A Data-Analytical Way of Estimating Rice Crop Yield: Economic and Water Related Causative Factors

Nilabja Ghosh, M. Rajeshwor, Alka Singh, and Satarupa Chakravarty

Abstract Data analytical method using both economic and weather parameters is not just an alternative but is supportive and complementary to other commonly used techniques like remote sensing, agro-meteorological modeling, and field surveys to assess crop outlooks. This study, based on a model and official data, finds that economic factors related to markets and policies play an important role in the determination of rice yield in India and the role of rainfall has complex spatio-temporal dimensions and interactions with water management infrastructure and protocols. The yield forecast based on the model and early information of weather can provide a reliable real time outlook for policy use and validation of other forecasts and can be updated over time with the flow of new information.

Keywords River basin · Crop yield · Climate change · Price effect · Rice · Modeling

1 Introduction

Monitoring the production of food crops around the world is becoming essential for ensuring global food security. Programs launched for the purpose across the globe mostly depend on hybrid methodology but, relying with decreasing centrality, traditional field-level information collection, and with greater emphasis on satellite imagery. Remote sensing (R.S.) has its own limitations in discriminating among vegetation that represents different crops and especially in capturing the field situation early in the season when only sparse vegetation is visible (Justice et al., 2015; Lasko et al., 2017, 2018a, b). The restraint is even more pronounced in measuring crop yield, which is not just an outcome of natural events but also technology and human decisions (Moorthi et al., 2014; Özyavuz et al., 2015). Vital for the robust

N. Ghosh (✉) · M. Rajeshwor · A. Singh · S. Chakravarty
Institute of Economic Growth, Delhi, India
e-mail: nila@iegindia.org

K. P. Vadrevu et al. (eds.), *Remote Sensing of Agriculture and Land Cover/Land Use Changes in South and Southeast Asian Countries*,
https://doi.org/10.1007/978-3-030-92365-5_11

use of R.S., cost-efficient supporting techniques are useful. Data analytical methods of estimating crop yield most commonly rely on modeling, which is ideally tied to related disciplines. This study attempts to model data to examine the determination of rice yield in major Indian growing states focused specifically on the role of rainfall, both current and past with reference to its location and seasonality, and accounting for the effect of prices and economic policy on farmer‘s behavior.

Modeling has a long history starting from the seminal work of Heady and Dillon (1961), moving on, as recounted by model historians (James et al., 2017). To chronicle, a continuous transition of the production outlook for real-time policymaking, analysis of data from the past and contemporary news can be useful if modeled to be parsimonious, quick, automatable and scientific method-based with transparency and objectivity. For making in-season forecasts, it is important to understand the vegetative processes and to identify causal parameters.

The purpose of modeling was initially to understand how plants perform, but increasingly models were oriented for decision support. Farm management is a social behavior transcending physio-chemical environments. To heed behavioral responses, market movements, policies and perceptions of the farmers about incentives would be necessary for modeling as economics remains an underlying factor that influences rational farmers‘behavior in production planning (Schultz, 1964; Krishna, 1962). Econometric models that have helped predict and guide social behavior through economic policy on incentives can be used to account for responses of crop production to prices, some of which are barely notional expectations based on experience and accessible contemporary information (Nerlove, 1958; Sheffrin, 1983).

In Indian agriculture, water has been the leading constraint (Nadkarni & Deshpande, 1983; Prasad et al., 2004). While some crops in specific regions gain from abundant water, excess moisture is damaging for others, and all crops gain from and are hurt by rainfall at certain points of their growth cycle. Untimely rain, poor drainage of past water from rain or irrigation, excessive rain and ill-planned water management, in general, can hurt the yields of most crops though in varying degrees. The river basin is a basic hydrological unit on which (MOJS, 2021) government intervenes to develop water resources but structural and operational interventions both by the planned construction of dams, barrages,[1] canals, reservoirs and spillways[2] and by informal private initiatives reshape directions and forces of water movements.

The majority of the public projects are for multiple purposes, including irrigation, flood control and power generation, but they often create conflicts over unequal distribution and are also not entirely successful in relieving the basins of floods,

[1] A barrage is generally built for diverting water. According to the World Commission on Dams, a key difference between a barrage and a dam is that a dam is built for water storage in a reservoir, which raises the level of water significantly.

[2] The water stored behind a dam is called its reservoir, and the term “spillway” usually is reserved for structures that release excess inflows, when the reservoir is already full (e.g. floods or heavy snowmelt).

water-logging and crop loss. By depriving rivers of space, dams are increasingly seen as 'counter-productive' (Shagun, 2019). A 'brimming' dam does not always bring cheer to the farmers, and rather, sudden releases of dams water are more often responsible for the flooding. Today, most dams serve as hydropower generators, which in turn promote well irrigation (World Commission, 2000) as digging wells to tap groundwater emerges as an attractive solution. Tube-well irrigation accounting for 63% of irrigated area, has now surpassed irrigation by canals, which once dominated India's irrigation. Yet, unregulated proliferation and deepening of wells, a transition described as a shift from 'gravity' to water'scavenging,' have created overdraft (NITI-AAYOG, 2015; Suhag, 2016; Sharma et al., 2010; Moran et al., 2014).

