Water Policy 23 (2021) 447–465

Improving economic water productivity to enhance resilience in canal irrigation systems: a pilot study of the Sina irrigation system in Maharashtra, India

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Abstract

This paper proposes scenarios to achieve more crop per drop and irrigation for all in water-scarce irrigation systems, with a particular reference to India. It uses economic water productivity (EWP) and water cost curve for EWP as tools to reallocate irrigation consumptive water use (CWU) and identify economically viable cropping patterns. Assessed in the water-scarce Sina irrigation system in Maharashtra, India, the method shows that drought-tolerant annual crops such as fruits and/or fodder should be the preferred option in irrigated cropping patterns. Cropping patterns with orchard or fodder as permanent fixtures will provide sustainable income in low rainfall years. Orchards in combination with other crops will increase EWP and value of output in moderate to good rainfall years. Governments should create an enabling environment for conjunctive water use and allocation of CWU to achieve a gradual shift to high-value annual/perennial crops as permanent fixtures in cropping patterns.

Keywords: Cropping patterns; Economic water productivity; Groundwater irrigation; Water cost curve; Water-scarce irrigation systems

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doi: 10.2166/wp.2021.231

Highlights

- Economic water productivity is a critical performance indicator when water has an opportunity cost.
- Water cost curve assesses the financial trade-off of different cropping patterns.
- Adapting to weather variability is imperative for water-scarce irrigation systems.
- Drought-tolerant annual crops should be a permanent feature in cropping patterns.
- Enabling a policy environment for conjunctive water use is necessary for change.

Introduction

Along with climate change, increasing population, changing lifestyles, and increasing sectoral water demand are expected to exacerbate the vulnerability to and risks of natural disasters (Scott *et al*., 2018; Rasul *et al*., 2019; Ray & Shaw, 2019; Shamsudduha & Panda, 2019). In South Asian countries, the agriculture sector uses about 80–90% of the water withdrawals and provides livelihoods for a large rural population. In India, agriculture's reliance on monsoon rainfall makes it highly vulnerable to climate variability and climate change. The projected implications of climate change for water and agriculture call for a much-needed focus on efficient water use in agriculture to build resilience and meet future water challenges (Mirza, 2011).

Efficiency and productivity of water use dominate the discourse on irrigation performance in general and canal irrigation systems in particular (Shah, 2013; Kumar, 2018). In India, low water-use efficiency (WUE) and water productivity (WP), and the widening gap between the irrigation potential created (IPC) and the irrigation potential utilized (IPU) are the major concerns in canal irrigation. Given the increasing incidence and magnitude of natural disasters (IPCC, 2014), more crop per drop or higher water productivity and access to irrigation are timelier solutions now than ever before to enhance resilience in the agriculture sector (Brauman *et al*., 2013; Kumar & van Dam, 2013). In India, the government's initiative for the agriculture sector, named Prime Minister's Krishi Sinchayee Yojana (PMKSY) (https://pmksy.gov.in), has twin goals: more crop per drop and 'Har Kheth ko Pani' or irrigation for all farms. How water-scarce canal irrigation systems can realize these two goals is the focus of this paper.

First, what do we mean by more crop per drop? The most commonly cited measure of this proposition is the quantity of production per unit of water use, i.e., physical water productivity (PWP), expressed in kg/m^3 (Molden *et al*., 2003, 2010). The other popular measure is the value of production per unit of water use, i.e., economic water productivity (EWP), expressed in \$/m^3. However, with water scarcities and risks increasing, EWP also needs to consider the net value of output, i.e., profit per unit of water use (Fernández *et al*., 2020). The water use in the denominator of PWP and EWP can be total or irrigation water use. In irrigation systems, the water use measure frequently used is either irrigation supply, or irrigation, or full consumptive water use (CWU).

Water productivity in India varies substantially. Between states, rice PWP varies from 0.57 kg/m^3 in Punjab, predominantly under groundwater irrigation, to 0.24 kg/m^3 in Karnataka with mainly surface irrigation (Sharma *et al*., 2018). The wheat PWP between districts varies from 0.24 kg/m^3 in the eastern and western regions to as high as 2.03 kg/m^3 in the north-western region (Sharma *et al*., 2018). In the Indo-Gangetic basin, rice PWP varies from 0.5 to 1.32 kg/m^3 from the north-western to eastern regions (Cai & Sharma, 2010). In Uttar Pradesh in the Ganges Basin, wheat PWP varies from 0.41 to 0.81 kg/m^3 (Sharma *et al*., 2018). In the western region, in Maharashtra in the Bhima river basin, sugarcane PWP varies from 8 to 12 kg/m^3, and sorghum and millet PWPs vary between 0.01 and 1.8 kg/m^3 (Garg *et al.*, 2012). These PWPs are significantly smaller in dry years. For example, the EWP of millet ranges from 0.026 to 0.047 \$/m^3. These variations in PWP and EWP show a substantial scope for improvement of PWP and EWP, and they can play a major role in water-scarce basins such as Bhima.

However, when water is plentiful and the opportunity cost of water use is low, WP has little role to play in water management. When water demand is high, water scarcities emerge, and the opportunity cost of water use is high, WP has a substantial role to play. In such cases, planning for interventions needs to shift focus, first to increasing PWP (the physical production of different crops per unit of water, kg/m^3), and then to increasing EWP (the value of production per unit of water, \$/m^3) at the system level (Sharma *et al.*, 2018; GOI, 2019). Ultimately, when the opportunity cost is too high, the economic productivity of water (value of production per value of water) will play a role, and water transfers from low-value to high-value production processes will emerge.

However, the more crop per drop principle can sometimes curtail access to irrigation for all. In water-scarce irrigation systems, the potential for increasing irrigation CWU or crop evapotranspiration is not high (Perry *et al.*, 2009; Grafton *et al.*, 2018), except where the non-beneficial evaporation part of the CWU is substantial (Kumar & van Dam, 2013). Better agronomic practices, including management of inputs, can reduce non-beneficial evaporation and increase yield, and hence PWP. Therefore, the potential for increasing beneficial CWU is low in highly water-scarce irrigation systems. Further, an increase in irrigation CWU in one location could be at the expense of beneficial CWU in other locations. Therefore, the next option for water-scarce irrigation systems is to increase EWP (value and profit/m^3) (Fernández *et al.*, 2020). With the focus on EWP, all stakeholders can potentially receive irrigation and income even under increased climatic variability and water scarcity.

