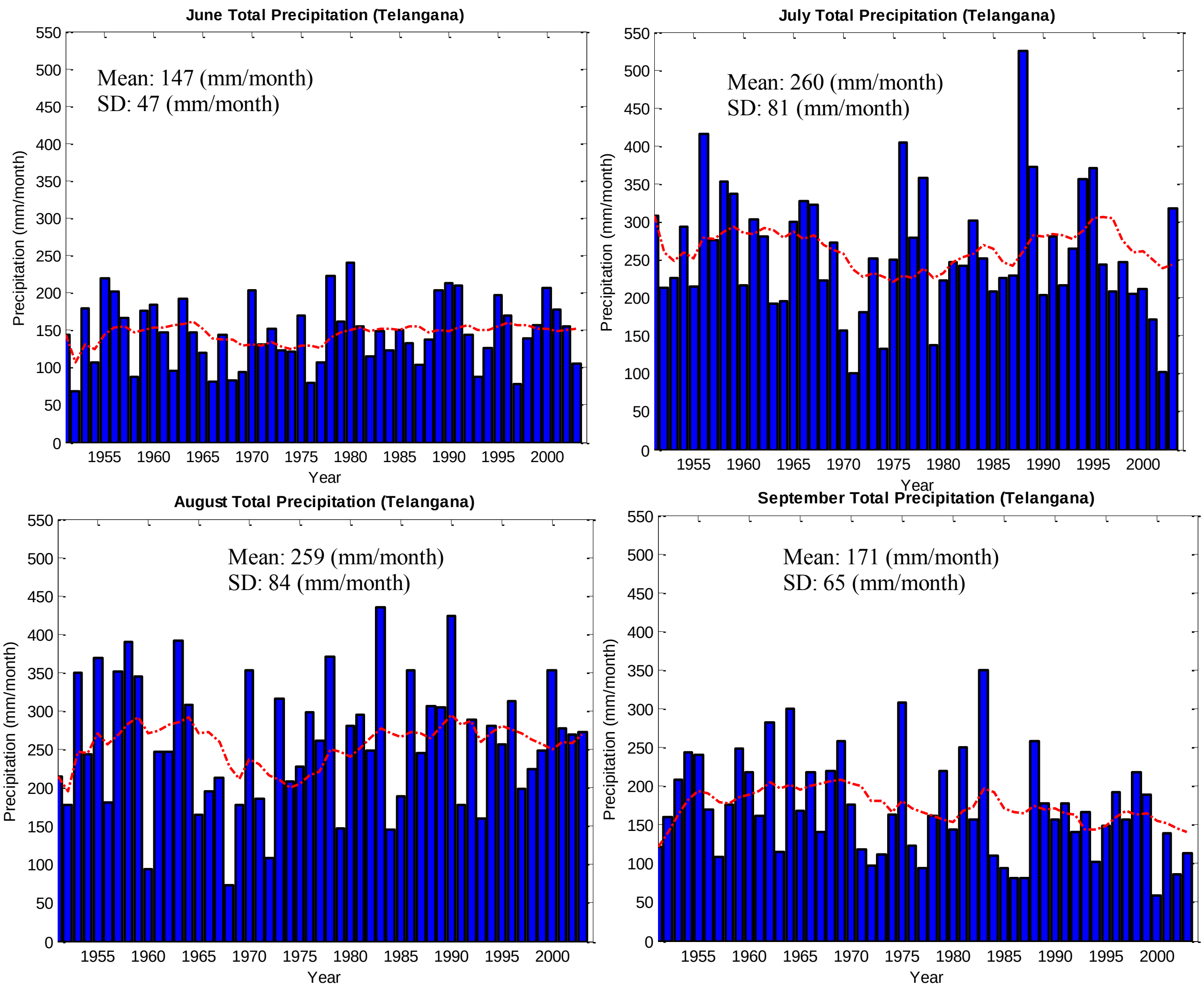


Figure S-4: Punjab Regional Daily Monsoonal Precipitation. Precipitation in the northwest daily amount increased steadily over time. Variability increased in southeast and southwest Punjab.