Despite severe floods in parts of the country, water shortages remain a prime cause of agrarian distress (Agarwal & Narayan, 1991; Nandargi & Shelar, 2018). Lack of perennial water flow in most rivers, especially in the peninsula, defeats canals for drawing surface water. Groundwater reserves are not independent of surface water management because canals end up as sub-surface recharge structures, and wells help drainage and utilize excess water in canal-rich areas. While reservoirs, tanks, and spillways of dams help to store and channelize excess water for redistribution to needy areas, turbines placed strategically on river create a potential for conjunctive use of water by design though a trade-off between the two types of irrigation in disparate locations cannot be ruled out (Dhawan, 1995; Ramaswamy, 2015). India's National Water Policy (2012) underscores the maintenance of hydrological structures, including river basins, and the urgency for mapping aquifers and their flows.

2 Rivers and Water Redistribution

The northern Indo-Gangetic plains (IGP) of India are drained by rivers Ganga, Yamuna, Indus, and Brahmaputra, while Narmada, Tapi, Godavari, Krishna and Kaveri are major rivers of the south. The confluence of many Himalayan streams creates the Ganga in Uttarakhand in India. It flows towards the southeast across Uttar Pradesh, Bihar, and West Bengal, where two of its distributaries fall into the Bay of Bengal while another branch enters Bangladesh to meet the Bay as river Padma. The Yamuna too arises in Uttarakhand and flows through Uttar Pradesh, Haryana and Delhi. Many rivers recharge the Ganga-Yamuna basin. The northern tributaries, fed by melting snows of the mountains, are perennial, some of them being trans-border. Some have their mouths in the Padma in Bangladesh. On the right banks, Yamuna is charged by rivers from the south-central regions. Downstream of Prayagraj, where it meets the Yamuna, Ganga is recharged by voluminous waterbodies from the south. Beyond the four states, the Ganga-Yamuna basin, therefore hydrologically links a far larger catchment embracing western and central Indian plateau regions.

With a long course even outside India, Brahmaputra in the northeast is also a tributary of Ganga. Starting in Tibet (China), flowing eastwards as Yarlang Tsangpo and entering India to flow westward through multiple states, it enters Bangladesh, forming the Meghna basin with the large Barak River from north-east India before it merges with the Padma. The turbulent and erosive north-eastern rivers carrying a heavy load of water and silts and frequently changing their courses are watered by uphill snows, heavy rainfall of the Himalayan slopes and confluences of many other mountain rivers. In the west, river Indus, which like the Brahmaputra, originates in Tibet and flows westward, drains Ladakh (till October 2019, a part of J&K state) in India before crossing over to Pakistan as its primary source of water. Indus has five tributaries In India, of which waters of the three eastern ones are used for India‘s irrigation before they all flow into Pakistan. Together, the Indus river system drains J&K, Himachal Pradesh, and Punjab states and also irrigates Haryana, Madhya Pradesh, and Rajasthan. Rivers independent of the main rivers in states Jharkhand, Odisha, and West Bengal, seasonally inland rivers of Rajasthan and Haryana, and upstream tributaries of Indus in Ladakh further supply water to IGP.

In the peninsular south, west-flowing rivers are few in number and tributaries. Rivers flowing east, cutting across the discontinuous Eastern Ghat mountains, are in many cases long, flowing right from the Western Ghats mountains close to the Arabian Sea. The southern rivers are charged by heavy rainfall in the numerous watersheds during the southwest monsoon season. With the Northeast monsoon and cyclones recharging the rivers of the south, rainfall is the dominant source of water in all rivers but with the unequal spatial distribution associated with varying geography of the peninsular terrains. Therefore, the typical southern basin is divergent in the quantity and quality of water the rivers carry, making access to both groundwater and surface water a challenge. Groundwater availability depends on the porosity and fault lines on the rocky plateau. The coastal plains on both sides of the peninsula are relatively water-rich but not spared of salinity and waterlogging.

Irrigation water and hydropower, both generated by multipurpose projects, serve agriculture in all states. Ganga faces several interventions starting with the high Tehri dam and a diversion at Haridwar till it meets the Yamuna. Further down, the water is managed by several river valley projects associated with hydro projects. Interventions on the Brahmaputra are meant chiefly for flood and erosion control and power generation that can help tap the groundwater. Bhakra-Nangal project (BNP) was the first intervention on Indus in post-independence India. Haryana is a common state served by both Indus and Ganga basins. Southern India is irrigated with waters from tributaries of the major rivers and some independent rivers. Many of the southern river valley projects are pre-independence in history but revamped and expanded in stages by the government. River linkages are made between the Godavari–Krishna, Krishna–Pennar, Polavaram-Vijayawada, in the south, and similar processes are in progress in northern plains though much more limited in scale, but a large and contentious river linking project (IRLP) to connect the deficit basins of south and surplus ones in north is in a planning stage (IDNP, 2002; Sarkar, 2019; Singh et al., 2020).