Many irrigation systems in India face increasing climatic risks. The Sina irrigation system in Maharashtra is a typical water-scarce irrigation system in India. It had sufficient water for irrigation through canals in just 3 years in the past decade (Amarasinghe *et al.*, 2020). Inadequate monsoon rainfall restricts water releases to the canal command area (CCA) and reduces groundwater irrigation in the water influence zone (WIZ). However, there is potential for more crop per drop and irrigation for all, even in dry years through reallocation of irrigation CWU.

This paper assesses strategies for reallocation of CWU and thereby increasing EWP in the Sina irrigation system. It develops scenarios of water allocation and a water cost curve (WCC) to assess the trade-off. The baseline for scenario development is a year with good rainfall and reservoir storage. The WCC assesses the hydro-economic trade-off of increasing EWP through different cropping patterns. The scenario analysis considers EWP of profit per unit of irrigation CWU as an instrument for water reallocation.

In the next section on methodology and data, we present the approach to developing these scenarios and the WCC for an assessment of the reallocation of CWU and the relevant trade-offs. Next, we present the results of our assessment and discuss the impacts of CWU reallocation. In the final section, we discuss policy recommendations.

Methodology and data

Data

The critical set of data for scenario analysis is a reliable estimate of the baseline cropping pattern. The primary source of data for cropping patterns is the land-use pattern derived from satellite data (Figure 1).

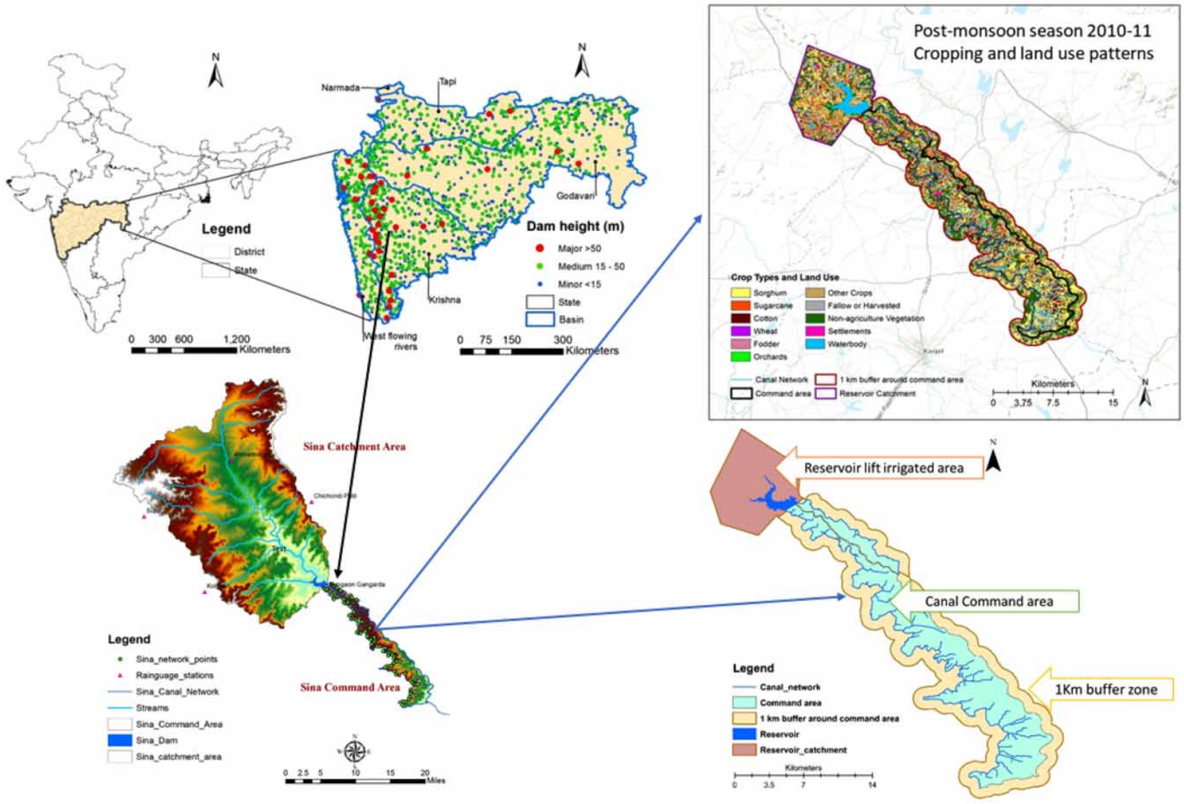

Fig. 1. The land-use pattern in the Sina water influence zone (WIZ) in 2010–11 post-monsoon season. *Source:* Amarasinghe *et al.* (2020).

Satellite-based data give an accurate picture of the land-use pattern in the Sina WIZ, including the CCA, a 1 km buffer zone outside the CCA, and the reservoir lift irrigated area (RLIA), the area of the catchment where farmers lift water for irrigation directly from the reservoir.

Sina irrigation scheme is in the Pune irrigation circle of Ahmednagar district in Maharashtra, India (Figure 1). Sina is a water-scarce medium irrigation system, and the reservoir has gross and live storage capacities of 67.95 million cubic meters (Mm^3) and 52.30 Mm^3, respectively. Amarasinghe *et al.* (2020) show that groundwater irrigation is widespread in Sina WIZ, which mainly lies in the hard-rock region of Maharashtra. Basalt is the aquifer system underneath. The basalts usually have medium to low permeability. The soil in the Sina command area is medium to fine-textured with some clay and sand content. The depth of soil in 85% of Sina project command falls under moderately deep to very deep.

Natural groundwater recharge from rainfall is estimated as 10% of total available water through rainfall (GoI, 2017) in the Sina command area. In the year 2016–17, the total available water through rainfall in the command area is estimated as 70.8 Mm^3, in which 7.08 Mm^3 contribute to groundwater recharge. The other major source for groundwater recharge is the unlined right bank canal, which runs in 73 km length with variable water depth in the head, middle, and tail region and having an average running of 35 days per year. The recharge of 2.5 cumecs per million square meters of the wetted area through the canal is taken based on GEC-2015 guidelines. Sina left bank canal is a closed conduit, and hence, the total groundwater recharge through Sina right bank canal is estimated as 4.63 Mm^3. Overall, the total groundwater recharge obtained through rainfall and unlined canal is 11.71 Mm^3.

The Sina WIZ experiences substantial water scarcities due to variation of rainfall (Figure 2). Due to low monsoon rainfall (from June to September), the primary water source for Sina reservoir storage, there was little or no water supply in 4 years (2011–12, 2012–13, 2015–16, and 2016–17) since 2007. In 4 years (2008–09, 2009–10, 2010–11, and 2017–18), reservoir storage was full due to high monsoon rainfall, but the irrigation supply still has substantial variation. In fact, the rainfall, irrigation supply, and cropped area in 2010–11 were among the highest in the past two decades. Moreover, the cropping pattern was diverse too. Therefore, we use the 2010–11 cropping pattern as the baseline data for the scenario–trade-off analysis (Table 1).

