Water Scarcity Effects on Equitable Water Distribution and Land Use in a Major Irrigation Project—Case Study in India

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Abstract: In many river basins, upstream development and interannual variations in rainfall can cause both episodic and chronic shortages in water supplies downstream. Continued rapid development of surface and groundwater throughout the Krishna Basin in southern India resulted in historically low inflows to the main canals of the Nagarjuna Sagar irrigation project (8,955 km^2) during a recent drought (2002–2004). This paper presents an integrated approach to assess how cropping patterns and the spatial equity of canal flow changed with water supply shocks in the left canal command area (3,592 km^2) of Nagarjuna Sagar. We combined 3 years (2000–2003) of canal release data with census statistics and high temporal resolution (8–10 days) moderate resolution imaging spectrometer (MODIS) 500-m resolution satellite imagery. The impact of water scarcity on land use pattern, delineated by MODIS images with moderate spatial resolution, was comparable with the census statistics, while the MODIS data also identified areas with changes and delays in the rice crop area, which is critical in assessing the impact of canal operations. A 60% reduction in water availability during the drought resulted in 40% land being fallowed in the left-bank canal command area. The results suggest that head reach areas receiving high supply rates during a normal year experienced the highest risks of fluctuations in water supply and cropped area during a water short year compared to downstream areas, which had chronically low water supply, and better adaptive responses by farmers. Contrary to expectations, the spatial distribution of canal flows among the three major zones of the command area was more equitable during low-flow years due to decreased flow at the head reach of the canal and relatively smaller decreases in tail-end areas. The findings suggested that equitable allocations could be achieved by improving the water distribution efficiency of the canal network during normal years and by crop diversification and introduction of alternative water sources during water shortage years. The study identified areas susceptible to decreases in water supplies by using modern techniques, which can help in decision-making processes for equitable water allocation and distribution and in developing strategies to mitigate the effects of water supply shocks on cropping patterns and rural livelihoods.

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Introduction

The performance of large irrigation systems may be evaluated using several criteria, including agricultural productivity, reliability of water supply, and equity of water distribution over the command area (Bhutta and Van der Velde 1992; Bos 1997; Gorantiwar and Smout 2005). Major canal irrigation schemes often suffer from inequitable distribution of water due to overuse in head reaches, which is partly caused by farmer preferences for water intensive crops like rice and sugarcane (Bhutta and Van der Velde 1992). In southern India, for example, originally the irrigation projects were commissioned for "protective irrigation" intended to provide supplemental irrigation to one essentially rainfed crop per year, such as grains and oilseeds. In reality, the majority of farmers in head-end parts of command areas have shifted to intensive irrigation (with up to three crops per year) and crops with high consumptive use such as sugarcane and paddy (Wallach 1984).

The equity of water distribution is expected to change in response to interannual fluctuations in water supply. In many river basins, upstream development and interannual variations in rainfall can cause both episodic and chronic shortages in water supply downstream. Priority in allocation is often given to urban areas and industry, which can exacerbate the supply shocks to irrigated command areas during water deficit years. How these shortages, both temporary and chronic, are distributed over the command area will determine their net impact on agricultural production, equity, and farmers' livelihoods within the irrigated command area. Spatial and temporal analysis of actual water supply in different parts of the irrigation project can identify how and where to improve the performance of an irrigation scheme (Gorantiwar and Smout 2005) and hence improve water and land productivity. Variability in water supply is also linked with the issue of equity, and the spatial uniformity of water supply can be expected to change under different water supply regimes.

