Paradigm shift in irrigation sector of Andhra Pradesh (united) and its impact on irrigation efficiency and drought induced loss of crop productivity

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Irrigation sector in Andhra Pradesh observed a sustained shift towards tube-wells. While tube-well boom brought about efficiency in the agricultural sector; unregulated use of groundwater threatened the sustainability of groundwater resources in the state. Using district level data from united Andhra Pradesh, we demonstrate that groundwater boom generated adaptive benefits and increased effectiveness of irrigation; however, adaptive and efficiency effects of groundwater were far from being economically sustainable. Risk augmenting effects of groundwater use on crop yield indicate that groundwater policies in the state not only compromised environmental sustainability but also adversely affected economic sustainability of agriculture in the state.

Key words: Drought, Adaptation, Groundwater, Climate Change, Rice

1. Introduction

Historically, irrigation played a critical role in agricultural growth and development in India and elsewhere due to its direct as well as indirect favorable impact on economy (Dhawan 1988; Narayanmoorthy 2006; Narayanmoorthy et al. 2013). Irrigation augments effective land supply by increasing cropping intensity and its spillover effect include increasing use of complementary inputs (Dhawan 1988). However, irrigation effects in Indian agriculture were found to be heterogeneously distributed across regions (Fan et al. 2000; Binswanger, Khandker, Rosenzweig 1993; Fan et al., 2000b; Binswanger, Khandker, Rosenzweig 1993; Fan and Hazell, 2000). In comparison to canals, tube-well irrigation is a recent phenomenon in peninsular India (Shah 2012). Considering constrains associated with expanding surface irrigation; peninsular states in India began subsidizing groundwater use and electricity supply to reduce regional disparities in agriculture sector. In particular, development of groundwater sources has been more critical from agricultural growth perspective in historically low irrigated semiarid regions of India (Srivastava et al. 2014; Shah 2012).

Andhra Pradesh is a major agricultural state located in peninsular India. Since independence, Andhra Pradesh invested heavily in its irrigation sector to double its irrigation potential in 2011 from what it was in 1970 (figure 1). While canal based irrigation flourished in the state during centralized planning era; limitations of gravity based irrigation forced state to subsidize groundwater based well irrigation (figure 1). Incentive driven groundwater exploitation brought a boom in well irrigation to shift irrigation paradigm in the state towards groundwater based micro irrigation during 1987 to 1991 (figure 1). However, injudicious use and excessive reliance on groundwater due to lack of access to surface based irrigation also endangered the sustainability of groundwater sources in hard rock regions of Andhra Pradesh (see, figure 2). Direct consequences of groundwater overexploitation in Andhra Pradesh include declining groundwater table, rising irrigation cost, increasing inequality in access and reduced profitability (Ratna Reddy 2003; 2006). These emerging fault lines have increased the uncertainty associated with the agriculture water supply in Andhra Pradesh (Kumar et al. 2011).

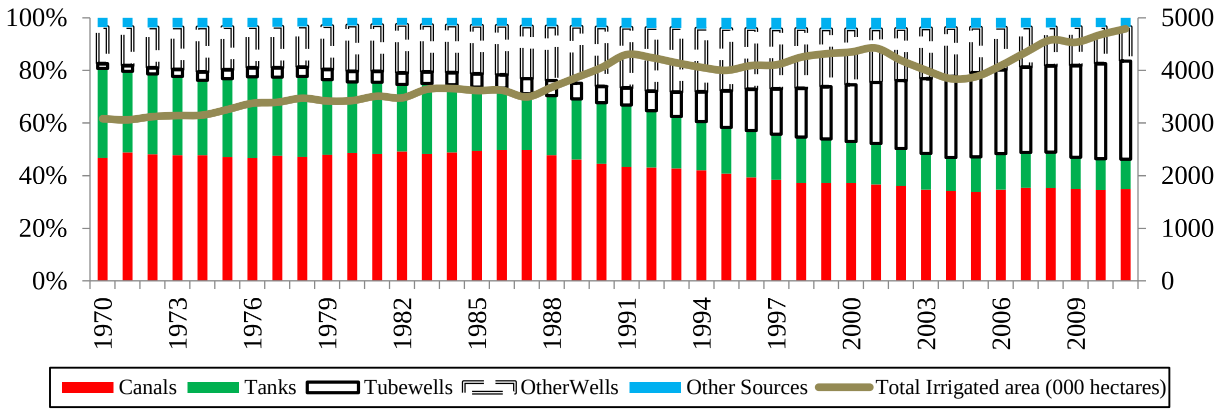

Figure 1: Irrigation development in Andhra Pradesh

Environmental concerns apart, groundwater played major role in growth and development of rural economy in Andhra Pradesh. Land augmenting and productivity enhancing roles of groundwater are well documented in India and elsewhere (see, Shah 2007; 2009; 2012). A critical difference between groundwater and surface irrigation can be described in terms of *flexibility of use* which comes with "*atomic groundwater irrigation*" (Shah 2007; 2009; 2012). Flexibility associated with groundwater use increased efficiency of irrigation sector and is also hypothesized to be critical for climate change adaptation (Shah 2007, 2009, 2012; Schlenker et al. 2005; Birthal et al. 2014). In this connection, Shah et al. (2009) argued that groundwater plays a risk stabilizing role which is distinct from the production role of irrigation water. However, arguments in favor of groundwater were challenged by Dinesh Kumar et al. (2009). In a recent study, Birthal et al. (2015) examined impact of irrigation on drought resilience of rice yields in the case of Indian agriculture. Predictions in this study showed that irrigation increased rice yield resilience against drought; however, adaptive benefits of irrigation were found to be decreasing over the years. Adaptation and efficiency hypotheses associated with groundwater use demand further investigation for drawing any meaningful conclusion.

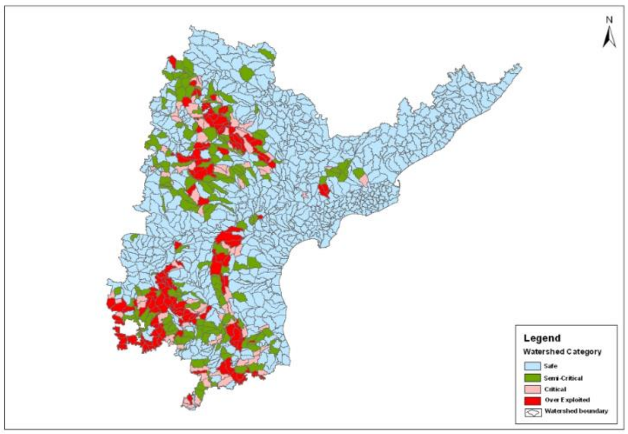

Figure 2: Groundwater status in Andhra Pradesh
Source: Government of Andhra Pradesh, groundwater department (2008)

Despite increasing realization of climate change effects on monsoon and rising number of overexploited aquifers in hard rock regions of Andhra Pradesh, there exist no study examining implications of groundwater boom for climate change adaptation and output growth. To address this research gap, present study analyses the impact of groundwater boom on agricultural yields in Andhra Pradesh. Two crops, examined in this study, are rice (paddy) and groundnut.[1] Contribution of both crops in agriculture output in Andhra Pradesh is significant. These two crops together hold more than 40 percent of total cropped area in the state. While rice is a water intensive crop; groundnut is known for its drought tolerance. Major groundnut producing districts in the state are located in Rayalseema region; however, rice cultivation is more homogenously distributed among all the districts.

Rest of the paper is organized as follows. Section 2 describes data sources, variables and methodology. Section 3 explores relationship between drought and crop yield using sample

[1] Henceforth and elsewhere, we have used paddy and rice, interchangeably.

information. Section 4 presents results of the econometric exercise. Section 5 presents concluding remarks.

2. Data Sources, Variables and Methodology

2.1. Data

For analysis, we borrowed data from secondary sources. Major data sources include NICRA which provides district level daily information on rainfall and temperature and Village Dynamics in South Asia (ICRISAT) which provides data on agricultural and various socio-economic parameters. Sample period in NICRA climate dataset was from 1971 to 2007; however, time period covered in VDSA dataset was from 1966 to 2011.