The design command area of the Sina irrigation system is 8,444 hectares (ha). The recommended cropping pattern included 41% of the command area (about 3,460 ha) sown to seasonal crops in the *Kharif* season (monsoon season, June to September), another 56% (4,728 ha) is sown in *rabi* (post-monsoon season, October to March) and the hot-weather season (summer season, March to June). Annual crops account for 3% of the command area. Normally, the *monsoon* season crops use only rainfall. Irrigation starts in mid-October for the rabi season.

However, the total irrigated area in the Sina CCA in the 2010–11 post-monsoon season alone was about 8,400 ha, twice the area under the recommended cropping pattern. The total irrigated area in the WIZ in the post-monsoon season was about 20,000 ha, including 5,500 and 6,100 ha of cropped area in the RLIA and 1 km buffer zone.

The consumptive fraction of the Sina WIZ, even in high rainfall years such as 2010–11, was almost 100% (Amarasinghe *et al*., 2020). The consumptive fraction is the ratio of crop evapotranspiration from (intended and unintended processes) irrigation to total irrigation water withdrawals. Thus, Sina is a physically water-scarce system, in which not much water is available for further increase in irrigation CWU (IRCWU). The IRCWU is the evapotranspiration (from intended and unintended processes) of crops from the irrigation withdrawals (surface and groundwater). The total CWU is the sum of IRCWU and effective rainfall from cropped areas (see Amarasinghe *et al*. (2020) for details). Therefore,

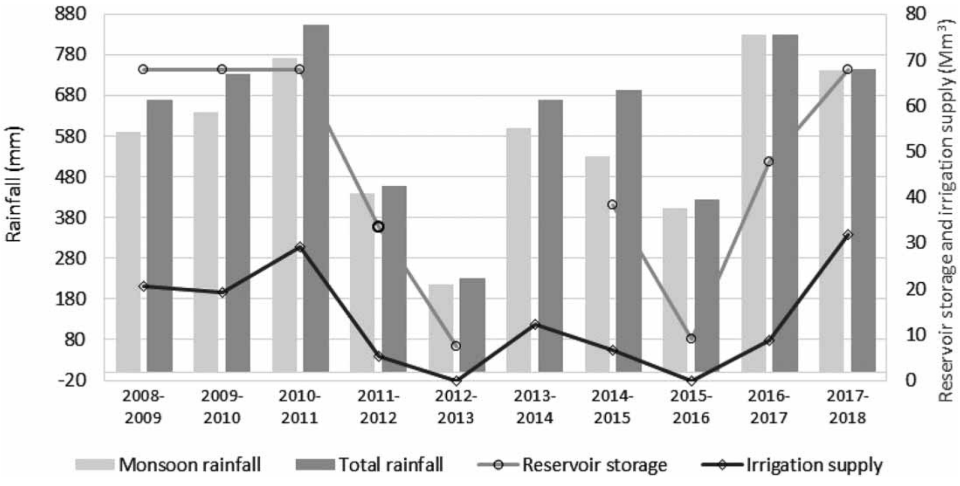

Fig. 2. Rainfall, reservoir storage, and irrigation supply of Sina. *Source*: Authors.

Table 1. Remote sensing/GIS estimates of cropping patterns in the Sina irrigation system in Maharashtra, India, in 2010–11 (post-monsoon seasons and annual crops).

			Cropped area (ha)					
Season	Land-use pattern	Recommended cropping pattern for CCA (% of the total area)	CCA	% of total	1 km buffer	% of total	RLIA	% of total
Post-monsoon[a]	Sorghum	47	2,799	33	2,114	34	1,251	23
	Wheat	27	186	2	123	2	165	3
	Fodder	7	45	1	26	0	30	1
	Other crops[b]	–	2,828	34	2,165	35	1,641	30
	Oilseeds	7	100	1	–	–	313	6
	Vegetables	7	390	5	–	–	1,024	19
Annual crops	Sugarcane	4	544	6	344	6	483	9
	Orchards[c]	1	102	1	171	3	59	1
	Cotton	0	1,442	17	1,190	19	545	10
Total	*Post-monsoon*	95	6,348	75	4,428	72	4,424	80
	Annual crops	5	2,088	25	1,705	28	1,087	20
	Total	100	8,436	100	6,133	100	5,511	100
Other land use								
• Fallow or harvested		–	1,850	–	2,292	–	1,526	–
• Non-agricultural lands		–	1,544	–	2,479	–	1,402	–
• Settlements		–	92	–	60	–	86	–
• Area of surface water bodies		–	4	–	45	–	693	–
Total area		–	11,435	–	11,010	–	8,195	–

Source: Recommended cropping patterns are from the irrigation department, and the areas are the authors' estimates.

[a] Post-monsoon season includes both Rabi (October to March) and summer season (March to June) crops. Oilseeds (groundnuts or soybeans) and vegetable area are based on the cropped area in the summer season.

[b] Other crops include pulses and oilseeds.

[c] Orchards include pomegranate, orange, lime, etc.

Notes: Post-monsoon season includes both Rabi and summer season crops. Oilseeds and vegetables IRCWU are based on the cropped area in the summer season.

the strategy for Sina should be to increase the value (and the profit) of crop production with available CWU. For that, it is necessary to reallocate the available irrigation CWU.

Scenarios of CWU reallocation

The goal of the reallocation of CWU is to generate net income for farmers even in water-scarce years. Scenario analysis explores potential cropping patterns that increase EWP in non-water-scarce years and provide a profit even in water-scarce years. Interventions to increase EWP include crop or agricultural diversification, technological interventions such as micro or solar irrigation, or institutional innovations in water management (Cameira & Pereira, 2019). In Sina, high-value, less water-intensive annual/perennial crops should be an integral part of the cropping patterns.

The EWP (at constant 2010 prices) and irrigation CWU per ha of different crops in 2010–11 (Table 2) provide us with the baseline or business-as-usual scenario (BAU) information. This analysis considers only the post-monsoon and summer seasons and the annual crops since the irrigation CWU only pertains to these crops.

The analysis generated the following scenarios, assuming available irrigation CWU as the primary constraint.

Scenario A: Generate the same value of output as in good rainfall years such as 2010–11, with smaller irrigation CWU.