Decadal Changes in Monthly Precipitation

	June					July				
	1951-1959	**1960-1969**	**1970-1979**	**1980-1989**	**1990-2003**	**1951-1959**	**1960-1969**	**1970-1979**	**1980-1989**	**1990-2003**
Mean (mm/month)	150.11	128.75	147.06	150.95	154.81	292.70	263.41	225.15	282.53	243.01
Standard Deviation (mm/month)	51.92	40.51	43.90	41.41	44.49	68.91	52.02	101.42	97.88	72.16
Coefficient of Variation	0.35	0.31	0.30	0.27	0.29	0.24	0.20	0.45	0.35	0.30
	August					**September**				
Mean (mm/month)	291.16	210.89	247.60	280.20	267.54	3723.63	4159.58	186.18	207.98	157.56
Standard Deviation (mm/month)	85.90	94.64	87.28	81.34	68.44	1050.79	1221.54	52.54	61.08	65.93
Coefficient of Variation	0.30	0.45	0.35	0.29	0.26	0.28	0.29	0.28	0.29	0.42

Figure S-5: Telangana Monthly Precipitation. A simple (no weights) 10 year moving average is used to visually inspect changes in total monthly monsoon precipitation. Daily gridded data was aggregated over the region of Telangana to analyze monthly precipitation and decadal changes from 1951-2003. No clear trends are visible except for a continuous decline in precipitation for September.

Table S-2: Telangana Daily Precipitation Descriptive Statistics

		1951-1959	1960-1969	1970-1979	1980-1989	1990-2003
June	Mean*	5.00	4.29	4.90	5.03	5.16
	Standard Deviation*	6.81	4.76	6.82	5.89	7.22
	Coefficient of Variation	1.36	1.11	1.39	1.17	1.40
	90th Percentile*	13.82	10.71	13.08	12.79	12.84
	95th Percentile*	18.85	13.44	19.19	16.12	21.31
	99th Percentile*	34.06	22.96	34.22	29.96	36.17
July	Mean*	9.44	8.50	7.26	9.11	7.84
	Standard Deviation*	7.52	7.65	7.67	9.74	7.58
	Coefficient of Variation	0.80	0.90	1.06	1.07	0.97
	90th Percentile*	20.16	19.86	17.73	20.78	17.77
	95th Percentile*	23.94	23.97	21.73	27.55	22.12
	99th Percentile*	31.24	31.55	31.15	49.36	34.11
August	Mean*	9.39	6.80	7.99	9.04	8.63
	Standard Deviation*	7.86	6.32	7.96	10.46	8.57
	Coefficient of Variation	0.84	0.93	1.00	1.16	0.99
	90th Percentile*	19.89	15.38	18.14	20.14	19.68
	95th Percentile*	25.15	18.45	22.74	28.98	25.76
	99th Percentile*	33.69	31.46	36.07	53.18	41.17
September	Mean*	6.21	6.93	5.25	5.68	4.87
	Standard Deviation*	6.26	7.95	6.40	6.31	5.69
	Coefficient of Variation	1.01	1.15	1.22	1.11	1.17
	90th Percentile*	14.34	16.80	13.54	13.17	12.55
	95th Percentile*	17.11	21.93	18.51	18.37	15.94
	99th Percentile*	30.47	41.69	31.18	31.32	24.02

* mm/day

increase decrease

The coefficient of variation (and variability) has increased in time for both July and August and their extremes at the 99th percentile are markedly different of those pre-1980. Mean daily precipitation as well as the extremes for the month of September have decreased in time.