Due to discrepancy in time span between two datasets, time period considered in econometric study was confined to the period for which weather data was available i.e. 1971 to 2007. A balanced panel consisting data of 20 districts (as per 1965-66 boundaries) covering period from 1971 to 2007 was used for data analysis.[2]

2.2. Variables

a. Climate Region Dummy

For climate classification, we used relative aridity index of De Mortonne (1926). De Mortonne index measures moisture adequacy as:

$$A_M = \frac{P}{T+10}$$

In which, A_M is the index of soil moisture adequacy, P is the total precipitation of the year and T is the annual mean temperature. Based on relative aridity index, a climatic classification of the state was performed, results of which are given in table 1.

[2] Post 1965-66, three new districts were formed in Andhra Pradesh increasing total number of districts to 23. Therefore, there existed an anomaly in district boundaries in two datasets. For simplicity, we assumed that weather of mother district in climate data set was representative despite reorganization of district boundaries in the state.

Table 1: Climate Classification of Andhra Pradesh

A_M	Climate classification[3]	Districts
I<10	Dry or arid	-
15≤I≤24	Semiarid	Anantpur, Kurnool, Mahbubnagar Nalgonda, Kadapa, Hyderabad Guntur
24<I≤30	Moderately arid	Medak, Chittoor, Nizamabad Warangal, Nellore, Krishna Karimnagar, West Godavari, Adilabad
30<I≤35	Slightly humid	Khammam, East Godavari Srikakulam, Visakhapatnam

Source: Hydrological Observatory of Athens

Based on the classification provided in table 1, regional dummy were constructed. Details of other explanatory variables included in the analysis are explained in following sections.

b. Drought Index

Major indices used for measuring severity of droughts include *Palmer drought severity index*, *rainfall deciles,* and *standardized precipitation index*. In a recent study, Birthal et al. (2015) used an index which defines drought as the product of standardized deviations from rainfall being below the normal and standardized temperature deviations above the normal. McCarl et al. (2008) used Palmer drought severity index (PDSI) to assess impact of drought on US crop yields. PDSI intends to 'measure the cumulative departure of moisture supply' and takes a dimensionless value typically ranging between 4 and -4, with negative values showing a shortage of moisture of moderate to extreme kind.

While PDSI is widely used in applied research; it shows difference in the severity of drought when occurrence of wet months is interchanged by the dry months within a rainfall season (Bhalme and Mooley 1980) i.e. severity of drought will change if we interchange the occurrences of a dry and a wet month while holding the magnitude of wetness and dryness of respective months constant. Bhalme and Moole (1980) argued that *drought intensity must be considered on an incremental basis such that each successive month is evaluated in terms of its contribution to the intensity of the drought* and proposed a new index to measure drought intensity.

[3] Climate classification based on De Mortonne aridity index was conducted using table provided by Hydrological Observatory of Athens.

Another issue is related with using standardized drought indices in a panel (fixed effects) setting. *Standardized indices ignore context (here, mean rainfall)*; therefore, are not useful in a panel setting where cross sectional units exhibit heterogeneous rainfall endowment which eventually determines land productivity differentials across districts.[4] Districts with identical drought index may, in real experience, exhibit different absolute and/or relative yield gain/loss due to difference in their rainfall endowment i.e. climate which directly affects land quality and, thus, long run land productivity.[5] It is more obvious that *droughts of same intensity damage agricultural yields more in better rainfall endowed regions* (see, Hsiang 2016). Additionally, *giving higher weights to droughts in high rainfall regions is also important from food security perspective as these regions contribute more to total crop production*. In conclusion, damage to agriculture yields due to drought remains underestimated in a fixed effects (FE) model which uses standardized drought index as an explanatory variable.[6] Our argument relies on the assumption that while regions with lower mean rainfall are more vulnerable to climate change; yield losses due to droughts of similar magnitude should be relatively higher in regions of relatively more benign climate as these regions often show high land productivity but historically lack responsive behavior due to favorable climatic endowment (Hsiang 2016).

Drought Index (Bhalme and Moole 1980), used in this study, is based on a moisture anomaly index (*M*) which is defined as the *deviation of rainfall from long run average rainfall in a month weighted by the inverse of coefficient of variation of rainfall in the corresponding month*. Bhalme and Moole (1980), then, defined *rainfall anomaly intensity* for a given month as:

$$I_k = 0.50 I_{k-1} + \frac{M_k}{48.55}$$

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[4] Econometrically speaking, variables are used in mean differenced form in a fixed effects (FE) model; therefore, standardization adds nothing but complications to regression model by dividing mean differenced variables to district specific standard deviation.

[5] It is very unlikely that climate change will affect climatic differences between two regions. Hot regions will become hotter and cold regions will become less cold due to climate change. Holding technology changes constant, climate change induced shift influence long run land productivity.

[6] This problem, to some extent, can be taken care of by controlling district fixed effects. A better option can be to include mean rainfall as an explanatory variable in a fixed effects model while assessing impact of drought/floods. However, such treatement will mean that effects of climate (long run average rainfall) and weather (drought) on yield are additively separable.

Equation 2 is the *drought index equation*, in which *I* represent intensity of drought for month *k* and *M* is the moisture anomaly index.[7] By introducing past month's rainfall anomaly intensity, I_k for any month indirectly includes the effect of duration of wetness/dryness during entire monsoon. In other words, continuation of drought situations contributes to increase (decrease) intensity of droughts (floods) in next months. It can be observed that index takes negative values in the case of droughts. Additionally, weighing by inverse of coefficient of variation of rainfall instead of standard deviation of rainfall is equivalent to weighing standardized rainfall anomalies with long run average rainfall. Such weighting, in our view, removes bias from panel data estimates of drought impact. We used rainfall data of months from June to December to construct drought index.[8]

c. Crop Irrigated Area and Irrigation Quality Index

We employed crop wise irrigated area (thousand hectares) as a proxy for irrigation access. Similarly, *ratio of area irrigated by groundwater sources and area irrigated by surface sources* was taken as a proxy for irrigation quality (see, subrahmaniam and Satya Shekhar 2003). The ratio acts as an *indicator of irrigation quality* which changed due to embodied technological change in irrigation sector. Groundwater boom changed the manner in which irrigation used to happen under large gravity based canal irrigation. Summary of variables used in the analysis and details of variable construction is provided in table 2.

Table 2: Variables and their Construction

Independent Variable	Symbol	Construction	Unit of measurement
Yield	*YLD*	Total production of crop/Total area under crop	Kilogram per hectare
Drought index	*DI*	$I_k = 0.50 I_{k-1} + \frac{M_k}{48.55}$; in which *I* represent severity of rainfall for month *k* and *M* is the moisture anomaly index defined as the *weighted deviation in rainfall in which inverse of coefficient of variation in rainfall* was used as weight. *DI* is defined as the mean of I_k from *June* to *December*.	Millimeter
Groundwater dominance	*GWD*	$GWD = \frac{Area\ irrigated\ by\ wells}{Area\ irrigated\ by\ other\ sources}$	Ratio
Crop area	*IA*		Thousand hectares

[7] Past month rainfall anomaly index for first month is considered zero (see, Bhalme and Moole, 1980).

[8] Andhra Pradesh not only receives rainfall from southwest monsoon but also attains significant amount of rainfall in northeast monsoon.

irrigated			

3. Drought Index and Yield

While hypotheses which we seek to test were drawn from literature; it is useful to examine relationship between drought index and crop yield before model construction. Such cross tabulation is critical as there exists almost no theoretical insight regarding functional relationship between droughts and crop yield. In this connection, figure 3 presents frequency diagram of drought index.[9] Since the index was weighted by average district rainfall, range of drought index distribution was big. However, it can be observed that incidence of rainfall anomalies was tilted towards deficient instead of surplus rainfall.[10] Outlier flooding events also occurred in few districts as the frequency distribution of drought index indicates.

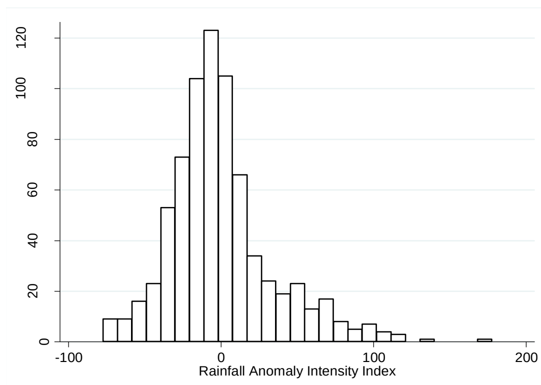

Figure 3: Frequency distribution of drought index

Figure 4 plots relative yield loss, defined as *trend deviation of yield divided by observed yield*, and drought index using sample data.[11] While it is a naïve way to examine the impact of drought index on agricultural yield, it is useful in understanding drought-yield relationship. It can be observed that relationship between drought index and crop yield was stronger in the case of rice yields.