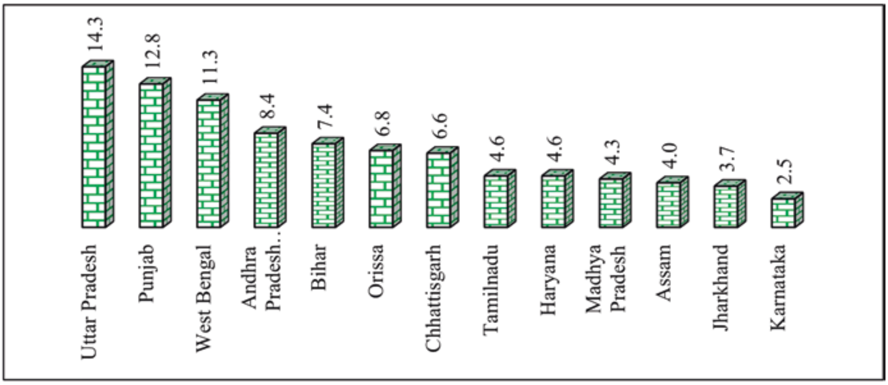

Fig. 1 State-wise Rice kharif Area share (%) in India

Well-irrigation in India is aided by hydel power stations located on the river basins, but power is shared or traded across states through grids. Clearly, in the integrated river system, with water and power-sharing, the effect of past rainfall in catchment regions is essential for assessing the prospects of crop productivity. Water availability in a state is therefore determined not just by the rain at the site or upstream sites but also in other states of the basin that share the water as arbitrated and administered by river boards and judicial bodies. Prevention of downstream or even upstream floods is part of the task of water management (Fig. 1).

3 Method

The analysis uses a complete model with econometric corrections for data to estimate the production of a crop. A comprehensive database covering agronomic, economic and meteorological information is used, supported by information conveyed by meteorological, administrative, hydrological and crop-cluster maps. All information sources are official from the Government of India. Rice, a staple crop grown across India, is water-guzzling, best grown in humid and hot weather with flooding at some stages of its growth cycle. Twelve states selected for study are Punjab, Haryana and Uttar Pradesh in the north, West Bengal, Bihar, Odisha and Jharkhand in the east, Assam in the northeast, Madhya Pradesh and Chhattisgarh in central India, and Andhra Pradesh, including Telangana, Karnataka, and Tamilnadu in the south which are major rice growers together contributing to 91% of India‘s rice production. The rivers and projects that drain or serve these states are discussed above.

The spatial unit of rainfall is the Meteorological sub-division (MET), of which 34 are considered (see Table 1). They are primarily chosen for their rainfall effects on the study states based on both proximity and river linkages allowing for commonality of geography and climate with bordering districts of a politically defined

Table 1 Abbreviations (Abb) of meteorological region and average rainfall of sample in India

Abb	Meteorological regions	Monsoon Rainfall (mm) (1985–2019)	Annual Rainfall (mm) (1985–2019)
AR	Arunachal Pradesh	2307	3373
AS	Assam & Meghalaya	1471	2240
EH	Nagaland,Manipur,Mizoram,Tripura	1186	1927
HW	Sub-Himalayan W. Bengal & Sikkim	2079	2748
GW	Gangetic West Bengal	1225	1635
OR	Orissa	1153	1497
JH	Jharkhand	1036	1262
BH	Bihar	981	1168
EU	East Uttar Pradesh	814	925
WU	West Uttar Pradesh	683	783
UT	Uttarakhand	1280	1628
HD	Haryana Chandigarh And Delhi	505	622
PJ	Punjab	528	668
HP	Himachal Pradesh	826	1293
JK	Jammu & Kashmir	515	1172
WR	West Rajasthan	282	322
ER	East Rajasthan	602	652
WM	West Madhya Pradesh	856	929
EM	East Madhya Pradesh	1015	1125
GJ	Gujarat Region, D & N Haveli	828	865
SK	Saurashtra And Kutch	522	551
KG	Konkan & Goa	2756	2938
MM	Madhya Maharashtra	662	814
MT	Marathwada	677	817
VD	Vidarbha	919	1059
CH	Chhattisgarh	1109	1261
CA	Coastal Andhra Pradesh	586	1031
TL	Telangana	735	936
RY	Rayalseema	439	776
TN	Tamilnadu & Pondicherry	304	977
CK	Coastal Karnataka	3099	3564
NI	North Interior Karnataka	529	757
SI	South Interior Karnataka	566	939
KL	Kerala	1773	2706

state, but the final specification is decided at the model selection. Specifications of the crop seasons are made less restrained than traditionally set calendars (MoA&FW, 2019), keeping in mind the emergence of resilient seeds and weather-adaptive cropping practices. The entire period for the Kharif crop covers 22 months (June of the previous year to March of the following year) divided into the following seasons.

Previous year/pre-season rainfall (PSR): June to December of the previous calendar year.
Early-season rainfall (ESR): January to April, traditionally the pre-Kharif period.
Mid-season rainfall (MSR): Rainfall in May to September, the monsoon months.
Late-season rainfall (LSR): October to March, post-monsoon, harvest and marketing season.