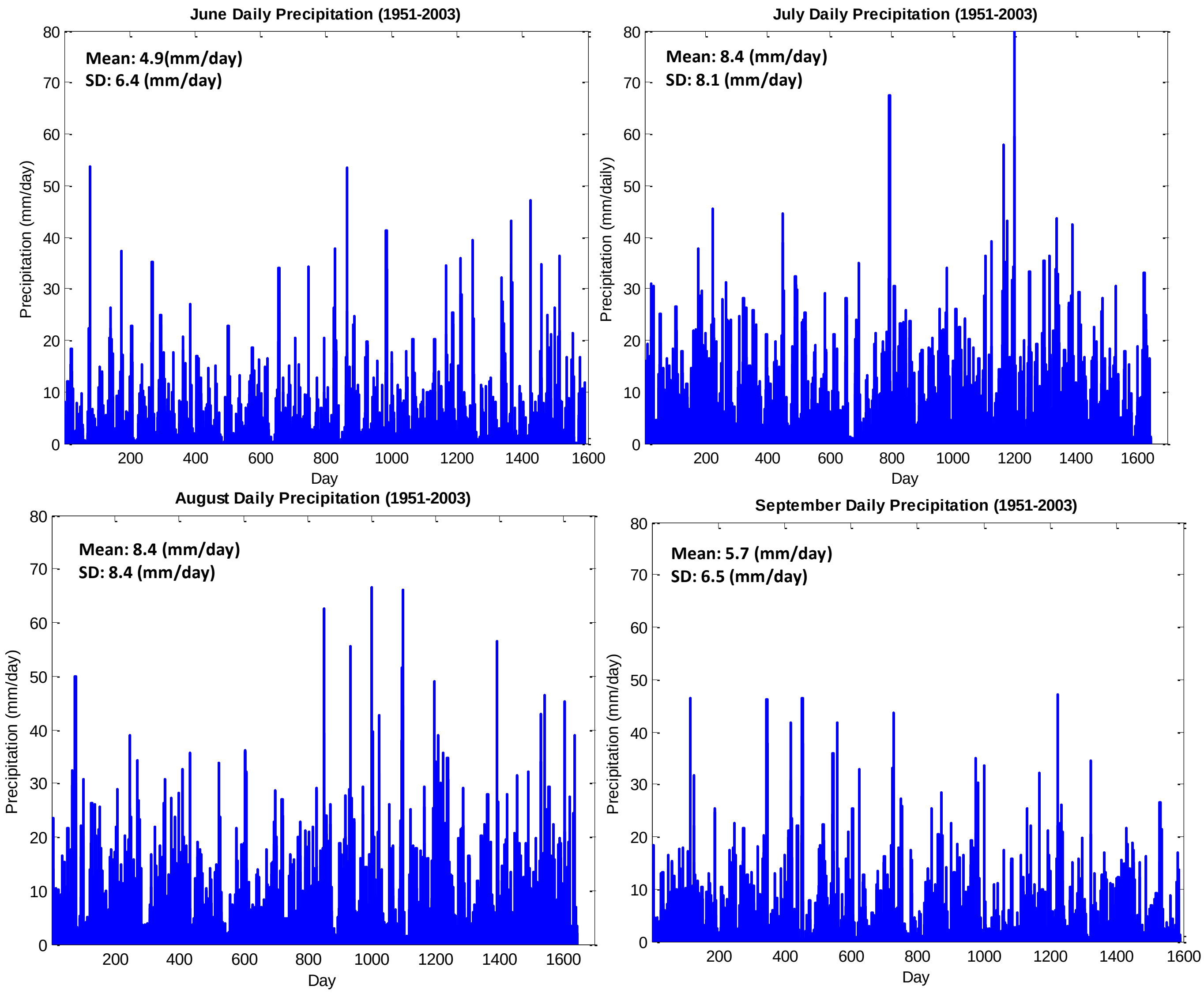


Figure S-6: Telangana Daily Precipitation. Daily precipitation for the months of June, July, August, and September (1951 – 2003) is shown. July and August have seen an increase in variability accompanied by an increase in the magnitude and frequency of extreme events (mm/day). Both mean daily precipitation and the magnitude of extreme events have decreased in time for the month of September. Daily variability has increased in time for July and August.