[9] Values which *DI* takes in frequency diagram are inflated due to weighing normalized index by district mean rainfall.

[10] Frequency of events where index takes values less than zero is higher.

[11] In this section, we used relative yield loss instead of absolute yield losses due to ease of interpretation. However, we used absolute yield as dependent variable in econometric model. Linear specification was consistent with our argument that droughts of equal magnitude in terms of standardized drought index create more yield damage in absolute terms in more productive regions which also possess benign rainfall regime.

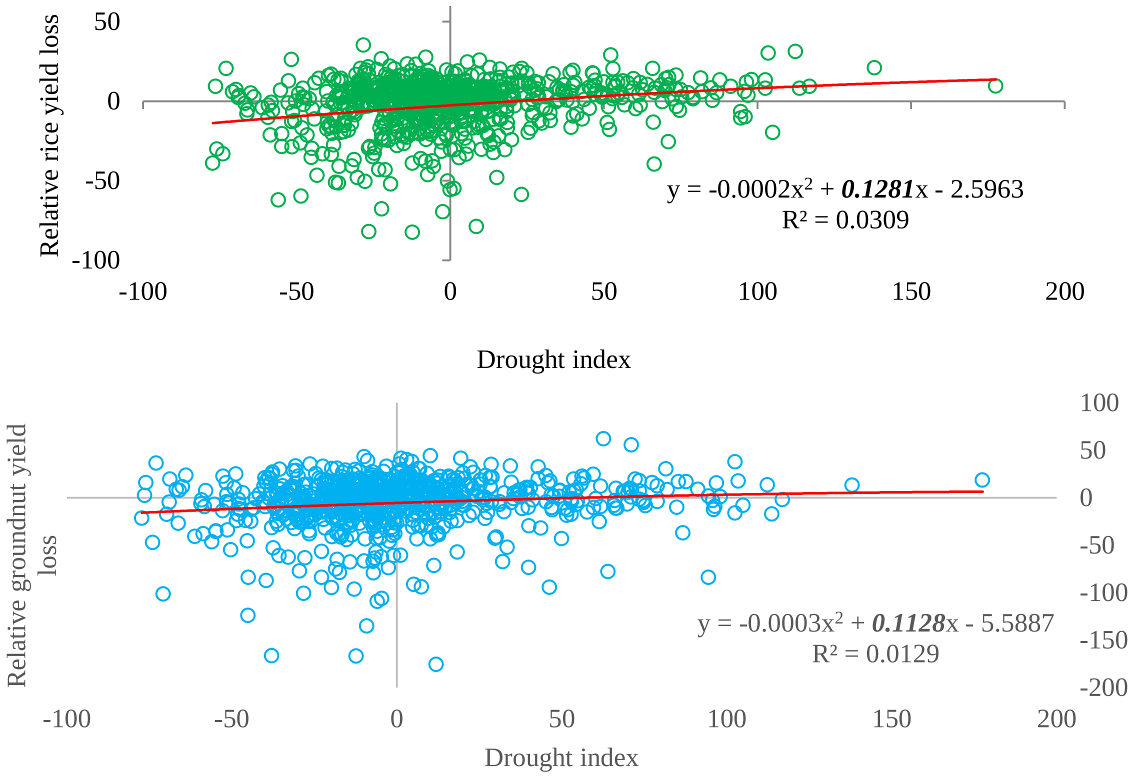

Figure 4: Relative yield loss due to floods and droughts. Relative yield loss, defined as the trend deviation in yield divided by realized yield in a year, was plotted against drought index.

In another check, we classified drought index into three categories to examine how drought effects were different from flood effects. Results of this exercise are plotted in figure 5. Three such categories of drought index considered were below 30th percentile (droughts), between 30th and 70th percentiles (normal), and above 70th percentile (floods) of drought index. This categorization was chosen to separate flood effects from drought effects.[12] It can be observed that mean relative yield loss in drought percentiles was marginally higher for groundnut. Range of drought index percentiles considered as normal indicated that mean relative yield loss in this range of drought index distribution was substantially bigger for groundnut in comparison to rice. Most of the important droughts in semiarid regions may also fall in this range due to lower mean rainfall in semiarid districts. Since semiarid region of the state has been the dominant producer of groundnut in the state, results do not surprise. While average relative rice yield loss was less in middle category of droughts; standard deviation of relative yield loss was high. Mean relative deviation in rice yield was positive for rice; however, it remained negative

[12] Bottom 30 percent observations in drought index distribution represent droughts and top 30 percent observations represent flood.

for groundnut in higher percentiles which represent normal to surplus rainfall.

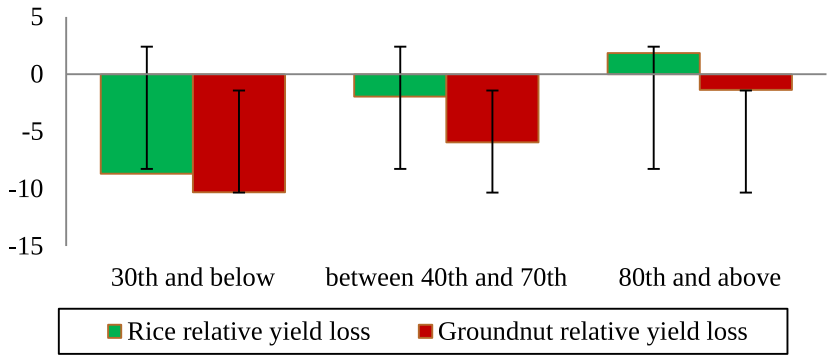

Figure 5: Relative yield loss due to floods and droughts. Relative yield loss is defined as the trend deviation in yield divided by realized yield in a year. In each category, mean and variance of yield anomaly was estimated for comparing the difference between drought and flood effects.

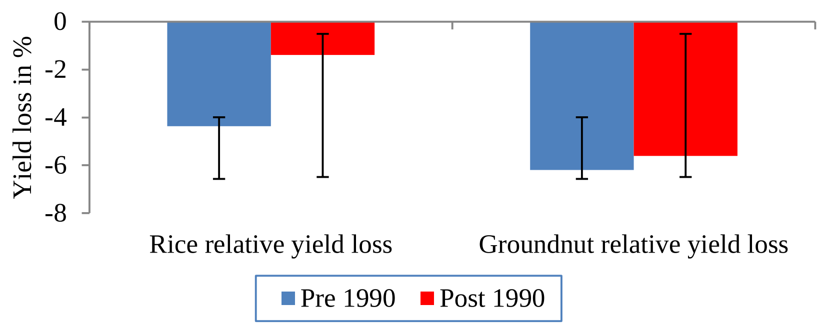

Figure 6: Relative yield loss due to floods and droughts. Relative yield loss is defined as the trend deviation in yield divided by realized yield in a year. Year 1990 was included in the definition of post 1990. Mean and variance of yield anomalies was estimated for comparing the difference between periods.

To examine presence of any temporal change in drought induced yield losses as hypothesized; we plotted mean and standard deviation of relative yield losses of rice and groundnut in figure 6 in pre and post 1990 period. It can be seen that relative yield loss was significantly lower in post liberalization period in the case of rice. It can also be observed that reduction in mean yield loss was marginal between pre and post 1990 period in the case of groundnut.

In following section, econometric scheme is explained which was used to understand effect of groundwater boom on drought adaptation and irrigation efficiency.