The model is specified in two stages. Yield is estimated in the second stage considering weather parameters, economic variables like market or support prices, crop revenues, input costs, substitution possibilities, and a time trend. The area, similarly estimated in the first stage, feeds into the yield equation as a variable. Adaptive expectations and rationality underlie subjective expectations formed about crop price measured as the reported wholesale (W.P.) or Minimum support price (MSP) in Rs. per Kg or the calculated returns from the crops in Rs. per hectare to be fetched only after harvest. Possible substitute crops are identified using pattern and calendar of cropping in the region after considering the statistical significance of each coefficient. Crop price or substitute price is expressed as price relative to input price.

The model incorporates water variables (W) shaped by rainfall by itself in various hydrologically linked regions, but rain can be qualified by irrigation which aims to bring control over the water. Irrigation (IRG) is measured as the land area under different sources is basic infrastructure and has limited variation over time. The IRG variable or the interacted water variable is standardized (deflated) by the crop area as estimated in the first stage. For simplicity and to allow variables to take zero values, the model is estimated linearly but allowing quadratic and interaction terms.

For any crop, the estimated equation for use

$$Y_t = b_0 + b_1 t + b_2 p_t + b_3 p_t^c + \sum\left(b_{4j} * w_t^j\right) + \sum(b_{5s} I_{ts)} + \sum\left(b_{6mMf} * TX_{tmMf}\right) + \sum\left(b_{7mMf} * TN_{tmMf}\right) + \sum\left(b_{8k} D_{tk}\right) + \sum\left(b_{9mM} * R_{tmM}^2\right) + \sum\left(b_{10z} C_{tz}\right) \tag{1}$$

Y_t = yield (Kg) per hectare of study crop, $p_t = p_{t1}$ or p_{t2} in alternate specifications $p_{t1} = (WP^c_{tm})/(WP^F_t)$, $p_{t2} = (WP^c_{tm} * Y_{t-1})/(WP^F_t)$

WP_t is the corresponding wholesale price (WSP) of crop in previous year, or latest MSP or the average of both, $W^j_t = W^j_{t1}$ or W^j_{t2} and $w^j_t = w^j_{t1}$ or w^j_{t2} in alternate specifications where $W^j_{t1} = = w^j_{t1} = R_{tMm}$, $W^j_{t2} = (R_{tMm}) * I_{ts}$ and $w^j_{t2} = W^j_{t2}/\exp(A_t)$, where $\exp(A_t)$ is the expected value of acreage A_t which is obtained as estimate in the auxiliary equation (2).

$$A_t = a_0 + a_1 A_{t-1} + a_2 P_t + \left(\sum a_{3j} * W_t^j\right) + \sum a_{4s} IRG_{ts} + \sum a_{5z} Z_{tz} \tag{2}$$

A_t = area in hectares under study crop, $P_t = P_{t1}$ or P_{t2} in alternate specification where $P_{t1} = (WP^c_{tm})/(WP^s_{tm})$, $P_{t2} = (WP^c_{tm} * Y_{t-1})/(WP^s_{tm} * Y^s_{t-1})$, And R_{tMm}= rainfall averaged across different alternate sets of M and m, IRG_{ts} is command area under any irrigation sources, TX_{tmMf} = maximum of daily temperatures or their average across M, m and f of growing season. TN_{tmMf} = minimum of daily temperatures or their average across M, m and f of growing season, D_k = kth dummy variable for any known change in technology or policy, C_{tz} = any other relevant z^{th} variable.

Subscripts: t is year (2000–2001 onwards), M = met region (1, 2…34), m = month (1…22), f = fortnight (1, 2) in any m^{th} growing month, *s* = source of irrigation (Canal = 1 Tube well = 2, Canal + Tube well = 3, all others = 4, total = 5). Superscripts: c = crops, s = Substitute/Competing crop or crops (1, 2, . .n), F = fertilizer (NPK), j = j^{th} water variable identified by season and region of rainfall and $\exp(A_t)$ is expected area for auxiliary separate Eq. (2) in the model. Error (E) is the difference (%) of estimate over observed officially recorded value from data.

In vast hydrologically linked spatial expanses (Sect. 3) with temporal storage possible, the large number of rainfall variables reduces degrees of freedom and enhances the possibility of multicollinearity caused by spatial interdependence of weather. Data reduction is accomplished by checking the statistical effect of each rainfall variable at a time and averaging the causative variables categorized by the four seasons to make up a set of composite rainfall values in a water variable with a cumulative effect in any specific direction. The sample period is fairly contemporary at 2000–2001 to 2018–2019. Autocorrelation is corrected where indicated by D.W. statistic, stability of the equation is tested by comparing the coefficients estimating the model after dropping the last sample year, the errors are examined for stationarity by Dickey-Fuller (D.F.) test statistics. Selection of the equation for further analysis is made keeping the following mathematical and economic conditions on diagnostics:

Therefore, $b2 > 0$, $b_3 < 0$, $b_9 < 0$ and all t-statistics of coefficients >1.96 (level of significant at 5%), $R_{bar}^2 > 0.90$, DW is near 2 and E is between +5% and − 5% in the sample period with the direction of estimate matching by and large with data. The predictive power of the model is also assessed by matching a one-step forward forecast for 2019–2020 with the actual data available.