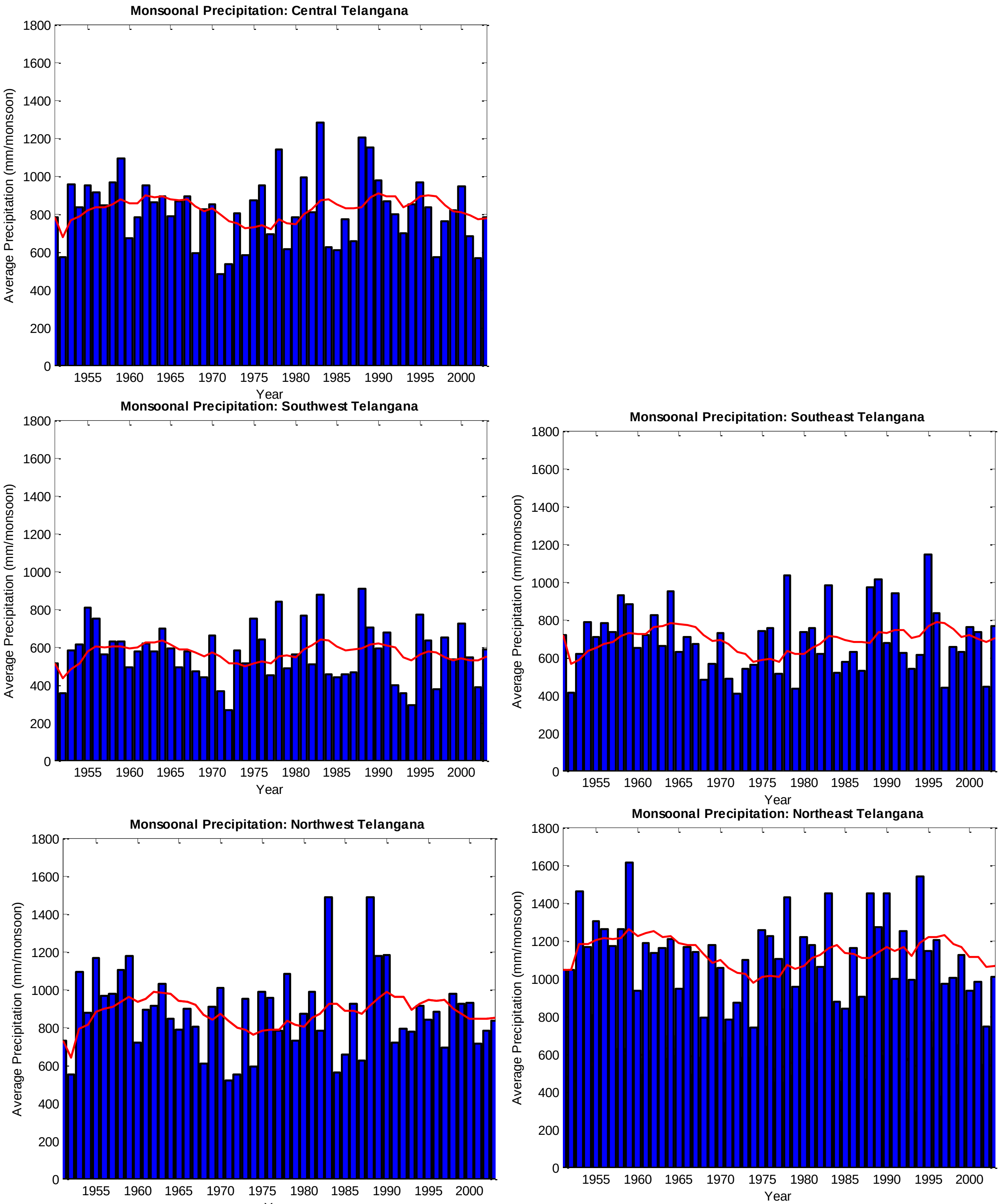


Figure S-7: Telangana Regional Monsoonal Precipitation. A 10 year moving average is used to inspect changes in total monsoon precipitation (bin size: 0.3) for Monsoon Precipitation over Northeast, Northwest, Southeast, and Southwest Telangana. A Steady decrease in total monsoonal precipitation can be observed since the early 1990's in all regions, and since the early 1980's in Northwest Telangana.