4. Econometric Model

Fixed effects (FE) model is an ideal choice to examine impact of drought and irrigation on crop yields. Fixed effects model allows controlling time invariant effects which may be correlated with the independent variables. Additionally, FE model, unlike random effects model, doesn't impose restrictive assumption regarding unobserved time invariant effects. Model specifications for hypotheses testing are as follows:

$$YLD_{it}^{rc,gn} = \alpha_i + \delta_i D_i T + \theta_1 DI_{it} + \theta_2 IA_{it}^{rc,gn} + \theta_3 GWD_{it} + \varepsilon_{it} \tag{1}$$

$$\begin{aligned} YLD_{it}^{rc,gn} = {} & \alpha_i + \delta_i D_i T + \theta_1 DI_{it} + \theta_2 IA_{it}^{rc,gn} + \theta_3 GWD_{it} + \\ & \phi_1 (DI_{it} \times GWD_{it}) + \phi_2 (IA_{it} \times GWD_{it}) + \varepsilon_{it} \end{aligned} \tag{2}$$

$$YLD_{it}^{rc,gn} = \alpha_i + \delta_i D_i T + (\theta_1 DI_{it} + \theta_2 IA_{it}^{rc,gn} + \theta_3 GWD_{it}) \times (\lambda_1 + \lambda_2 D_{HARID} + \lambda_3 D_{MARID}) + \varepsilon_{it} \tag{3}$$

$$\begin{aligned} YLD_{it}^{rc,gn} = {} & \alpha_i + \delta_i D_i T + (\theta_1 DI_{it} + \theta_2 IA_{it}^{rc,gn} + \theta_3 GWD_{it}) + \\ & (\theta_1 DI_{it} + \theta_2 IA_{it}^{rc,gn} + \theta_3 GWD_{it}) \times (\lambda_1 D_{HARID} + \lambda_2 D_{MARID}) \times \phi T + \varepsilon_{it} \end{aligned} \tag{4}$$

$$\begin{aligned} YLD_{it}^{rc,gn} = {} & \alpha_i + \delta_i D_i T + \theta_1 DI_{it} + \theta_2 IA_{it}^{rc,gn} + \theta_3 GWD_{it} + \\ & (\phi_1 DI_{it} \times GWD_{it} + \phi_2 IA_{it}^{rc,gn} \times GWD_{it}) \times (\lambda_1 D_{HARID} + \lambda_2 D_{MARID}) + \varepsilon_{it} \end{aligned} \tag{5}$$

$$\begin{aligned} YLD_{it}^{rc,gn} = {} & \alpha_i + \delta_i D_i T + \theta_1 DI_{it} + \theta_2 IA_{it}^{rc,gn} + \theta_3 GWD_{it} + \\ & (\phi_1 DI_{it} \times GWD_{it} + \phi_2 IA_{it}^{rc,gn} \times GWD_{it}) \times (\lambda_1 D_{HARID} + \lambda_2 D_{MARID}) \times \phi T + \varepsilon_{it} \end{aligned} \tag{6}$$

In equation 1 to 6, *y* stands for crop yield; super-scripts *rc* and *gn* stand for rice and groundnut respectively.[13] Subscripts *i* and *t* denote district and year, respectively. α_i stands for district specific intercept in fixed effects model. D_iT denotes interaction of district dummy

[13] While using interaction of variables, original variables were kept as regressors in regression model (see, Balli and Sorensen 2013). Linear specification was chosen over a logarithmic specification as it was less restrictive in present case. A full model specification was also estimated and results of model estimates and related hypotheses tests are reported in the appendix A3.

variables with time trend *(T)* to allow estimation of heterogeneous technological change in district yields. ε_{it} is *identically and independently distributed* (IID) error term.

Equation 1 depicts a production function in which drought index (*DI*), irrigated area (*IA*) and irrigation quality index (*GWD*) as inputs to determine crop yield. Description and definition of other explanatory variables is provided in table 2.

Equation 2 examines adaptation and irrigation efficiency hypothesis related with groundwater boom. Measuring adaptation and irrigation efficiency in this manner assumes *GWD* as a measure of technical change which affects marginal productivity of drought index (bad input) and irrigation (good input) to shift yield frontier. Differentiating equation 2 w.r.t. *DI*/*IA*, first and, then, w.r.t. *GWD* gives adaptive and efficiency gains with increasing groundwater use.

$$\begin{aligned} &Adaptativegain = \frac{\partial}{\partial GWD_{it}}\left(\frac{\partial y_{it}}{\partial DI_{it}}\right) = \phi_1; \\ &Efficiencygain = \frac{\partial}{\partial GWD_{it}}\left(\frac{\partial y_{it}}{\partial IA_{it}}\right) = \phi_2 \end{aligned} \tag{7}$$

Equation 3 is meant to examine the regional differences in the relative contribution of independent variables in explaining crop yields. Equation 4 further extends equation 1 to access whether relative contribution of drought index, irrigation and irrigation quality index in explaining variations in crop yield increased/decreased or remained constant over time in different climatic regions. Differentiating equation 4 w.r.t. independent variables first and then w.r.t time trend (*T*) variable gives;

$$\textit{Temporal change in drought impact:}\ \frac{\partial}{\partial T}\left(\frac{\partial y_{it}}{\partial DI_{it}}\right) = \theta_1\left(\lambda_1 D_{HARID} + \lambda_2 D_{MARID}\right) \tag{8}$$

Similarly, temporal change in relative contribution of irrigation (*AI, GWD*) variables in explaining annual crop yield can be estimated across different climatic regions. Equation 5 is an extension of equation 2 and was meant to access the regional heterogeneity in adaptive and efficiency gains due to increasing groundwater use. Equation 6 further extends equation 2 to examine whether adaptive and efficiency gains of groundwater use changed over time.

5. Groundwater Boom, Droughts and Crop Yield

Sample summary of variables is provided in table 3 and table 4 reports correlation matrix of explanatory variables used in the regression analysis. It can be seen from table 2 that drought variance was highest in slightly humid region followed by moderately arid region. Similarly, groundwater boom was mostly confined to districts falling in semiarid climate followed by moderately arid region. Mean groundnut irrigated area was lower and standard deviation in groundnut irrigated area was higher.

Table 3: Sample Summary of Variables

	Full sample		Slightly humid region		Moderately arid region		Semiarid region	
Variable	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
RCYLD	2165.75	644.14	1869.76	603.83	2224.16	654.33	2259.78	605.16
GNYLD	1053.78	418.72	954.54	261.37	1176.16	463.13	953.14	390.02
DI	0.00	34.32	0.00	40.84	0.00	37.17	0.00	25.39
GWD	1.42	2.56	0.70	1.29	1.49	2.49	1.73	3.07
RCAI	93.85	9.43	87.55	8.81	93.87	10.58	97.40	5.60
GNAI	36.12	28.14	19.96	19.87	48.93	30.38	28.88	21.01

Table 4: Correlation among Independent Variables

	DI	GWD	RCAI	GNAI
DI	1.00			
GWD	-0.06	1.00		
RCAI	0.01	0.17	1.000	
GNAI	-0.01	0.31	0.11	1.00

Regression results for all models depicted in equation 1-6 are reported in table 5 and table 7 for rice and groundnut, respectively.[14] Important diagnosis and regression performance tests for all models are reported in table 6 and table 8, respectively, for rice and groundnut. Dependent variable in all models was crop yield measured in kilogram per hectare. We tested model errors for heteroscedasticity and cross sectional dependence. Statistically significant test statistics inferred to reject null of homoscedasticity and no cross section dependence. For efficient estimation of standard errors, Driscoll-Kraay (1998) estimator was used which provides robust standard error of model estimates in presence of heteroscedastic, temporally and spatially correlated errors (Hoechle, 2007).

[14] Unit root test results are provided in table A1 (see, appendix). All variables were found stationary at levels.

In the case of rice, coefficient associated with drought index (*DI*) turned statistically significant (table 5) implying that any increase in drought intensity in districts will reduce rice yield. One unit increase in drought intensity reduced rice yield by 1.14 kilogram per hectare to 1.58 kilogram per hectare depending on the model specification. However, drought effect on rice was distributed homogenously across climatic regions as coefficients associated with interaction of drought and region dummies didn't turn statistically significant. Considering that rice is major crop in majority of the districts, results are not surprising. Contrary to droughts, we failed to confirm any significant impact of irrigated area on rice yield. However, coefficient associated with interaction of irrigated area and moderately arid region dummy turned statistically significant at 10 percent level implying that irrigation significantly contributed to explain variation in rice yield in moderately arid region of the state (see, column 3; table 5). Most of the gain in irrigated area and rice cultivated area was observed in moderately arid region. Low irrigation penetration and low rice cultivated area might be a reason why coefficient associated with DI was not statistical significant.