Scenario B: Generate some output under water-scarce conditions with no water supply from the reservoir and assuming only groundwater irrigation. Generally, with no irrigation supply, it is not possible to grow seasonal crops in the post-monsoon seasons. In such a scenario, farmers are left with virtually no income. Scenario B assesses the value of drought-tolerant annual crops – the cropping patterns that can generate some output under extremely dry weather conditions corresponding to a low rainfall year (once-in-10-years rainfall of about 250 mm/year). We estimate natural groundwater recharge as per the guidelines issued by the GoI (2017). For the semi-arid region in Sina, the natural recharge is 10% of the rainfall.

Scenario C: Generate more output than Scenario B under moderate rainfall conditions (3-in-4 years, or 75% dependable rainfall of about 450 mm/year. This amount of rainfall allows both canal and groundwater irrigation, although the reservoir has no full storage level by October 15.

Scenario D: Generate more output than 2010–11 under high rainfall conditions of more than 650 mm/year, which is the median rainfall in the Sina WIZ. Under high rainfall conditions, the reservoir has full storage by October 15 and allows full irrigation potential under both canal and groundwater irrigation.

Table 2. Yield, market price, EWP, and irrigation CWU (IRCWU) of different crops in 2010–11.

Season	Crop	Yield (t/ha)	Price (USD/t)	IRCWU (m^3/ha)	EWP (USD/m^3 unit of IRCWU)
Post-monsoon[a]	Sorghum	0.6	500	3,226	0.10
	Wheat	2.1	317	3,769	0.18
	Fodder (Lucerne)	40.0	69	4,206	0.56
	Other crops (pulses)	1.2	636	2,669	0.28
	Oilseeds	1.1	411	4,279	0.10
	Vegetables (onion)	13.2	308	5,090	0.81
Annual/perennial crops	Sugarcane	134.9	27	9,209	0.40
	Orchards (pomegranate)	7.2	939	6,326	1.07
	Cotton	0.4	895	2,732	0.12

Source: Yield and prices are from the cost of cultivation survey database of the Maharashtra Government maintained by the Mahatma Phule Krishi Vidyapeeth (MPKV). The EWP and IRCWU are the authors' estimates (Amarasinghe *et al.*, 2020).

Notes: [a]Post-monsoon season include both Rabi and summer season crops. Oilseeds and vegetables IRCWU are based on the cropped area in the summer season.

WCC for EWP

The WCC for EWP assesses the trade-off of CWU reallocation. It assesses the annual cost of cultivation and the net value of the production (the value of production − the cost of cultivation) of different crops per unit of irrigation CWU. The cost of cultivation includes the cost of conventional methods as well as the annualized cost of various technologies used for cultivation or irrigation. The technologies and practices include the system of rice intensification (SRI), direct seeding of rice (DSR), alternate wetting and drying (AWD), alternate furrow irrigation (AFI), etc. (see Table 6 in the cost curve section for more details).

The cost of technology/practices is the direct cost associated with implementing them in the field. For practices such as SRI, it is the additional cost of inputs and resources required to implement key components of the technology and included as a variable cost. For technologies such as drip or sprinkler irrigation and subsurface irrigation, the annualized cost of the technology is the capital investment, which is estimated using

$$\text{Annualized cost} = \text{Capital cost} \times \left(\frac{i(1+i)^n}{(1+i)^n - 1} \right)$$

where i is the interest rate (at 12.5% per annum) and n is the lifetime of the technology in years, here assumed to be 10 years.

Data for developing the cost curve are available from various studies conducted by research stations and irrigation agencies in India. They include the cost of technologies, cost of cultivation, delivery of irrigation water, crop yield, and farm harvest prices.

Results

Cropping patterns for the CCA

The actual cropping pattern in the 2010–11 BAU scenario is substantially different from those recommended at the design stage of the irrigation project (Table 3). Crops with low EWP, such as sorghum, cotton, and pulses, occupy a large irrigated area. Scenarios SA1, SA2, and SA3 cropping patterns under scenario A, showing the percentage of area under fodder, orchard (pomegranate), and vegetables (onion) that can generate the same output as of BAU.

The total irrigation CWU under the BAU scenario was 29.5 Mm^3 and generated only USD 8.01 million value, with an overall EWP of 0.28 USD/m^3 of irrigation CWU. Under a similar water supply regime, Scenario A cropping patterns SA1–SA3 can match the BAU output in a much smaller area. For example:

Scenario SA2 shows that pomegranate orchards, an annual crop, require only 14.4% of the BAU cropped area (i.e., only 1,181 ha of the 8,432 ha of the BAU area), and only 25% of the irrigation CWU.

Scenarios SA3 and SA1 show that seasonal crops such as vegetables (tomatoes) and fodder (Lucerne) require a little more area and CWU to generate the same output; tomatoes need only 1,948 ha, and fodder requires only 3,381 ha. Sugarcane has the fourth-highest EWP among the 2010–11 cropping patterns. Although sugarcane requires 26% of the area, it requires 67% of the irrigation CWU to generate the same output.

Table 3. Scenario A cropping patterns in the CCA.

		Cropping patterns (%) of post-monsoon and annual/perennial crops				
				Scenario A		
Season	Crop	Recommended for Sina	2010–11 (BAU)	SA1	SA2	SA3
Post-monsoon[a]	Sorghum	47	33			
	Wheat	27	2			
	Fodder	7	1	40.1		
	Pulses	-	34			
	Oilseeds	7	1			
	Vegetables	7	5			23.1
Annual/perennial crops	Sugarcane	4	6			
	Orchard	1	1		14.4	
	Cotton	0	17			
Total percentage		100	100	40.1	14.4	23.1
Total area (ha)		4,982	8,432	3,381	1,181	1,948
Total IRCWU (Mm^3)		20	29.50	14.22	7.47	9.91
Total output (M USD)		5.23	8.01	**8.01**	**8.01**	**8.01**
Total output (% of BAU output)		65	100	100	100	100

Source: Authors' estimation.

Notes: [a]Post-monsoon season include both Rabi and summer season crops. Oilseeds and vegetables IRCWU are based on the cropped area in the summer season.

Bold values indicate that SA1–SA3 provide the same output.

However, the SA1, SA2, and SA3 cropping patterns are not feasible under dry weather conditions when only groundwater irrigation is possible. The potential groundwater recharge in the CCA under conditions of once-in-10-years rainfall of 250 mm is about 2.8 Mm^3. But the SA1–SA3 cropping patterns require more irrigation CWU than the available groundwater can supply under extremely dry weather conditions. The scenarios SB1 to SB3 show the fodder, orchards, or vegetable area that can grow with the available groundwater under extremely dry weather conditions.