A positive effect of a water variable is ideal, while a negative coefficient is a sign of shortfalls in water management, especially poor drainage. The past rainfall (PSR) effect implicitly signifies the management quality of rain and river water. An interaction between upstream PSR and canal is ideally positive, though river water also flows under gravity, and excess release may be damaging. The temperature effect reflects agronomic necessities for fruition at different growth phases. Time trend will be positive for yield in the presence of technical progress not captured by the other variables in the model, while the dynamic lagged acreage variable in the area equation reflects the effort to catch up and adjust to the desired acreage by farmers. National Food Security Mission, National Food Security Act and similar other policy launches are represented by Dummy variables. The results based only on estimated yield equations are summarized in Table 2.

Table 2 Economic, Spatial Rainfall and Irrigation factors' contribution to yield equation

State	Economy	Spatial Rainfall								Irrigation	Temperature
		PSR		ESR		MSR		LSR			
	Price	+ve	-ve	+ve	-ve	+ve	-ve	+ve	-ve		
Andhra Pradesh (incl. Telangana)*	WSP, MSP	(CA,SI)^{1}, KG, CK	–	–	KG,CK	CA, SK, GJ, WM, TL, CK	MT, MM, NI, TN	TN	TL, SI, CK, OR,	–	+: -: 16D1TL
Assam*	WSP, MSP	EH, AM, JH, GW	–	–	AM	HW, GW, EH, BH	AR, JH, AM	HW, EH	AR	5+	+: 19D2AM -:
Bihar*	WSP, MSP	(GW, HW)^{1}, EU^{1}	BH^{1}	HW, GW	–	HW, EU, BH	AR, AM, CH	–	HW, JH, BH	–	+:21N2BH -:
Chhattisgarh	WSP	(TL, VD, CH)^{2}, OR^{1}, HW^{5},	EM, BH, EU	–	–	CH, VD, CA, HW^{1}	–	CH, EM	TL	5+	+: -:
Haryana*	MSP	(UT, JK, HP, HC, WR)^{1}	EU^{1}, PJ	(HC, UT, WU)^{2}, PJ^{1}	HP, ER	WR	PJ, HC	–		5+	+:16N2HC -:
Karnataka	WSP, MSP	NI^{1}	–	TN,	–	NI, SI, GJ	RY, MT, VD, CA, MM	TN, RY, CA	CK	2+	+:19NDSI -:16N2NI, 17N2NI, 17N2SI

(continued)

Table 2 (continued)

	Economy	Spatial Rainfall									
State		PSR		ESR		MSR		LSR			
	Price	+ve	-ve	+ve	-ve	+ve	-ve	+ve	-ve	Irrigation	Temperature
Madhya Pradesh*	WSP, MSP	–	EU,CH,WM,MT^{1},VD,(KG,GJ)^{1}	WM,BH	–	WM, WR, ER, VD, WU, CH	EM, EUP, BH, UT	KG, UT, WM, VD	–	–	+: -:15D1EM, 15D1WM
Punjab*	MSP	(WR, ER)^{1}, (HP, UT)^{1}	PJ, HC, JK, WM, EM	JK, PJ	–	(PJ, JK, HC, WR)^{5}	UT	PJ, WR,	HP, JK, EU, UT	–	+:15D1PJ, 20N1PJ -:
Odisha	MSP, WSP	(GW, CA)^{5},TL	HW, EM	VD	–	CH, CA, TL, EM, GW^{1}	–	OR	CA	–	+:15D1OR -:17D1OR
Tamil Nadu	WSP, MSP	(RY, SI)^{1}	–	KL^{1}, TN, CA, TL,	CK	SI, RY, NI, TN, TL, CK,	–	NI,	SI, TL, CK	–	+: -:15D1TN
Uttar Pradesh*	WSP, MSP	PJ^{1}, WM^{1}	UT, HC	–	WU	EU, WU, BH^{1}, EM^{1}	PJ, HP, HC	BH, CH	WM	–	+: -:
West Bengal	WSP, MSP	HW, CH^{5}	BH, EU, AR	EU, AM^{5}	–	HW, GW, AM	BH, JH	HW	GW, JH	–	+:18D1GW -:

Notes: Only direction of effect indicated by the sign of coefficient is presented but all coefficients are statistically significant. All prices are deflated by price of Fertilizer (NPK). Superscripts denote interaction with irrigation sources = 1: Canal, 2: Well, 3: Canal + Well, 4: Oth, 5: All. * Price variable (P) is Revenue (P x Y) per hectare. Temperature is for Month-Light-fortnight- MET where Month = 15: Aug, 16: Sept,…., 22: March. Fortnight =1, 2, Light = D: Day (7 am to 7 pm), N: Night (7 pm to 7 am), MET is the region within study state (eg,. 16D1TL = Sep_maximum -1st fortnight _TL)

4 Findings on Yield Determination: Spatio-Temporal Rainfall Impacts

MSP was the crop price variable in all cases barring Chhattisgarh and as the only one in Punjab and Haryana, so that, other than these three states, both market price and the MSP are important in yield determination along with fertilizer price with which the crop price is compared. No substitute crop is identified for the allocation of resources.[3] Yield dynamics also matters as an economic incentive shown by the selection of the 'returns per hectare' as a price variable in 7 of the 12 cases and reflecting the dynamics that rice yield is still undergoing years after the agrarian revolution, exceptions being a few states of the east and south.