As far as temporal change in impact of drought on rice yield is concerned, results failed to reject null hypothesis of no significant change in both moderately and semiarid regions (column 4, table 5). As far as temporal growth in impact of irrigation on rice yield is concerned, results were not statistically significant in any of the two regions (column 4, table 5). Impact of irrigation quality index (*GWD*) on rice yield was significantly negative in different climatic regions; however, negative impact of GWD on rice yield was less prominent in semiarid region. Temporal change in GWD effect on rice yield was significantly negative which indicated that this effect was decreasing over time. Twofold justification can be provided to explain negative relationship between *GWD* and crop yield. First, groundwater boom brought marginal lands into cultivation as well as permitted intensive cultivation which contributed to reduce the mean annual yield. Secondly, another interpretation of results is that regions where area irrigated by surface irrigation sources was low; yields were also low in those regions. Statistically significant and negative temporal change in GWD-yield relationship hints that cultivated area expansion effects of groundwater use was decreasing over time.[15]

[15] Similar explanation can be given in the case of groundnut yields too.

Table 5: Drought, Irrigation and Rice Yield

Variables	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
DI	**1.585****	**1.144***	**1.340***	**1.369****	**1.201****	**1.258****
	(0.593)	**(0.574)**	**(0.796)**	**(0.534)**	**(0.584)**	**(0.569)**
DI*HARID			0.375			
			(0.818)			
DI*MARID			0.112			
			(0.710)			
RCAI	8.041	8.965	3.615	2.158	7.181	7.627
	(4.894)	(5.853)	(3.881)	(3.506)	(5.127)	(5.008)
RCAI*HARID			-4.587			
			(5.391)			
RCAI*MARID			**15.07***			
			(9.072)			
GWD	-24.30	34.72	**-98.23****	**-62.57*****	**-92.89*****	**-51.06****
	(14.64)	(182.9)	**(42.17)**	**(19.62)**	**(29.54)**	**(21.07)**
GWD*HARID			**79.00****			
			(38.19)			
GWD*MARID			73.69			
			(47.26)			
DI*GWD		**0.343*****				
		(0.0515)				
RCAI*GWD		-0.545				
		(1.867)				
DI*HARID*T				0.00171		
				(0.00173)		
DI*MARID*T				0.000322		
				(0.00119)		
RCAI*HARID*T				-0.0102		
				(0.0155)		
RCAI*MARID*T				0.0514		
				(0.0387)		
GWD*HARID*T				**0.123*****		
				(0.0337)		
GWD*MARID*T				**0.0997****		
				(0.0456)		
DI*GWD*HARID					-0.00650	
					(0.165)	
DI*GWD*MARID					**0.388*****	
					(0.0572)	
RCAI*GWD*HARID					**0.776*****	
					(0.250)	
RCAI*GWD*MARID					**0.757****	
					(0.307)	
DI*GWD*HARID*T						0.000200
						(0.000648)
DI*GWD*MARID*T						**0.000743*****
						(0.000147)
RCAI*GWD*HARID*T						**0.000921***
						(0.000496)
RCAI*GWD*MARID*T						**0.000781***
						(0.000418)
Constant	669.9	583.9	614.3	431.2	750.2	710.4
	(447.2)	(538.1)	(407.0)	(606.0)	(469.0)	(457.8)
Observations	740	740	740	740	740	740
District wise trend	yes	yes	yes	Yes	yes	yes

Note: *, **, *** indicate statistical significance at 10 percent, 5 percent and 1 percent level, respectively. Standard errors reported in parentheses were estimated using Driscoll-Kraay (1998) estimator.

Table 6: Diagnosis Test for Rice Yield Regression Model

Test name/model	1	2	3	4	5	6
Model Goodness of fit: F Test	1027.62 (22, 36)***	1053.00 (24, 36)***	1562.86 (28, 36)***	1331.48 (28, 36)***	777.41 (26, 36)***	986.90 (26, 36)***
Within R sq.	0.69	0.69	0.69	0.70	0.69	0.69
Hausman test	327.05 (22)***	324.85 (24)***	289.62 (28)***	547.58 (26)***	328.25 (26)***	320.26 (26)***
Panel heteroskedasticity Test: $\chi^2(20)$	196.14***	193.86***	174.79***	175.13***	193.24***	540.98***
Cross section correlation test: $\chi^2(190)$	536.012***	538.244***	515.799***	514.576***	540.334***	195.02***
Joint significance of district wise trend: F(19, 36)	577.22***	637.32***	505.29***	163.67***	534.73***	505.35***

Note: *, **, *** indicate statistical significance at 10 percent, 5 percent and 1 percent level, respectively. Rejection of homoscedasticity confirms presence of risk (Just and Pope 1978; Asche and Tveteras 1999) postulate. Cross section correlation (Pesaran 2004) justifies the choice of a flexible estimation technique. Null hypothesis for F test (district specific trend)- H_0: all estimated coefficients associated with district specific time trend are simultaneously equal to zero. Figures reported in parentheses are degree of freedom.

As far as adaptive effect of groundwater use on rice yield is concerned, a statistically significant yield loss mitigating effect of GWD was confirmed by the regression results (column 2, table 5). However, econometric results failed to confirm any significant impact of increasing groundwater use on marginal productivity of irrigation in the case of rice (column 2, table 5). Further investigation revealed that the differences in adaptive effects of groundwater dominance on drought induced yield loss between semiarid and slightly humid region was statistically insignificant; however, the differences in reduction in drought induced yield loss between moderately arid and slightly humid region was statistically significant (column 5, table 5).

Interaction of groundwater dominance (GWD), irrigated area and regional dummies turned out statistically significant in rice yield model reiterating the heterogeneity in groundwater induced efficiency gains between semiarid region and moderately arid region. Nature of irrigation development in different regions could be a factor to explain heterogeneous impact of groundwater boom on drought induced yield loss and irrigation efficiency. While semiarid and most of the moderately arid districts are now dominantly irrigated by groundwater sources; canals and tanks are still important sources of irrigation in slightly humid region. Availability of robust surface irrigation network probably produced better dividends from groundwater boom in moderately arid region in the case of rice. Hypotheses regarding temporal change in adaptive and efficiency benefits of increasing groundwater dominance were also examined by interacting DI/IA, GWD, regional dummies and time trend. Adaptive effect of groundwater grew significantly over time in moderately arid region as statistically significant coefficient associated with the interaction of drought index, GWD and Moderately arid region dummy suggested (column 6 in table 5). Contrary to the adaptive effects, temporal growth in efficiency effects of groundwater use was statistically significant and positive in both climatic regions.

In the case of groundnut, drought effect on yield was statistically significant; however, this hypothesis was rejected only at lower level of statistical significance (10 percent level) (column 1, table 7). Further examination revealed that significant impact of drought on groundnut yield was limited to semiarid region only (column 3, table 7). This result is of special importance considering the concentration of groundnut cultivation in semiarid region. Accordingly, a unit increase in drought index reduced groundnut yield by 1.5 kilogram per hectare in semiarid region, which is large considering the low yield per hectare of groundnut in such region.

Irrigated area, unlike the case of rice, significantly explained variations in groundnut yield (column 1, table 7). Historical difference between proportion of irrigated rice cultivation and irrigated groundnut cultivation might be a reason explaining different behavior of irrigation in the case of two crops. A thousand hectare increase in groundnut irrigated area increased groundnut yield by 7.090 kilogram per hectare (column 1, table 7). Relative contribution of irrigated area in explaining groundnut yield was different across climatic regions (column 3, table 7). Unlike the case of rice, we failed to confirm any significant impact of increasing groundwater dominance on groundnut yield (column 1, table 7). However, statistically significant and negative coefficients associated with the interactions of GWD with climate region dummy highlighted that groundwater boom negatively influenced groundnut yield; however, its impact was heterogeneous across regions (column 3, table 7).