Scenarios SB1–SB3 show that groundwater irrigation CWU of about 2.8 Mm^3 can support fodder, fruits, and vegetables in 8.0, 5.3, and 6.6% of the BAU area and generate about 20, 38, and 29% of the BAU output, respectively.

Some orchard crops (pomegranate, mango) and fodder (Lucerne) are drought-tolerant. These crops, grown in a slightly larger area than in Scenario SB1–SB3 with deficit irrigation, can still survive a severe drought period. In deficit irrigation, farmers meet water requirements only during critical periods of crop growth. That may result in a marginal loss of productivity compared with Scenario A but may still generate higher output than Scenario B. These are the cropping patterns that can provide a sustainable income when there are no canal water releases from the reservoir. Therefore, an ideal cropping pattern to withstand a severe drought in the Sina CCA could include fruits, such as pomegranate, as a permanent crop. Fodder can also be a suitable crop in the cropping pattern if it supports milk production in farm households. Vegetables are seasonal and hence have the flexibility to change the area quickly according to rainfall.

Therefore, the next few scenarios (SC1–SC3, SD1–SD3 in Table 4) assume cropping patterns that include fruits (pomegranate) as the base crop in 5.3% of the BAU area, which consumes 2.83 Mm^3 of groundwater irrigation CWU and generates USD 3.03 million output. These scenarios then assess

Table 4. Scenarios B, C, and D cropping patterns in the CCA.

		Cropping patterns (%) of the post-monsoon, summer season, and annual/perennial crops								
		Scenario B (low rainfall)			Scenario C (moderate rainfall)			Scenario D (high rainfall)		
Season	Crop	SB1	SB2	SB3	SC1	SC2	SC3	SD1	SD2	SD3
Post-monsoon	Sorghum						3.3			20.0
	Wheat									8.0
	Fodder	8.0			8.0	8.0	8.0	8.0	8.0	8.0
	Pulses					7.2	3.3		76.3	20.0
	Oilseeds									7.0
	Vegetables			6.6	10.4	6.6	6.6	55.5	10.4	20.4
Annual/perennial crops	Sugarcane									
	Orchard		5.3		5.3	5.3	5.3	5.3	5.3	5.3
	Cotton									
Total percentage		8.0	5.3	6.6	23.7	26.8	26.4	68.8	100.0	88.8
Total area (ha)		672	447	555	1,991	2,281	2,223	5,798	8,432	7,488
Total IRCWU (Mm^3)		**2.83**	**2.83**	**2.83**	**10.10**	**10.10**	**10.10**	**29.50**	**27.29**	**29.50**
Total output (M USD)		1.59	3.03	2.28	8.21	7.36	7.20	23.87	13.07	14.90
Total output (% of BAU output)		20	38	29	103	92	90	298	163	176

Source: Authors' estimation.

Bold values indicate that SB1–SB2 and SC1–SC3 have same irrigation consumptive water use.

what other crops can be grown with the available CWU under different rainfall patterns (moderate and high rainfall).

Scenarios SC1–SC3 are based on 75% dependable rainfall of about 450 mm. This rainfall augments about 5.0 Mm^3 of natural groundwater resources in the CCA and 5.0 Mm^3 of additional canal irrigation CWU. The latter is estimated based on past rainfall and reservoir release patterns. The total irrigation CWU available under SC1–SC3 is 10.0 Mm^3.

The cropping patterns SC1–SC3 have fruits as a permanent feature in 5.3% of the BAU area. These cropping patterns can survive under moderate rainfall conditions with an irrigation CWU of 10.1 Mm^3 of canal and groundwater irrigation.

- Cropping pattern SC1, which includes only fruits, fodder, and vegetables, takes up only 23.7% of the BAU cropped area but can generate even higher output than the BAU cropping pattern.

Scenarios SD1–SD3 offer alternative cropping patterns to the BAU under high rainfall conditions. These cropping patterns too assume a fixed area for fruits (5.3% of the BAU area) and fodder (8%) as permanent crops, as in scenario C. Moreover, they assume that 29.5 Mm^3 (same as under BAU conditions) is available for irrigation CWU.

- SD1, which includes more vegetable area than SC1, occupies 68.8% of the BAU cropped area but generates three times the value of the BAU output.

- SD2 and SD3 have more diversified cropping patterns and generate substantially more output than those in SC1. In addition to fruit, fodder, and vegetables (as in scenario SC1), SD2 scenario assumes an additional area with pulses – the crop with the next highest EWP. The SD2 scenario generates 66% more output than BAU.

The scenario analysis for the CCA shows that Sina can generate the same or much higher output with different cropping patterns. To achieve this target, all cropping patterns can include a permanent feature such as orchards or fodder for milk production. The seasonal crops can vary according to rainfall and water availability patterns.

Scenarios for RLIA and 1 km buffer

Following the same methodology, Table 5 shows potential cropping patterns for the RLIA and the 1 km buffer zone. It only shows cropping patterns that can provide some income even in low to moderate rainfall years, but substantially more income in high rainfall years.

In the RLIA, which uses both groundwater irrigation and lift irrigation from the reservoir, the following cropping patterns hold potential:

- SA2: Fruits in 22.7% of the BAU area can generate the same value of output, with about one-third of the irrigation CWU. However, this CWU is substantially more than the available groundwater in a low rainfall year.
- SB2: RLIA can sustain 5.1% of the BAU area with fruits in a low rainfall year.
- SC3: Fruits (5.1%), fodder (7.7%), and vegetables can generate more output than the BAU cropping pattern in a moderate rainfall year.
- SD4: Fruits (5.1%), fodder (7.7%), and other crops with vegetables in at least 18.6% of the BAU area can generate more output than the BAU.

In the 1 km buffer zone, which primarily uses return flows of canal water supply in the CCA and natural recharge for groundwater irrigation, the following cropping patterns showed promise:

- SA2: It requires only 12.6% of the BAU area with fruits to generate the same output.
- SB2: In a low rainfall year, it can sustain only 5.9% of the BAU area with fruits.
- SC3: In a moderate rainfall year, fruits (5.9%), fodder (8.6%), sorghum, and pulses in 30% of the BAU area can generate more output than the BAU scenario.
- SD2–3: Fruits (5.9%), fodder (8.6%), and a combination of other crops in more than three-fourths of the BAU cropped area can generate substantially more output in a good rainfall year.

Scenario analyses show that SD3 type cropping patterns are more suitable for the Sina WIZ. It reallocates some of the BAU irrigation CWU from crops with low EWP such as sorghum and pulses to crops with high EWP such as fruits, fodder, and vegetables. In low rainfall years, such cropping patterns generate some income from fruits (and fodder) in a smaller area. Fruits, fodder, and vegetables as primary crops with a combination of other crops can generate even more output than BAU cropping patterns under moderate rainfall conditions and substantially higher output in high rainfall conditions.