Heat matters, but while higher night temperature improves rice yield mostly in northern India, higher temperatures in day or night can be a threat to yield in the south and center. The rainfall effect is a combined effect of both positive and negative responses to rainfall in various METs in and outside the study states and especially in the mountains, but in most cases, the effect is modified by the intensity and type of irrigation available. Independent of rainfall, the effect of the irrigation infrastructure is not always found significant for determining rice yield. Favourable effect of all sources of irrigation (5) is found for Assam, Chhattisgarh, Haryana, while in Karnataka only well irrigation (2) has a positive significant effect. No time trend is found anywhere, nor was any dummy variable found to produce a significant coefficient. Error (E) is fairly low, and the error series is stationary by the Dickey-Fuller statistics. Estimates account for the direction changes of the dependent variables in the sample period summarized by the RMSE (root mean square error %) of the sample period found to be less than 2%. Coefficients are found to be robust. The coefficients are found to be robust to changes in the sample (dropping observation randomly). Prediction made with the model for the post-sample year is in most cases not more than 5%.

PSR: Yield in many cases benefited from the previous year's monsoon in the mountains and in plain states. PSR in H.C. and P.J. was not much help for northern Rice growing belt where rainfall in Rajasthan helped. Past rainfall in P.J. has hurt yield in both Punjab and Haryana, but with the support of irrigation, it has helped Uttar Pradesh while PSR in Madhya Pradesh damaged yield in Punjab (E.M., W.M.) as also in Madhya Pradesh, Chhattisgarh and Odisha. Adverse effects of Himalayan rainfall is also observed as in Punjab (J.K.), Odisha (H.W.) and Uttar Pradesh (U.T.). While rainfall in the coastal METs are found to have favoured yield in Assam (G.W.), Bihar (G.W.), Andhra Pradesh (C.A., K.G., C.K.), Odisha (G.W., CA) and Chhattisgarh (OR), interior PSR proved important for higher yield in Tamil Nadu, Karnataka, Andhra Pradesh, Odisha and Chhattisgarh. Although proximity and

[3] Pulses are found major competitors for acreage in the first stage equation not reported but cash crop cotton also emerged as competitor of rice in Punjab and Haryana, jute in West Bengal and sugarcane and vegetables in Assam, Uttar Pradesh and Haryana. Coarse cereals too appeared as competitors for area in two of the states.

altitude have generally mattered, the basin effect could be far-reaching, as noticed in Haryana, West Bengal, Madhya Pradesh and Chhattisgarh. Past rains in water-scarce W.R. supported rice yield in Haryana and Punjab. No gain from PSR is found in Madhya Pradesh, where PSR in neighboring regions in the west and east and its own western part (W.M.) hurt yield. In contrast, the three southern states have only benefited from past rainfall. Interactions show that tube-wells made rainfall useful for Chhattisgarh, but local and neighboring rainfall helped in Assam only by gravity while different sources supported rainfall to enhance yield in West Bengal, Odisha, and Chhattisgarh. For the rest, in Punjab, Haryana, Bihar, Uttar Pradesh, Tamil Nadu, Karnataka, Andhra Pradesh canals had the strongest role in utilizing rainwater with also adverse effects seen in Bihar, Madhya Pradesh and Haryana.

ESR: Not surprisingly, the impact of ESR in most states was meager though it leaves soil moisture, recharges groundwater. Rice planting also precedes the arrival of monsoon in a few states that depend on irrigation, western disturbances, and local thunderstorms for water. Early rainfall in the Himalayan states helped the yield in Haryana (U.T.), Punjab (J.K.), Bihar (H.W.) and West Bengal (AM), while ESR in both METs of West Bengal was useful for neighboring state Bihar. On the other hand, yield in West Bengal and Odisha was favored by early rains in the west (E.U. and V.D., respectively). Both Tamilnadu and water-sharing state Karnataka benefitted from ESR in T.N. By and large, the rainfall helps rice yield, with irrigation having a limited role. Canals helped in Tamil Nadu, both canal and wells in Haryana, and irrigation from all sources served West Bengal to harness water from ESR.

MSR –Despite changing calendars, monsoon rainfall still seems to remain highly decisive for yield. The effect of Himalayan rainfall differs among the states. In fact, all three eastern states and a central state, Chhattisgarh, gained from higher monsoon rain (MSR) in West Bengal. MSR in Madhya Pradesh, a large state in central India, is influential for rice yield in a number of states, and the impact is mostly favorable though the state's own yield is damaged by MSR in E.M. Rainfall in W.R. helped yield in the Punjab-Haryana belt and in Madhya Pradesh. Rainfall in the entire Punjab-Haryana belt damaged yield in Haryana and Uttar Pradesh, but with irrigation, it helped yield in Punjab. The southern states derived benefit from rainfall in METs across the states, perhaps as a result of the interconnectedness of waterways and water sharing regulations. Yield in Uttar Pradesh was served by rainfall across the state, while no adverse effect of MSR was noted for Tamil Nadu, Odisha, and Chhattisgarh. Monsoon's performance in interior Karnataka helped yield in Tamilnadu and Karnataka and that in the interior, Maharashtra helped in Madhya Pradesh and Chhattisgarh but was damaging Andhra Pradesh and Karnataka. Canals brought water from rains in E.M. and B.H. to Uttar Pradesh but on the whole, irrigation helped less in harnessing monsoon rains.