Table 7: Drought, Irrigation and Groundnut Yield

Variables	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
DI	**1.011***	0.470	0.702	0.688	0.524	0.575
	(0.592)	(0.497)	(0.568)	(0.443)	(0.482)	(0.469)
DI*HARID			**1.463****			
			(0.628)			
DI*MARID			-0.0568			
			(0.468)			
GNAI	**7.090*****	**6.516*****	**3.116***	**2.406*****	**6.517*****	**6.414*****
	(2.041)	**(1.973)**	**(1.623)**	**(0.590)**	**(1.963)**	**(1.885)**
GNAI*HARID			**7.592*****			
			(1.992)			
GNAI*MARID			**3.508***			
			(1.945)			
GWD	-10.42	**-63.39*****	**-89.67*****	**-49.91*****	**-61.49*****	**-66.08*****
	(8.181)	**(20.60)**	**(28.85)**	**(12.03)**	**(15.02)**	**(16.54)**
GWD*HARID			**84.66*****			
			(29.50)			
GWD*MARID			**83.53****			
			(39.86)			
DI*GWD		**0.342*****				
		(0.0527)				
GNAI*GWD		**0.790*****				
		(0.229)				
DI*HARID*T				**0.00367****		
				(0.00161)		
DI*MARID*T				0.000432		
				(0.000798)		
GNAI*HARID*T				**0.0214*****		
				(0.00440)		
GNAI*MARID*T				**0.0157*****		
				(0.00427)		
GWD*HARID*T				**0.132*****		
				(0.0432)		
GWD*MARID*T				**0.106****		
				(0.0495)		
DI*GWD*HARID					**0.602*****	
					(0.189)	
DI*GWD*MARID					**0.250*****	
					(0.0573)	
GNAI*GWD*HARID					**0.965*****	
					(0.185)	
GNAI*GWD*MARID					**0.691*****	
					(0.197)	
DI*GWD*HARID*T						**0.00174*****
						(0.000554)
DI*GWD*MARID*T						**0.000408****
						(0.000165)
GNAI*GWD*HARID*T						**0.00374*****
						(0.000798)
GNAI*GWD*MARID*T						**0.00173*****
						(0.000478)
Constant	607.9***	638.4***	600.2***	572.0***	640.2***	646.0***
	(52.63)	(49.98)	(47.40)	(54.80)	(48.07)	(45.79)
Observations	740	740	740	740	740	740
District specific trend	Yes	Yes	Yes	Yes	Yes	Yes

Note: *, **, *** indicate statistical significance at 10 percent, 5 percent and 1 percent level, respectively. Standard errors reported in parentheses were estimated using Driscoll Kraay (1998) estimator.

Table 8: Diagnosis Test for Groundnut Yield Regression Model

Test name	**1**	**2**	**3**	**4**	**5**	**6**
Model Goodness of fit: F test	1320.44 (22, 36)***	2038.68 (24, 36)***	2866.00 (28, 36)***	319.37 (26, 36)***	2711.12 (26, 36)***	2250.48 (26, 36)***
Within R sq.	0.58	0.60	0.59	0.61	0.70	0.60
Hausman test	240.50 (22)***	232.61 (24)***	207.58 (28)***	167.08 (26)***	234.45 (26)***	218.10 (26)***
Panel heteroskedasticity Test: $\chi^2(20)$	678.25***	545.50***	695.64***	583.32***	544.49***	573.91***
Cross section dependence Test: $\chi^2(190)$	667.551***	562.245***	636.162***	682.218***	551.521***	565.944***
Joint significance of district wise trend: F(19, 36)	173.28***	149.15***	118.68***	47.10***	102.22***	105.06***

Note: *, **, *** indicate statistical significance at 10 percent, 5 percent and 1 percent level, respectively. Rejection of homoscedasticity confirms presence of risk (Just and Pope 1978; Asche and Tveteras 1999) postulate. Cross section correlation (Pesaran 2004) justifies the choice of a flexible estimation technique. Null hypothesis for F test (district specific trend)- H_0: all estimated coefficients associated with district specific technological trend are simultaneously equal to zero. Figures reported in parentheses are degree of freedom.

Interaction of *DI* with semiarid dummy and time trend turned statistically significant in groundnut yield model with a positive sign inferring that negative impact of drought on groundnut yield was decreasing over time in dominant groundnut producing regions (column 4, table 7). This result indicates the general adaptation behavior of agricultural sector against climate change in semiarid regions. The results also highlight existence of other factors which contribute to increase risk associated with groundnut cultivation in this region. Increasing monoculture can be one such factor. Similarly, positive influence of irrigated area on groundnut yield also exhibited positive growth over time in both moderately and semiarid regions (column 4, table 7). Impact of irrigation quality index (GWD) on groundnut yield also experienced statistically significant positive growth over time (column 4, table 3). Adaptive and efficiency effects of increasing groundwater use on groundnut yields were observed to be statistically significant across both climatic regions (column 5, table 7). Null hypothesis stating no significant change in adaptive and efficiency gains of increasing groundwater use was rejected in the case of groundnut in both climate regions (column 6, table 7). Here also, it can be observed that annual growth in adaptive and efficiency effects of groundwater use were relatively higher in semiarid region.

6. Discussion

The results of econometric analysis presented in the previous section highlight that increasing frequency and severity of droughts/floods due to climate change may increase rice yield loss in the state; however, drought effects on groundnut yield were significant only in semiarid region which is a major center of groundnut cultivation in the state. Interestingly, drought impact on groundnut yield was decreasing over time in semiarid region which indicates that drought proofing of agriculture worked in semiarid region. Paradigm shift in irrigation sector played great role in drought proofing of agriculture in the state.[16]

Adaptation and efficiency benefits accrued from groundwater use are already accepted in literature (Shah 2009; 2012); however, findings in the earlier section also confirm that drought resilience of agricultural yield grew significantly over time due to groundwater expansion. However, growing benefits of groundwater use also inferred that unregulated groundwater boom increased yield risk of major crops.[17] Risk augmenting effect of groundwater use indicate risk neutral use of groundwater in water scarce regions of the state (see, Tveteras 1999; Ramaswami 1992). While adaptive and efficiency gains due to groundwater boom look lucrative; risk augmenting effects of groundwater use indicate that groundwater boom in Andhra Pradesh failed to generate *economically sustainable* outcomes.

Invisible and open access nature of ground water resources encouraged overdevelopment of resource. In the case of surface resources, it is relatively easy to establish ownership/withdrawing rights as well as to document and tax resource utilization. In the case of groundwater, resource ownership, availability, flows, and relationship between actions and consequences are difficult to identify and monitor (Shah 2009, IWMI 2000). Furthermore, wells and pumps tend to be located on private lands and are often individually owned. The only constraint in accessing ground water in Andhra Pradesh, where majority farmers are marginal

[16] While we have not quantified the magnitude of drought impact on yield or efficiency/adaptive gains of increasing irrigation quality due to increased groundwater use; a full model was estimated and results are reported in table A3. Estimated coefficients of model parameters can be used for prediction (see, Birthal et al. 2015).

[17] Results of Just and Pope (1978) production function estimation are provided in table A2 (see, appendix) to support our claim that increasing impact of groundwater use on drought induced yield loss and marginal productivity of irrigated area indicates that yield risk increased with rising use of groundwater for irrigating crops. Production function was estimated using a two-step estimation procedure detailed in Asche and Tveteras (1999).

cultivators, was the expenses related to well construction and pumping equipment which, to a large extent, were brought down to nominal levels through subsidies. Effect of electricity and other subsidies is reflected not only in increasing number of wells but deepening of wells also partly due to dropping water tables and also due to availability of cheap electricity (see, table 9).

Table 9: Status of wells in Andhra Pradesh

Type of Wells	1993-94		2000-01		2006-07	
	Wells In use	Wells with Less water discharge	Wells In use	Wells with Less water discharge	Wells In use	Wells with Less water discharge
Dug Wells[a]	1018370	440016	946393	376303	812826	211604
Shallow tube Wells[b]	304358	68204	637003	177967	884760	334741
Deep tube Wells[c]	29839	8020	85601	34216	268788	131117
Total	1352567	516240	1668997	588486	1966374	677462

a. Depth normally 15 meters or less
b. Depth less than 70 meters
c. Depth equals to 70 meters or more.
Source: Government of Andhra Pradesh (2009)

Environmentally, effects of unregulated groundwater use are manifested in increasing number of overexploited aquifers in semi and moderately arid regions of the state (figure 1). There exists a direct link between increasing adaptation benefits of groundwater use and increasing numbers of overexploited aquifers. Therefore, climate change adaptation by facilitating use of groundwater cannot be termed as sustainable in the case of Andhra Pradesh. Considering the superiority of groundwater irrigation as far as effectiveness of irrigation and climate change adaptation is considered; groundwater sustainability becomes critical for sustainable agricultural growth.

In fact, state government has applied various instruments to manage negative externalities emanating from groundwater boom in hard rock regions. Andhra Pradesh Farmer Managed Irrigation System (APFMIS 1997) and Andhra Pradesh Farmer Managed Groundwater Irrigation Systems (APFMGS 2002) are innovative programs to support community management of irrigation resources. APFMGS (2002) includes innovative measures such as applying water meters to monitor groundwater water levels and crop water budgeting at aquifer level. To support community management of groundwater resources, Andhra Pradesh government initiated WALTA Act- 2002 which made registration of new wells mandatory.