Table 5. Potential cropping patterns for RLIA and 1 km buffer.

		Reservoir lift irrigated area (RLIA)						1 km buffer zone					
				Rainfall patterns						Rainfall patterns			
		2010–11	Same output	Low	Moderate	high		2010–11	Same output	Low	Moderate	high	
Season	Crop	BAU	SA	SB2	SC3	SD2	SD3	BAU	SA	SB2	SC3	SD2	SD3
Post-monsoon	Sorghum	22.7					22.7	34.5			8.2		41.6
	Wheat	3.0					3.0	2.0					2.0
	Fodder	0.5			7.7	7.7	7.7	0.4			8.6	8.6	8.6
	Pulses	29.8					29.8	35.3			7.7		41.6
	Oilseeds	5.7					5.7	0.0					
	Vegetables	18.6			25.4	66.6	21.6	0.0				63.2	
Annual crops	Sugarcane	8.8						5.6					
	Orchard	1.1	22.7	5.1	5.1	5.1	5.1	2.8	12.6	5.9	5.9	5.9	5.9
	Cotton	9.9											
Total percentage		100	22.7	5.1	38.2	82.4	95.6	100	12.6	5.9	30.3	77.6	100
Total area (ha)		5,512	1,249	281	2,105	4,373	5,269	6,134	770	362	1,858	4,763	5,291
Total IRCWU (Mm^3)		22.23	7.91	1.78	10.69	22.23	22.23	25.21	5.83	2.74	8.91	25.21	23.99
Total output (M USD)		8.47	8.47	1.90	8.67	18.00	9.67	5.22	5.22	2.45	6.08	19.64	6.49
% of BAU total output		100	100	22	102	213	114	100	100	47	114	363	124

Source: Authors' estimates.

Notes: Low, medium, and high rainfall years correspond to 10th, 25th, and 50th percentile rainfall of 250, 450, and 700 mm, respectively.

The cost curve for EWP

Assuming that water is the major constraint in the irrigation system, and that crop area and inputs depend on availability of water, this study estimates the EWP and net value of output (i.e., output – cost) per m^3 of irrigation CWU. The cost includes both annualized capital cost of technology and the cost of cultivation of the crop (Table 6).

Figure 3 shows the cost curve for different crops and technologies. The *Y*-axis shows the net value of output (value of production – the cost of cultivation) per m^3/ha of irrigation CWU. The *X*-axis shows the EWP (gross output per m^3/ha of irrigation CWU). The bars indicate the crop and the technology used for cropping. The values within parentheses show the EWP per m^3/ha of irrigation CWU. The bars are in increasing order of the net value of output per irrigation CWU.

The bars on the extreme right of the cost curve show that fruits (banana, pomegranate, etc.), vegetables (onion, tomatoes, etc.), and fodder (Lucerne) crops have relatively higher gross and the net value of output per m^3 of irrigation CWU. Sugarcane and mango have higher EWP than Lucerne but have a lower net value of output per m^3. Groundnut – INM and chickpea – IWM also have a higher net value of production than Lucerne, although the EWP is slightly smaller.

The cost curve also shows the differences in EWP between technology use and conventional methods. For example, banana with tissue culture has the highest EWP and the net value of output, more than twice the traditional methods. Tomatoes with precision land leveling have more than twice the production of conventional methods.

Financial trade-off analysis for different scenarios

The financial trade-off analysis of different cropping patterns uses the technologies or practices that generate the highest net value of output. The crops and technologies/practices considered are fruits (pomegranate with drip irrigation), fodder (Lucerne with sprinkler irrigation), vegetables (onion with sprinkler irrigation), sorghum and wheat with conventional irrigation, pulses (chickpea with integrated water management), oilseed (groundnut with integrated nutrient management), and sugarcane with drip, fertigation, and integrated pest management.

Figure 4 shows the benefit–cost ratio (BCR) of scenarios of potential cropping patterns under low (SB), moderate (SC), and high (SD) rainfall conditions over a 10-year period. The following assumptions hold for the BCR scenario analysis.

- There are three low rainfall (less than 250 mm), four moderate (between 250 and 450 mm) rainfall, and three high rainfall years (more than 600 mm rainfall) over the 10-year spell.
- In low rainfall conditions, no canal irrigation supply is available. Under these conditions, the BAU scenario assumes that perennial/annual crops (pomegranate and sugarcane) can be cropped with available groundwater CWU. The alternative scenario is assumed to have only fruit (pomegranate).
- In moderate rainfall years, past trends show that only about 40–60% of the cropped area in high rainfall years can be irrigated. Under moderate rainfall conditions, the BAU scenario assumes that perennial/annual crops (pomegranate and sugarcane), and sorghum and pulses are cropped with the available irrigation CWU. The alternative scenario assumes the SC3 cropping patterns, as shown in Tables 4 and 5.

Table 6. Economic water productivity (EWP) of various crops in the Sina irrigation system in Maharashtra, India.