LSR- Contrary to expectation, some favorable influence of late rainfall was detected mainly of local or neighboring rainfall. For example, north-east monsoon rainfall in T.N. helped Andhra Pradesh and Karnataka, and none of the rainfall effects came as interaction with irrigation.

5 Discussion

During the sample period, rice yield responded to economic incentives, including public price policy and exposed the weak role of the market in states having dominant public support. Rainfall effect on yield over the period of growth was far from simple as approximated by the local monsoon performance. Spatial and temporal dimensions of rainfall effect were strong, and local rainfall often had little consequence. Early rain in the Himalayas dominantly helps to increase yield in Punjab and Haryana. In many cases, the rainfall effect was adverse, suggesting an inefficient redistribution of water across regions or time. In particular, shortfalls in the utilization of water from Himalayan rainfall deserve attention. Punjab and Haryana are observed to suffer from less than optimum water management of the local rainfall of Haryana and the outstanding adversity of directing water from Himachal Pradesh by the Bhankra-Nangal system. Shortcomings of the functioning of the river basin projects on Indus, drainage problems, leakages from unlined canals, faulty slopes of canals, and geological shape are widely discussed (Singh et al., 2020). Rainfall in H.P. carries a potential of being used more gainfully. On the contrary, rainfall in J.K. has been highly useful. Also, a favorable effect of rainfall in Rajasthan, which does not itself raise Rice but shares water with rice-producing states, is observed. The southern states are highly sensitive to each other's rainfall.

6 Concluding Remarks

It is clear that production is deeply related to geography and interventions that determine the quality of access to water, but while economic implications are relatively straightforward, the effect of rainfall is temporally and spatially varied and dispersed. The exercises divulged the complexity and dynamics of water linkages to determine rice production in various locations. Interventions create new pathways for water flow on river basins and river water sharing protocols. Despite flooding in the current year, high rainfall can help production in the future, even negating a drought, while a poor rainfall effect can spill over to coming years. Other known or unknown hydrological integrations at the surface and sub-surface levels and sharing of hydroelectric power (Srinivasan et al., 2018; Shweta et al., 2017) produced from water stored in common reservoirs are other forms of integration. While surface linkage of Satluj with the Yamuna remains in the process[4] despite disputes and Sind River, joining the Yamuna, links northern India with Madhya Pradesh, the effect of IRLP can prove more sweeping. Limited knowledge about nature, inadequate access to information on physical and spatial interconnectedness among weather and

[4] Sutlej River flows though the states of Himachal Pradesh, Punjab, Jammu and Kashmir and Haryana states. There is a proposed 214 kilometer Sutlej Yamuna link canal out of which 92 km canal has been already completed (MOJS, 2021).

groundwater and paucity of transboundary data make the study and the explanations of the results best a suggested approach though not all linkages could be covered. Dynamics also result from climate change which is projected to make seasons less well-defined and rainfall regionally erratic and often intense.

Acknowledgement The authors thank Ms. Yashika Rani for data operation and acknowledge the funds provided by the Government of India, Ministry of Agriculture & Farmers Welfare for the FASAL project for which the data is collected and analyzed.

References

Agarwal, A., & Narayan, S. (1991). *State of India's environment: Floods*. Centre for Science and Environment.

Dhawan, B. D. (1995). Magnitude of groundwater exploitation. *Economic and Political Weekly, 30*(14).

Heady, E., & Dillon, J. L. (1961). *Agricultural production functions*. Iowa State University Press.

Indo-Dutch Network Project (IDNP). (2002). *Recommendations on waterlogging and salinity control based on pilot area drainage research*. CSSRI, Karnal and Alterra-ILRI.

James, et al. (2017). Brief history of agricultural systems modeling. *Agricultural Systems, 155*., Elsevier, 240–254.

Justice, C., Gutman, G., & Vadrevu, K. P. (2015). NASA land cover and land use change. *(LCLUC): An Interdisciplinary Research Program, 148*(15), 4–9.

Krishna, R. (1962). A note on the elasticity of the marketable surplus of a subsistence crop. *Indian Journal of Agricultural Economics, 17*, 79–84.

Lasko, K., Vadrevu, K. P., Tran, V. T., Ellicott, E., Nguyen, T. T., Bui, H. Q., & Justice, C. (2017). Satellites may underestimate rice residue and associated burning emissions in Vietnam. *Environmental Research Letters, 12*(8), 085006.

Lasko, K., Vadrevu, K. P., & Nguyen, T. T. N. (2018a). Analysis of air pollution over Hanoi, Vietnam using multi-satellite and MERRA reanalysis datasets. *PLoS One, 13*(5), e0196629.