The spatial equity of water flows in an irrigation system and

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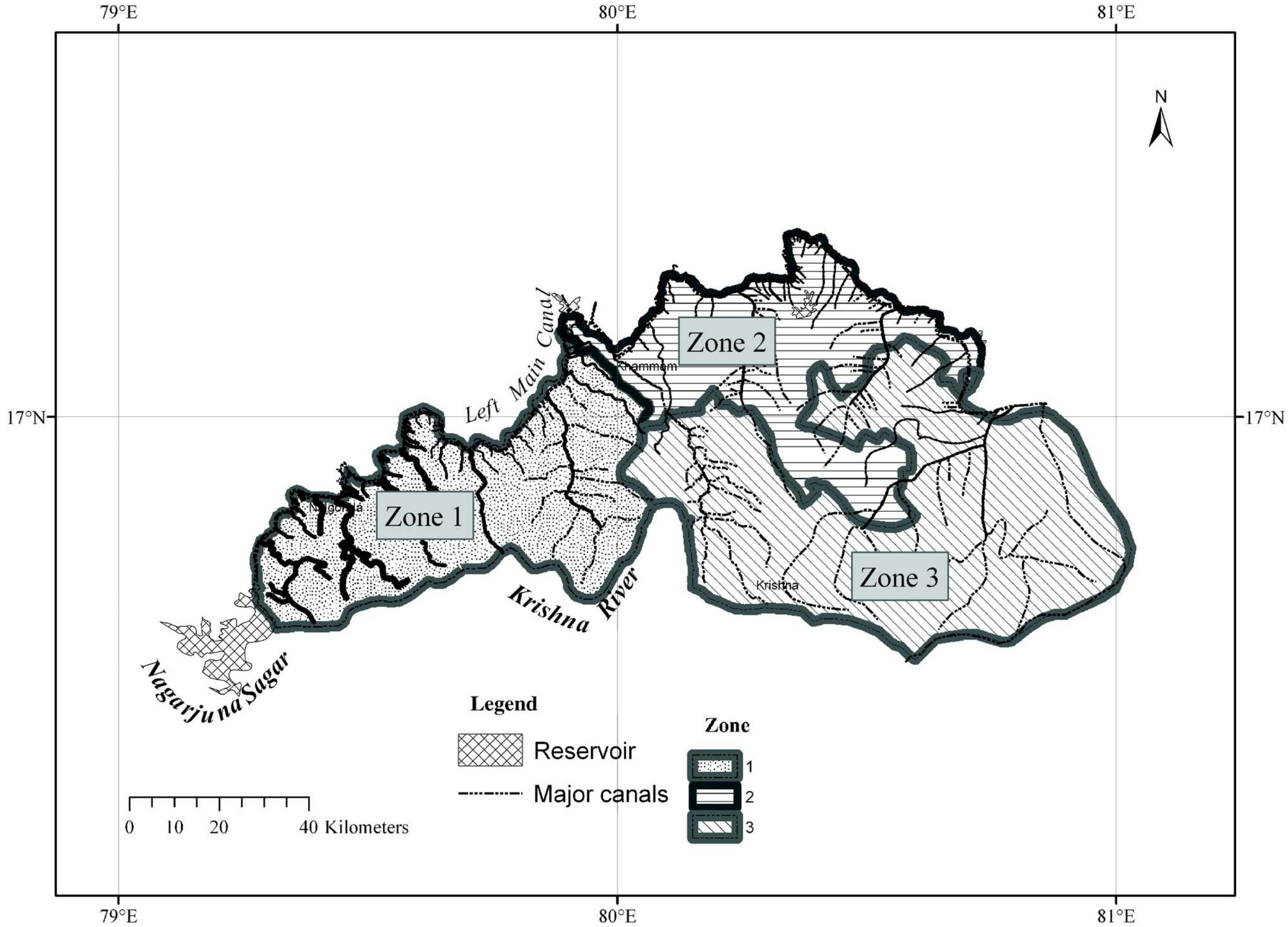

Fig. 1. Nagarjuna Sagar left main canal command area with zones (the zones refer to district boundaries)

the effect of water supply shocks may be measured using several methods. First, canal flows directly measure water supply to the command area (Bhutta and Van der Velde 1992). Census data on agricultural production provide a coarse view of how cropped areas change under irrigation supply fluctuations, and satellite imagery can provide spatially detailed maps of where cropping patterns changed the most for a given variation in water supply (Thiruvengadachari et al. 1997). Satellite imagery has been increasingly used to quantify water use and productivity in irrigation systems (Bastiaanssen and Bos 1999; Thiruvengadachari and Sakthivadivel 1997), but has less frequently been used to identify parts of irrigated command areas that change in response to interannual variations in water supply.

The Nagarjuna Sagar reservoir is one of the largest and most important irrigation projects in the lower Krishna basin in India. Continued rapid surface and groundwater development throughout the basin resulted in historically low inflows to the Nagarjuna Sagar reservoir during a recent severe drought period 2002–2004. This hydrological drought presented challenges to allocate water equitably among different irrigation zones and water use sectors. Due to continuing upstream development, the frequency of such events will increase in the future (Biggs et al. 2007). A drastic change was reported in both canal supplies and land use in the irrigation project. This paper presents an integrated approach to assess changes in the spatial equity of canal flow and land use with water supply shocks in the head, middle, and tail reaches of the left main canal command (359,200 ha) of Nagarjuna Sagar during water surplus, normal, and deficit years. We combine flow data for 3 water years from 107 canals with crop data from the agricultural census and multitemporal satellite imagery, in order to document the effect of changing canal flows on the spatial distribution of water supply and cropping patterns. The spatial distribution of cropping changes was mapped using multitemporal imagery from the moderate resolution imaging spectrometer (MODIS), which can identify areas in single, double, or continuous cropping (Biggs et al. 2006). The integrated approach is used to test the hypothesis that a reduction in canal releases to the main canals in large irrigation systems increases the spatial inequality of water distribution and has the largest effects on the tail and middle portions of the command area.