On the other leg, state promoted special crop programs to divert cropping pattern. Increasing proportion of drought tolerant crops in semiarid region signals adaptation success in semiarid tropics (SAT). While political constraints restrict state from using hard economic measures; it is also true that hard economic measures are economically unviable unless property rights are well defined. In this connection, registration of wells under WALTA is a first step towards applying economic measures to regulate and manage groundwater use. Considering the fact the drought intensity and frequency may increase due to climate change, effective implementation of WALTA provisions is required. Due to opposition from farming class, registration of wells is a challenging job.[18] "Regulation by stealth" policy of government due to political repercussions has hindered effective implementation of WALTA provisions; however, such approach may worsen the farm distress situation in the state.

Along with it, state is also sensitive regarding criticality of surface irrigation for managing groundwater demand; however, lift irrigation schemes currently running in the state are not environmentally benign as they are energy intensive and open to corruption (Ratna Reddy 2003, 2006). In past, government ran a program for converting beleaguered tanks into percolation tank (Sakthivadivel et al. 2004). In recent years, state began providing subsidies for farm ponds and reviving existing tanks.[19] Integrating farm pond programs with horticulture, sericulture and fishery can bring environmental benefits in terms of increasing biodiversity and economic benefits in terms of rising income or risk reduction.

Andhra Pradesh has also taken initiatives regarding promotion of micro irrigation methods among farmers using subsidies. Andhra Pradesh established a special purpose vehicle (SPV) under the department of horticulture to ensure expansion of drip and sprinkler. Micro irrigation methods such as drip and sprinkler are useful to increase irrigation efficiency. While such subsidized technologies are often claimed to be water saving; it is very erroneous to assume that promotion of such technologies will save water unless groundwater withdrawal is directly regulated and priced. Water saving technology, by saving water use per unit of production, increases effective water supply and reduces marginal cost of irrigation which, in turn, increases

[18] http://www.downtoearth.org.in/coverage/no-one-is-following-regulations-1542

[19] http://www.financialexpress.com/india-news/andhra-pradesh-to-launch-water-conservation-programme-tomorrow/628548/; and, http://www.thehindu.com/news/national/andhra-pradesh/1-lakh-pond-programme-launched-in-anantapur/article7973078.ece

producers' profit and incentivize them for intensive cropping thereby increasing overall groundwater use.[20] Spreading micro irrigation can compensate productivity losses due to erratic climate change; therefore, can be promoted in areas facing critical shortage of irrigation water (semiarid region). However, such technologies are expansive and are profitable for certain high value crops only, therefore, are biased against drought tolerant coarse cereals.

While Andhra Pradesh is leading the movement as far as irrigation management is concerned; there are many areas where reforms are needed apart from fine tuning existing irrigation management policies and tools. One left out area in the case of Andhra Pradesh has been electricity reforms. Since groundwater use can be managed by managing electricity supply; separating agriculture power supply in the state may provide additional teeth to evolving groundwater management paradigm in the state (Shah 2012).

7. Conclusion

This paper attempts to understand the dynamics among irrigation, drought and agricultural yield in the case of undivided Andhra Pradesh. The major objective of the study was to examine few hypothesized claims regarding the impact of groundwater on drought proofing of crops. Results confirmed that increasing irrigation quality due to groundwater boom improved performance of crop yields not only by improving irrigation efficiency but also by mitigating drought induced yield loss. However, the positive effects of groundwater boom were partially offset by risk augmenting effects of groundwater boom. Risk effects of groundwater boom can be attributed to unregulated exploitation of groundwater in the state. Risk implications of unregulated groundwater use violate economic dimension of sustainable agriculture. Groundwater exploitation in hard rock regions of the state demands effective regulation of groundwater use.

For adapting agriculture to climate change in the state, inter-temporal crop-water budgeting (increasing production in good monsoon years and decreasing efforts in drought years) along with effective intra-temporal crop-water budgeting is required. Since many of the initiatives for irrigation management are new; state is going to face serious problems associated with

[20] This phenomenon is called Jevons Paradox.

groundwater in short run. In medium to long run, sustainability issues emerging in agricultural environment can partially be addressed by regulating water use in agriculture.

In addition, Andhra Pradesh (now Seemandhra and Telangana) can learn from water management experience of other states. Rain water harvesting program in Tamil Nadu extends an opportunity to learn reducing nonagricultural demand pressure from groundwater sources by creating water harvesting structures. Andhra Pradesh (including Telanagana) can also learn sustainable management of water bodies from Tamilnadu's rainwater harvesting program. Similarly, Gujarat has innovated immensely in managing groundwater demand by managing electricity supply. It has been possible in Gujarat by separating electricity distribution for agriculture. Accepting these policy innovations would help improving the recharge of groundwater and improve sustainability.

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APPENDIX

A1. Unit root test results of variables

Table A1: Unit root test results of variables

Variable Name	Symbol	Level/Difference	IPS test (t-bar test)	
			No trend	With trend
Rice yield	YLD^{RC}	*L*	-2.2334***	-5.2760***
Groundnut yield	YLD^{GN}	*L*	-3.2241***	-5.0644***
Drought index	DI	*L*	-5.4680***	-5.5235***
Irrigated area under rice	IA^{RC}	*L*	-4.1854***	-5.0430***
Irrigated area under groundnut	IA^{GN}	*L*	-1.9991***	-4.0128***
Groundwater dominance	GWD	*L*	-2.2075***	-4.3211***

Note: Exact critical values of t-bar test statistic at 1 %, 5%, 10% level of significance are -1.98, -1.85 and -1.78 respectively when stationarity test is conducted without time trend in the equation. We accepted 5% level of significance as benchmark i.e. we went ahead with differencing if test statistic didn't turn significant at least 5% level of statistical significance. With trend variable in test equation, critical values of the test at 1%, 5%, 10% level respectively are -2.59, -2.48 and -2.41. *L*, *D1* and *D2* stand respectively for level, first difference and second difference of variable.

A2. Groundwater Boom and Yield Risk

Table A2: Estimation of risk function using Just and Pope (1978) production function approach

	Rice		Groundnut	
Variables	Mean	Variance	Mean	Variance
DI	1.201**	**-0.00518***	0.524	-0.00210
	(0.592)	**(0.00295)**	(0.489)	(0.00292)
AI	7.181	0.0171	6.517***	**0.0175****
	(5.197)	(0.0138)	(1.990)	**(0.00722)**
GWD	-92.89***	-0.584***	-61.49***	0.106
	(29.94)	(0.125)	(15.22)	(0.131)
DI*GWD*HARID	-0.00650	0.00114	0.602***	-0.000352
	(0.167)	(0.00116)	(0.191)	(0.00151)
DI*GWD*MARID	0.388***	0.000350	0.250***	-0.000607
	(0.0580)	(0.000610)	(0.0581)	(0.000618)
AI*GWD*HARID	0.776***	**0.00776*****	0.965***	0.000351
	(0.253)	**(0.00164)**	(0.188)	(0.00273)
AI*GWD*MARID	0.757**	**0.00575*****	0.691***	-0.000138
	(0.311)	**(0.00163)**	(0.200)	(0.00182)
Constant	2,047***	10.06***	1,049***	8.797***
	(543.4)	(1.301)	(111.6)	(0.625)
Observations	740	740	740	740
R-squared	0.778	0.112	0.730	0.114
Test for goodness of fit: F (45, 36)	2939.25***	147.18***	13173.27***	592.94***
Test for district specific trend: F (19, 36)	520.48***	11.75***	99.50***	31.08***
Hausman test	328.25 (26)***	61.01 (26)***	234.45 (26)***	40.56 (26)**
Test for cross sectional dependence	540.334 (190)***		551.521(190)***	
Test for panel heteroskedasticity	193.24 (20)***		544.49 (20)***	
Number of groups	20	20	20	20

Note: *, **, *** indicate statistical significance at 10 percent, 5 percent and 1 percent level, respectively. LSDV technique was used for estimating parameters of the mean and variance models. To maintain positive variance, we used logged values of squared residuals of mean yield equation as dependent variable in variance models; therefore, coefficients of variance model give semi-elasticity specific to inputs. Standard errors reported in parentheses were estimated using Driscoll Kraay (1998) estimator.