Lasko, K., Vadrevu, K. P., Tran, V. T., & Justice, C. (2018b). Mapping double and single crop paddy rice with Sentinel-1A at varying spatial scales and polarizations in Hanoi. *Vietnam. IEEE journal of selected topics in applied earth observations and remote sensing, 11*(2), 498–512.

Ministry of Agriculture & Farmers Welfare (MoA&FW) (2019). Agriculture at a Glance 2019. Directorate of Economic and Statistics, Department of Agriculture & Farmers Welfare, GoI.

MOJS (Ministry of Jal Shakti (MoJS). (2021). Sutlej-Yamuna Link Canal. http://mowr.gov.in/sutlej-yamuna-link-canal

Moran, T., Janny, C., & Carolina, S. (2014). The hidden costs of groundwater overdraft. Understanding california groundwater, water in the west. https://waterinthewest.stanford.edu/groundwater/overdraft/

Moorthi, Manthira, S., Oza, M. P., Misra, I., Gambhir, R. K., Darji, N. P., Sharma, S., Jain, D. K., Dhar, D., Padia, K., Ramakrishnan, R., Chowdhury, S., & Parihar, J. S. (2014). FASALSoft – An ISRO software framework for crop production forecast using remote sensing data analysis. *Journal of Geomatics, 8*(1), 27–33.

Nadkarni, M. V., & Deshpande, R. S. (1983). Growth and instability in crop yields: a case study of agriculture in Karnataka, South India. *Regional Studies, 17*, 29–39.

Nandargi, S. S., & Shelar, A. (2018). Rainfall and flood studies of the Ganga River Basin in India. *Annals of Geographical Studies, 1*(1), 34–50. Sryahwa Publications.

National Water Policy (2012). Government of India. http://jalshakti-dowr.gov.in/sites/default/files/NWP2012Eng6495132651_1.pdf

Nerlove, M. (1958). *The Dynamics of Supply: Estimation of Farm supply Response to Price*. Johns Hopkins University Press.

NITI AAYOG. (2015). *Raising agricultural productivity and making farming remunerative for farmers*. An occasional paper, Government of India. https://niti.gov.in/sites/default/files/2019-08/Raising%20Agricultural%20Productivity%20and%20Making%20Farming%20Remunerative%20for%20Farmers.pdf

Özyavuz, M., Bilgili, C., & Salıcı, A. (2015). Determination of vegetation changes with NDVI method. *Journal of Environmental Protection and Ecology, 16*, 264–273.

Prasad, V. K., Badarinath, K. V. S., Yonemura, S., & Tsuruta, H. (2004). Regional inventory of soil surface nitrogen balances in Indian agriculture (2000–2001). *Journal of Environmental Management, 73*(3), 209–218.

Ramaswamy R, I. (2015). *Living rivers, dying rivers*. Oxford University Press.

Sarkar, S. (2019). Extreme rainfall and bad infrastructure lead to extreme Indian floods. August 23, the third pole.net Understanding Asia's water crisis. https://www.thethirdpole.net/2019/08/23/extreme-rainfall-and-bad-infrastructure-lead-to-extreme-indian-floods/

Schultz, T. W. (1964). *Transforming traditional agriculture*. Yale University Press.

Shagun, K. (2019). *Dams were built to control floods; they are now triggers*. Down to Earth, Wednesday 18 September.

Sharma, B., Amarasinghe, U., Xueliang, C., de Condappa, D., Shah, T., Mukherji, A., Bharati, L., Ambilia, G., Qureshif, A., Pante, D., Xenariosa, S., Singh, R., & Smakhtin, V. (2010). The Indus and the Ganges: river basins under extreme pressure. *Water International, 35*(5), 493–521. Routledge Taylor and Francis Group.

Sheffrin, S. M. (1983). *Rational expectations*. Cambridge University Press.

Shweta, S., Kholod, N., Chaturvedi, V., Ghosh, P. P., Mathur, R., Clarke, L., Evans, M., Hejazi, M., Kanudia, A., Koti, P. N., Liu, B., Parikh, K. S., Ali, M. S., & Sharma, K., (2017). Water for electricity in India: A multi-model study of future challenges and linkages to climate change mitigation. *Applied Energy*. https://www.osti.gov/pages/servlets/purl/1364388

Singh, A., Chakravarty, S., M. Rajeshwor, Ghosh, N. (2020). Food Production in Indo-Gangetic Plains: To Understand the Role of Water and Hydrology. *International Journal of the Science of Food and Agriculture, 4*(4), 413–426. https://doi.org/10.26855/ijfsa.2020.12.008

Srinivasan, S., Kholod, N., Chaturvedi, V., Ghosh, P.P., Mathur, R., Clarke, L., Evans, M., Hejazi, M., Kanudia, A., Koti, P.N. & Liu, B. (2018). Water for electricity in India: A multi-model study of future challenges and linkages to climate change mitigation. *Applied Energy, 210*, 673–684.

Suhag, R. (2016). *Overview of ground water in India*. PRS. https://ideas.repec.org/p/ess/wpaper/id9504.html

World Commission. (2000). *Dams and developments: A new framework for decision making. The report of the World Commission on Dams*. https://www.internationalrivers.org/sites/default/files/attached-files/world_commission_on_dams_final_report.pdf