Crop	Technology/practice	Crop-technology/practice	Cost of cultivation (1,000 INR/ha)	Cost of technology (1,000 INR/ha)	Yield (kg/ha)	Price of commodity (INR/m^3)	Irrigation CWU (m^3/ha)	Value of output per m^3 of irrigation CWU	
								Gross EWP (INR/m^3)	Net EWP (INR/m^3)
Rice	Conventional	Rice – conv.	55	0.00	4,295	13.33	4,908	11.66	0.38
Sorghum	Conventional	Sorghum – conv.	7	0.00	612	18.16	3,226	3.44	1.14
Wheat	Conventional	Wheat – conv.	14	0.00	2,274	8.12	3,769	4.90	1.23
Groundnut	Conventional	Groundnut – conv.	45	0.00	1,282	52.42	4,377	15.35	5.13
Rice	System of rice intensification	Rice – SRI	44	0.92	5,468	13.33	4,908	14.85	5.91
Rice	Alternate wet and dry irrigation (AWD)	Rice – AWD	51	1.60	6,580	13.33	4,908	17.87	7.44
Rice	Direct-sown seed	Rice – DSS	46	0.22	6,280	13.33	4,908	17.06	7.74
Groundnut	IW/cumulative pan evaporation (CPE) = 0.4	Groundnut – IW/CPE0.4	43	0.60	1,477	52.42	4,377	17.69	7.93
Groundnut	Border strip method	Groundnut – BSM	44	0.80	1,684	52.42	4,377	20.17	10.14
Mango	High-density plantation	Mango – HDP	510	15.80	15,000	40.00	6,326	94.85	14.25
Maize	Conventional	Maize – conv.	48	0.00	5,010	16.20	2,271	35.74	14.65
Maize	IW/CPE = 0.6	Maize – IW/CPE0.6	48	0.60	5,050	16.20	2,271	36.03	14.93
Maize	Alternate furrow irrigation	Maize – AFI	47	0.60	5,010	16.20	2,271	35.74	15.00
Lime	Conventional	Lime – conv.	110	0.00	8,614	24.03	6,326	32.72	15.33
Mango	Conventional	Mango – conv.	200	0.00	7,500	40.00	6,326	47.42	15.81
Sunflower	Conventional	Sunflower – conv.	26	0.00	1,890	33.00	2,301	27.10	15.89
Sunflower	Ridge and furrow irrigation	Sunflower – RFI	23	0.60	2,104	33.00	2,301	30.17	20.40
Sugarcane	Conventional	Sugarcane – conv.	118	0.00	110,000	2.85	9,209	34.04	21.24
Chickpeas	Conventional	Chickpea – conv.	18	0.00	1,870	59.33	3,457	32.09	26.81
Sugarcane	Drip with conventional planting	Sugarcane – DRIP	104	13.55	123,000	2.85	9,209	38.07	26.82
Sugarcane	Subsurface drip 100% PE and 100% RDF	Sugarcane – SSDRIP100PE	102	12.10	123,000	2.85	9,209	38.07	26.98
Sugarcane	Drip with fertigation	Sugarcane – DRIPFERT	104	14.45	126,000	2.85	9,209	39.00	27.65
Sugarcane	Subsurface drip 80 PE and75% RDF	Sugarcane – SSDRIP80PE	102	12.10	126,000	2.85	9,209	39.00	27.91

(*Continued.*)

Table 6. (*Continued.*)

Crop	Technology/practice	Crop-technology/practice	Cost of cultivation (1,000 INR/ha)	Cost of technology (1,000 INR/ha)	Yield (kg/ha)	Price of commodity (INR/m^3)	Irrigation CWU (m^3/ha)	Value of output per m^3 of irrigation CWU	
								Gross EWP (INR/m^3)	Net EWP (INR/m^3)
Sugarcane	Drip with improved planting method	Sugarcane – DRIPIPM	103	12.64	131,000	2.85	9,209	40.54	29.40
Sugarcane	Drip and fertigation with improved planting	Sugarcane – DRIPFERTIPM	104	13.55	132,500	2.85	9,209	41.01	29.76
Chickpea	Integrated water management	Chickpea – IWM	19	0.68	2,090	59.33	3,457	35.87	30.39
Groundnut	Sprinkler	Groundnut – SPRINK	37	6.86	3,280	52.42	4,377	39.28	30.86
Groundnut	Integrated nutrient management	Groundnut – INM	37	6.86	3,280	52.42	4,377	39.28	30.86
Lucerne	Sprinkler	Lucerne – SPRINK	2	0.00	40,000	3.50	4,206	33.29	32.77
Onion	Conventional	Onion – conv.	96	0.00	12,200	28.00	5,090	67.12	48.25
Onion	Sprinkler	Onion – SPRINK	97	1.45	13,000	28.00	5,090	71.52	52.37
Pomegranate	Drip irrigation	Pomegranate – DRIP	100	0.00	9,673	47.97	6,326	73.34	57.54
Tomatoes	Conventional	Tomatoes – conv.	41	0.00	35,000	13.00	5,090	89.40	81.36
Banana	Conventional	Banana – conventional	115	0.00	42,500	24.03	6,326	161.44	143.31
Banana	Drip irrigation	Banana – DRIP	90	12.64	56,250	24.03	6,326	213.67	199.38
Tomato	Precision land leveling	Tomato – PLL	42	1	40,000	28	5,090	220.00	212.00
Banana	Drip and fertigation	Banana – DRIFERT	114	22	63,000	24	6,326	239.00	221.00
Banana	Tissue cultured	Banana – TC	464	18	82,500	24	6,326	313.00	240.00

Notes: AWD, Alternative wet and dry irrigation; SRI, System of rice intensification; DSS, direct-sown seed; IWPCE, Irrigation water cumulative pan evaporation; HDP, High-density plantation; AFI, Alternative furrow irrigation; RFI, Ridge and furrow irrigation; SSDRIP100PE, Subsurface drip with 100% pan evaporation; DRIPFERT, drip with fertigation; DRIPIPM, drip irrigation with improved planting; IWM, Integrated Water Management; SPRINK, Sprinkler irrigation; PLL, Precision land leveling; TC, Tissue culture.

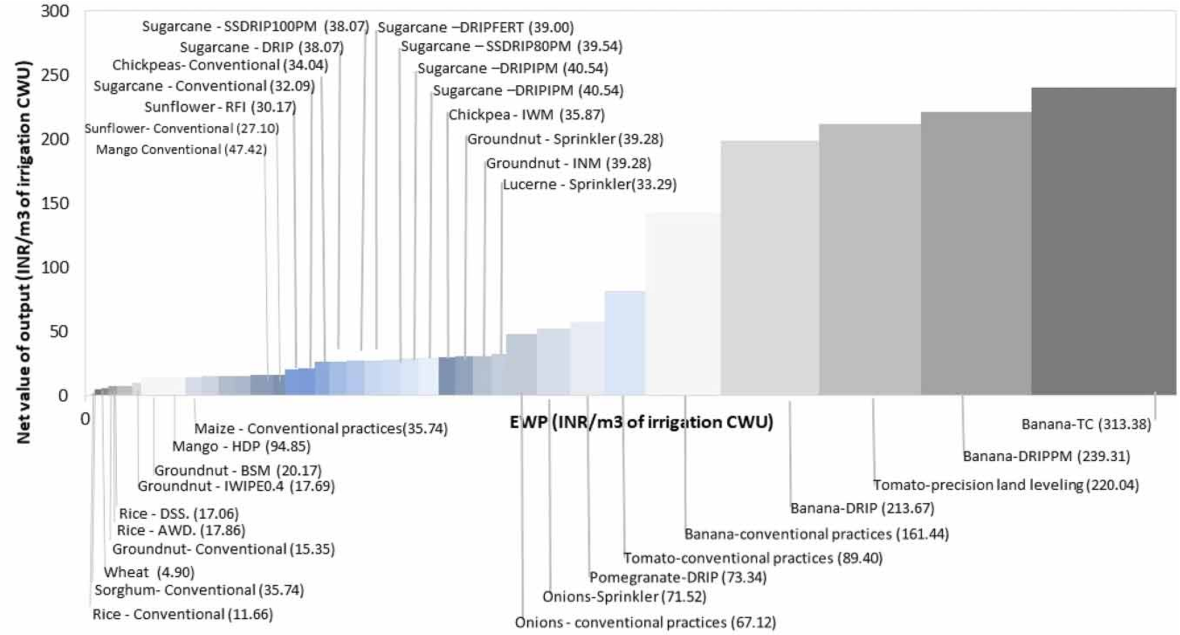

Fig. 3. The net value of output versus EWP per m^3 of irrigation CWU. *Source:* Authors' estimation. *Notes:* Prices were farm gate prices paid in 2015–16. In 2016, USD 1 = INR 67.2. The bars are in increasing order of the net value of output per irrigation CWU. The numbers within parentheses are the EWP of crops with technologies used for cropping.