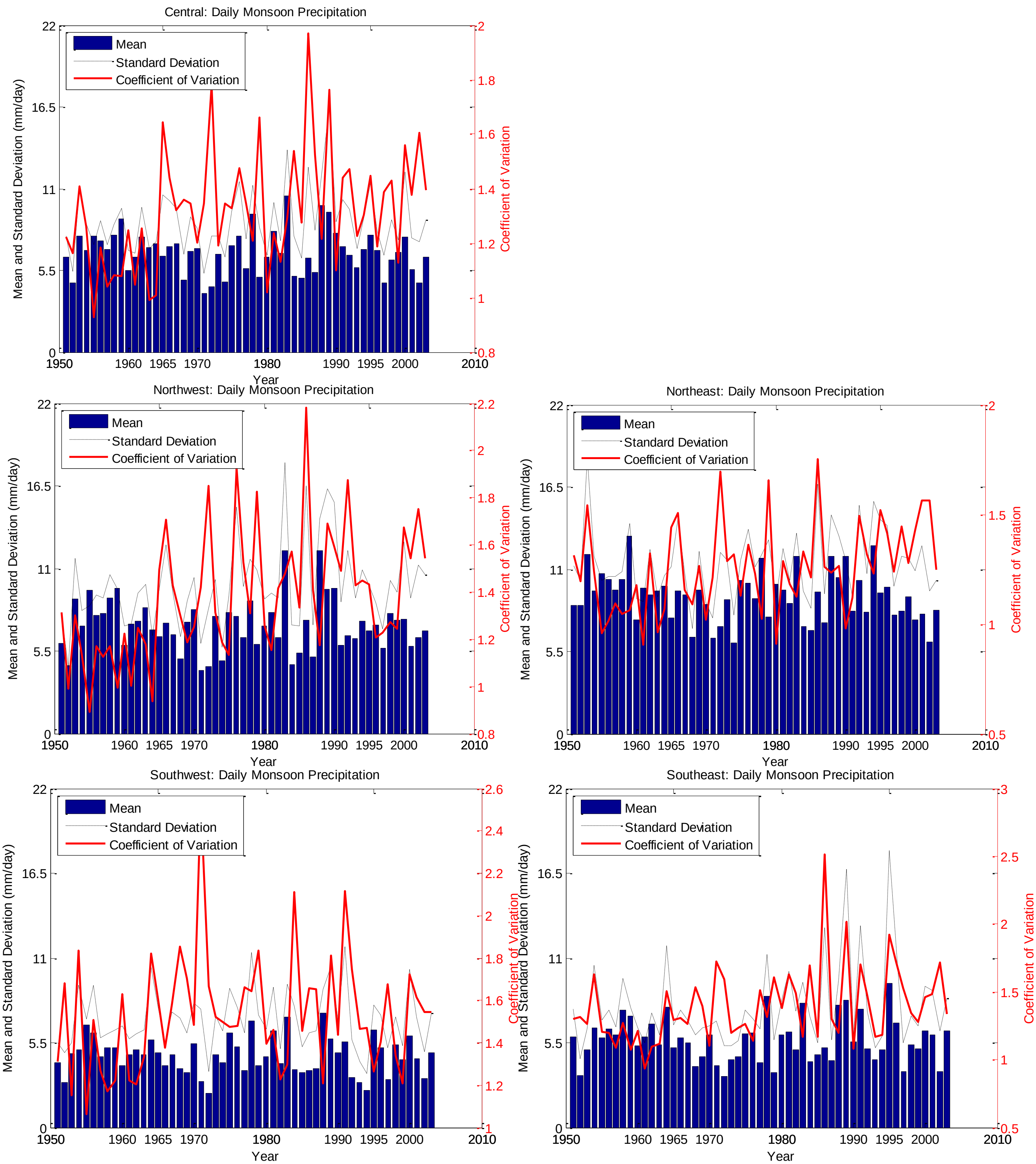


Figure S-8: Telangana Daily Precipitation. Mean, Standard Deviation, and Coefficient of Variation for daily monsoonal precipitation (bin size: 0.3; June, July, August, and September) over Central, Northeast, Northwest, Southeast, and Southwest Telangana (1951-2003). Northwest, Northeast and Central regions show a marked increase in daily precipitation variability.

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