A3. Measurement and Prediction of Adaptive and efficiency Gains due to Groundwater Boom

We estimated following flexible form of the yield model which includes variables used in model 1 to model 6 in the main text. Model estimates can be used for quantifying the magnitude of impact of independent variables on crop yield.

$$\begin{aligned} YLD_{it} = {} & \alpha_i + \left(\beta_1 DI + \beta_2 AI + \beta_3 GWD + \beta_4 \left(DI \times GWD\right) + \beta_5 \left(AI \times GWD\right)\right)_{it} + \\ & \left(\beta_1 DI + \beta_2 AI + \beta_3 GWD + \beta_4 \left(DI \times GWD\right) + \beta_5 \left(AI \times GWD\right)\right)_{it} \times \left(\lambda_1 HARID + \lambda_2 MARID\right) + \\ & \left(\beta_1 DI + \beta_2 AI + \beta_3 GWD + \beta_4 \left(DI \times GWD\right) + \beta_5 \left(AI \times GWD\right)\right)_{it} \times \left(\lambda_1 HARID + \lambda_2 MARID\right) \times \phi T + \\ & \sum_{i=1}^{19} \delta_i \left(D_i \times T\right) + \delta T + \varepsilon_{it} \end{aligned}$$

Model results were used to test various hypotheses regarding impact of independent variables on crop yield. Results of this exercise are reported in table A2.

Table A3: Estimation results of model given in equation 9

Variables	Rice	Groundnut
DI	1.935**	0.330
	(0.724)	(0.430)
DI*HARID	-1.930	1.004
	(2.663)	(1.165)
DI*MARID	-1.355	-0.231
	(0.928)	(0.561)
DI*HARID*T	0.00729	-0.000354
	(0.00840)	(0.00412)
DI*MARID*T	0.000310	0.000167
	(0.00126)	(0.00109)
AI	-10.91	2.265
	(9.309)	(1.663)
AI*HARID	11.00	2.116
	(19.74)	(3.859)
AI*MARID	26.36**	0.513
	(9.803)	(1.659)
AI*HARID*T	0.00774	0.0144
	(0.0482)	(0.00957)
AI*MARID*T	-0.0168	0.00645
	(0.0225)	(0.00406)
GWD	-1,438*	-97.49
	(822.1)	(74.59)
GWD*HARID	999.1	17.22

	(1,790)	(93.93)
GWD*MARID	1,258*	76.04
	(713.5)	(77.20)
GWD*HARID*T	1.967	0.115
	(4.293)	(0.160)
GWD*MARID*T	-2.271*	-0.117
	(1.239)	(0.113)
DI*GWD	-1.109	0.761
	(0.810)	(0.767)
DI*GWD*HARID	2.060	0.288
	(1.332)	(0.928)
DI*GWD*MARID	1.683*	-0.594
	(0.851)	(0.862)
DI*GWD*HARID*T	-0.00430	-0.00170
	(0.00404)	(0.00274)
DI*GWD*MARID*T	-0.000612	0.000168
	(0.000526)	(0.000584)
AI*GWD	12.54	2.065
	(8.386)	(1.223)
AI*GWD*HARID	-7.577	-0.756
	(18.27)	(1.731)
AI*GWD*MARID	-11.04	-2.220
	(7.198)	(1.438)
RAI*GWD*HARID*T	-0.0227	-0.00197
	(0.0439)	(0.00329)
AI*GWD*MARID*T	0.0233*	0.00218
	(0.0128)	(0.00205)
T	50.34***	18.50**
	(5.797)	(7.371)
D_1*T	-14.66*	5.777
	(7.039)	(6.441)
D_2*T	-18.59***	-16.77*
	(6.497)	(9.255)
D_3*T	-23.73***	-16.77*
	(5.398)	(8.750)
D_4*T	-2.568	-11.14
	(11.81)	(11.24)
D_5*T	2.350	5.193
	(6.013)	(5.962)
D_6*T	2.822	13.13**
	(8.686)	(5.583)
D_7*T	-13.47	-25.21**
	(8.553)	(10.78)
D_8*T	3.110	-1.521
	(5.465)	(3.839)
D_9*T	6.870	-2.668
	(7.510)	(9.336)
D_{10}*T	1.359	17.79***
	(8.097)	(4.183)
D_{11}*T	4.953	-5.039
	(7.728)	(6.510)
D_{12}*T	-9.334	-16.08**
	(8.261)	(7.081)
D_{13}*T	-4.138	-2.054
	(5.804)	(4.894)
D_{14}*T	-5.578	-21.82**

	(8.360)	(9.255)
D_{15}*T	14.56**	6.032
	(5.913)	(4.191)
D_{16}*T	-11.50	2.304
	(9.752)	(8.574)
D_{17}*T	-14.23	-17.60**
	(8.611)	(7.486)
D_{18}*T	-27.86***	-17.79**
	(8.527)	(7.081)
D_{19}*T	6.427	-14.41***
	(4.911)	(4.361)
Constant	-16,549***	-5,886**
	(1,916)	(2,612)
Observations	740	740
Model goodness of fit	5.71e+07 (45, 19)***	69102.05 (45, 19)***
Within R sq.	0.75	0.64
District fixed effects	yes	yes

Note: We kept all variables which were considered in equation 1 to equation 6. Figures reported in parentheses are standard errors of model estimates. These errors were estimated using Driscoll-Kraay (1998) estimator.

(1)

Hypotheses: Rice

1. Impact of drought on crop yield is not significantly different from 0 (DI=0).

$$(DI+(DI\times GWD))+(DI+(DI\times GWD))\times(HARID+MARID)+$$
$$(DI+(DI\times GWD))_{it}\times(HARID+MARID)\times T=0$$

F test statistic= 12.91 (10)***

2. Impact of irrigation quality index on crop yield is not significantly different from 0 (GWD=0).

$$(GWD+(DI\times GWD)+(AI\times GWD))+(GWD+(DI\times GWD)+(AI\times GWD))\times(HARID+MARID)+$$
$$(GWD+(DI\times GWD)+(AI\times GWD))\times(HARID+MARID)\times T=0$$

F test statistic= 65.04 (15)***

3. T=0

$$(DI+AI+GWD+(DI\times GWD)+(AI\times GWD))_{it}\times(HARID+MARID)\times T+\sum_{i=1}^{19}(D_i\times T)+T=0$$

F test statistic= 2559.32 (30)***

4. Adaptive effects of groundwater use are not significantly different from 0 (DI*GWD=0).

$$((DI\times GWD))_{it}+((DI\times GWD))\times(HARID+MARID)+((DI\times GWD))\times(HARID+MARID)\times T=0$$

F test statistic= 6.81 (5)***

5. There is no significant impact of increasing irrigation quality on marginal productivity of irrigation (AI*GWD=0).

$$((AI \times GWD)) + ((AI \times GWD)) \times (HARID + MARID) + ((AI \times GWD)) \times (HARID + MARID) \times T = 0$$

F test statistic= 6.19 (5)***

Hypotheses: Groundnut

1. DI=0

$$(DI + (DI \times GWD)) + (DI + (DI \times GWD)) \times (HARID + MARID) +$$
$$(DI + (DI \times GWD))_{it} \times (HARID + MARID) \times T = 0$$

F test statistic= 13.73 (10)***

2. GWD=0

$$(GWD + (DI \times GWD) + (AI \times GWD)) + (GWD + (DI \times GWD) + (AI \times GWD)) \times (HARID + MARID) +$$
$$(GWD + (DI \times GWD) + (AI \times GWD)) \times (HARID + MARID) \times T = 0$$

F test statistic= 35.25 (15)***

3. T=0

$$(DI + AI + GWD + (DI \times GWD) + (AI \times GWD))_{it} \times (HARID + MARID) \times T + \sum_{i=1}^{19} (D_i \times T) + T = 0$$

F test statistic= 563.73 (30)***

4. DI*GWD=0

$$((DI \times GWD))_{it} + ((DI \times GWD)) \times (HARID + MARID) + ((DI \times GWD)) \times (HARID + MARID) \times T = 0$$

F test statistic= 18.37 (5)***

5. AI*GWD=0

$$((AI \times GWD)) + ((AI \times GWD)) \times (HARID + MARID) + ((AI \times GWD)) \times (HARID + MARID) \times T = 0$$

F test statistic= 6.09 (5)***