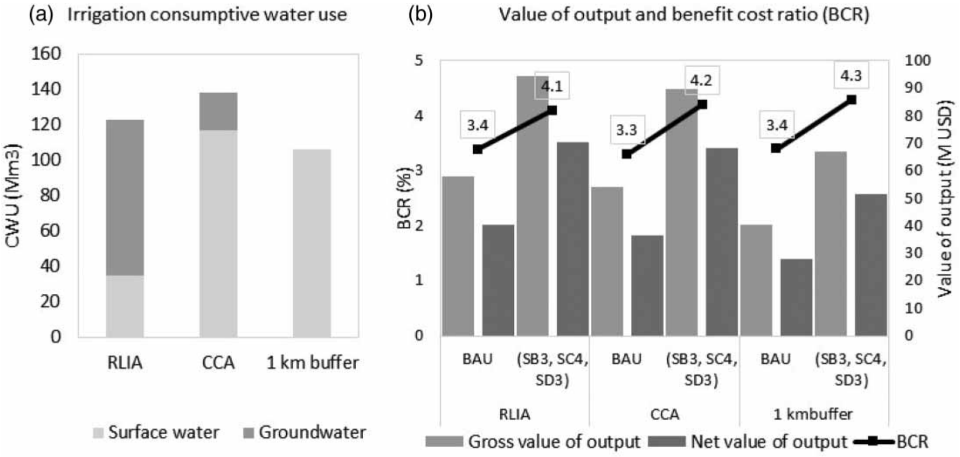

Fig. 4. (a) Irrigation CWU and (b) the trade-off of different cropping patterns in the WIZ regions. *Source:* Authors' estimation. *Notes:* The numbers within parentheses show the number of years under low (SB), moderate (SC), and high rainfall (SC) conditions in a 10-year period. The value of output is in 2010 prices.

- In high rainfall years, the BAU scenario assumes the cropping patterns as in 2010/11, and the alternative scenario assumes SD3, as shown in Tables 4 and 5.

The trade-off analysis shows that alternative cropping patterns to BAU can generate substantially higher outputs with the same quantity of irrigation CWU. In RLIA, a large part of the irrigation CWU in moderate to high rainfall years is from direct pumping from the reservoir. In the CCA, the majority of the irrigation CWU is from groundwater irrigation, and in the 1 km buffer zone, 100% of the CWU is from groundwater irrigation.

- The BCR shows that the alternative cropping patterns are also financially viable in the WIZ with different rainfall scenarios.

Conclusions and policy implications

The Sina irrigation system is a physically water-scarce system. In spite of physical water scarcity, it still grows low-value, high water-consuming crops. As a result, it has low EWP. With increasing variability of weather, water-scarce irrigation systems such as Sina cannot sustain these practices. They should explore increasing EWP by adopting alternative cropping patterns. The cropping patterns not only should increase EWP in moderate to good rainfall years but should also generate some income in low rainfall years.

The CWU water allocation scenarios found that the Sina irrigation system can improve EWP from the present level in all parts of its WIZ. Cropping patterns that include annual crops as a core feature can generate higher outputs with the same CWU in good to moderate rainfall conditions. Such cropping patterns can generate substantial output even in dry weather conditions with groundwater irrigation.

The inclusion of annual crops as a core feature of profitable cropping patterns is based on groundwater irrigation. This analysis used the method proposed by the Central Ground Water Board of India for estimating groundwater recharge. However, this method may be a limitation in the accurate estimation of groundwater availability in the Sina WIZ. Under low rainfall conditions, although there are no canal irrigation supplies, the reservoir still has some water storage. Reservoir storage recharges groundwater in the CCA and the 1 km buffer zone. Accurate estimates of groundwater recharge are needed for finalizing alternative cropping patterns.

The study leads to the following policy recommendations pertinent to the Sina irrigation system in particular and water-scarce irrigation systems in general. These will enable not only more crop per drop but also irrigation for all as envisaged in the Indian government's agriculture initiative, PMKSY.

All water-scarce irrigation systems should assess the groundwater recharge zones and the volume of groundwater storage that can support crop production in the WIZ. Groundwater irrigation is a key component in increasing the consumptive fraction and attaining irrigation for all in the WIZ. It is imperative to know the groundwater availability under different rainfall conditions to enable all stakeholders to use an appropriate crop as a potential feature of crop/agricultural production pattern. The groundwater availability estimation is now supported under the National Aquifer Mapping and Management program (NAQUIM) of the Central Groundwater Board of India at the block and village level in India. This will be useful information for the future with appropriate cropping patterns.

Conjunctive irrigation of canal water and groundwater should be promoted by design and not by default to reduce risks due to variable weather patterns. Groundwater irrigation contributed to the high irrigated area and CWU in the CCA of the Sina irrigation system. It is imperative to enable conditions for conjunctive irrigation in the canal command are to distribute irrigation benefits to all stakeholders in the WIZ.

There should be a gradual shift to cropping patterns that include high-value water stress-tolerant crops in a small area. These crops can primarily use groundwater with micro-irrigation even in a low rainfall year. Perennial crops such as fruits (pomegranate) are already in place in some parts of the Sina WIZ. How these cropping patterns are accommodated within the CCA is a question that needs policy intervention.

Determine the proportion of annual/perennial crops in the cropping pattern based on the available groundwater CWU in low rainfall years. Shift to improved technologies that can decrease non-beneficial evaporation and increase EWP.

The government should create an enabling environment for farmers to access groundwater without over-extracting the resources and incentivizing them to practice water conservation. Groundwater irrigation is not possible at present within the command area when canal irrigation is not available.

Data availability statement

Data cannot be made publicly available; readers should contact the corresponding author for details.

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Received 23 November 2020; accepted in revised form 15 February 2021. Available online 10 March 2021