Materials and Methods

Description of Study Area

The Nagarjuna Sagar (NJS) project (16 34′ 24″ N, 79 18′ 47″ E) is one of the major multipurpose reservoirs in South India (Fig. 1). It is located in the lower Krishna Basin, which is the fifth largest river basin in India. The gross capacity of the reservoir is 11,557 Mm^3 at a full storage level of +179.832 m above sea level, and live storage capacity is 6,841 Mm^3 with dead storage of 4,716 Mm^3 at 121.92 m. Dam construction was completed in 1974, although canals started serving the command from 1967. The NJS reservoir, in conjunction with the upstream hydropower reservoir, Srisailam (8,720 Mm^3), provides irrigation to the NJS

Table 1. Characteristics of Management Zones of Nagarjuna Sagar Left Canal (NSLC) Command and Irrigation Potential

Parameters		Zone 1	Zone 2	Zone 3	Left canal command
District		Nalgonda	Khammam	Krishna	—
Cultivable Command Area (CCA) (ha)		151,000	93,000	153,000	397,000
Number of major canals		55	46	10	111
Number of studied canals		52	46	9	107
Water allocated (Mm^3)		1,387	1,147	353	2,887
Design irrigation intensity	Water intensive	91	57	6	50
(% of CCA)	Irrigated dry	16	63	53	41
	Total	107	120	57	91
Design water Allocation criteria		Water intensive crops in monsoon season	Water intensive crops in monsoon season and irrigated dry crops in postmonsoon season	Irrigated dry crops in postmonsoon season	—
Water drawl capacity of pumping schemes (Mm^3)		225	38	348	611
Irrigation potential of pumping schemes					
Geographical area (GA) within NSLC (ha)		276,990	219,815	421,012	917,817
Canal irrigated (% of GA)	2000–2001	60	45	13	35
	2002–2003	10	3	3	5
Tank irrigated area (% of GA)	2000–2001	8	13	18	14
	2002–2003	2	6	11	7
Ground water irrigated (% of GA)	2000–2001	14	14	15	14
	2002–2003	14	17	16	16

command of 895,500 ha, with a water allocation of 8,436 Mm^3 (including releases to NJS canals+reservoir evaporation losses) by the first Krishna Water Disputes Tribunal (1976). The reservoir is also committed to supply 2,264 Mm^3 to Krishna Delta, which is downstream of the NJS. In addition, in 2004, Nagarjuna Sagar started to supply water (33 Mm^3) to Hyderabad, a major city of ~7 million inhabitants. Currently, the NJS project supplies 123 Mm^3 to Hyderabad and this is expected to increase to 370 Mm^3 by 2030 (Van Rooijen et al. 2005). This expected demand of Hyderabad is equivalent to 4% of water allocated to the Nagarjuna Sagar irrigation project. A state-level Committee for Integrated Operation of Krishna and Pennar Basin Projects (CIOKRIP) was formed for the integrated operation of the lower Krishna reservoirs, including Srisailam, Nagarjuna Sagar, and Krishna delta system (Prakasam Barrage) for optimum utilization of the water in an integrated manner. Releases from Nagarjuna Sagar are made in the following priority: Hyderabad Water Supply, Krishna Delta, and Nagarjuna Sagar canals.

The project consists of a dam and two main canals, the left main canal (NSLC) and right main canal (NSRC). The releases into the main river and both the canals are first used to generate hydropower. The main power station on the river has a hydropower potential of 960 MW, and NSLC and NSRC have a hydropower potential of 60 and 90 MW, respectively. In 1976, each main canal was allocated 3,738 Mm^3 for cultivable command areas (CCA) of 475,500 ha in NSRC and 420,000 ha in NSLC. So far the potential irrigated area created is 450,000 and 397,000 ha in NSRC and NSLC, respectively. The NSLC consists of three irrigation zones (Fig. 1) in three districts (Nalgonda, Khammam, and Krishna), which represent head (Zone 1), middle (Zone 2), and tail (Zone 3). These zones are further subdivided into 32 irrigation blocks, supported by 111 major distributaries (Table 1). Out of 111 major canals, a maximum of 107 major canals were reported in operation during 2000–2003. The canals are designed for gravity irrigation. There are lift irrigation (pumping) schemes along the main canal with a total capacity of 225, 38, and 348 Mm^3 in Zones 1, 2, and 3, respectively. These lift irrigation schemes have a potential to irrigate 72,700 ha.

Eighty percent of annual rainfall in the command area (800 mm) falls during the monsoon season (June–October), while annual potential evapotranspiration is ~1,670 mm. Rainfall decreases from 887 mm in Zone 3 in the eastern part of the command area to 689 mm in Zone 1 in the west. There are three distinct cropping seasons: monsoon (June–October), postmonsoon (November–February), and summer (March–May). NSLC supplies water from July through April and is designed to irrigate 199,000 ha (50%) of water intensive (WI) crops (paddy, sugarcane) and 163,200 ha (41%) of less water intensive crops or irrigated dry (ID) crops (grains, cotton, mangoes etc.) totaling 359,200 ha (i.e., 91% annual irrigation intensity) (Table 1). The command in Zone 1 is designed to supply 1,387 Mm^3 for water intensive crops in the monsoon season, Zone 2 is allocated 1147 Mm^3 for WI crops in the monsoon season and ID crops in the postmonsoon season, and Zone 3 is designed to supply 353 Mm^3 exclusively for ID crops in the postmonsoon season (Irrigation and CAD Department 2005). Postmonsoon season crops depend entirely on irrigation since there is relatively little precipitation during the postmonsoon season. Zone 1 is dominated by canal irrigated area, supplemented by groundwater; Zone 2 has a mix of canal, groundwater, and tanks, while Zone 3 is rich in tank and groundwater irrigated areas (Table 1). The tail end (Zone 3) is also supplemented by water from the adjacent delta region and partly from seepage or lift irrigation from canals in the delta region and along the Krishna River. In the summer season, there is very little rainfall and evapotranspiration is high (6.91 mm day^{-1}), so cropping is limited, until the monsoon, except in areas with reliable groundwater, which is commonly used for perennial crops, such as orchards, horticulture, and sugarcane. The soils in the command area are predominantly loam and gravelly loam.

The Indian Meteorological Department classifies rainfall as surplus, normal, and deficit if rainfall deviations from long term average rainfall are $>+20$, ±19, and $<-20\%$, respectively. The year 2000–2001 was a "surplus" year with 35% more rainfall than the previous 10-year average. Rainfall during 2001–2002 was "normal" (average rainfall), while 2002–2003 was in "water deficit" (25–45% less than average). In terms of water availability, the canal releases were 140, 110, and 26% of formal allocation (3,738 Mm^3) during 2000–2001, 2001–2002, and 2002–2003, respectively. Based on the total water availability from rainfall and canal releases, the water years were classified as surplus ($>125\%$ of normal water available, 2000–2001), normal (100±25%, 2001–2002), and water deficit ($<75\%$, 2002–2003) years. The study focuses on assessing the spatial pattern of land use in the NSLC command during these 3 water years in three zones of NSLC.

Data Collection and Analysis

Fortnightly reservoir levels, storage, and weekly main canal flows were collected from the Andhra Pradesh Irrigation and Command Area Development Department (ICAD) for 1967–2005. Canal water supply data were available for 107 out of 111 major canals from 2000 to 2003, covering the irrigated command area of all of Zones 2 and 3, and for 74% of Zone 1 (Table 1).

The season-wise irrigated area was available from ICAD for main canals, NSLC, and NSRC (Irrigation and CAD Department 2005). Spatial data on cropping and rainfall in each zone were obtained from Directorate of Economics and Statistics, Government of Andhra Pradesh. A municipality (mandal) is a subunit of a district (20–40 municipalities in a district) and the NSLC overlaps a total of 42 municipalities in three districts. Depending upon the source of data, the cropping areas were normalized by two different parameters:

The irrigation intensity (I) was calculated from the actual irrigated area and designed irrigated area reported by (ICAD) Department

$$I = \frac{A_I}{A_D} \cdot 100$$

where A_I=gross canal-irrigated area; and A_D=designed irrigated area. The cropping intensity (CI) was calculated from census statistics and MODIS images

$$\text{CI} = \frac{A_C}{A_G} \cdot 100$$

where A_C=gross cropped area in the zone; and A_G=total geographical area of each zone. The canal irrigated area (A_I) from the ICAD separates crops into two categories: water intensive crops like rice and sugarcane, and irrigated dry crops like cotton, chili, and chickpea. Gross cropped area (A_c)=sum of the cropped area for monsoon and postmonsoon seasons. The total areas under perennial crops, sugarcane, and orchards were counted twice representing cropping during both monsoon and postmonsoon seasons. Therefore, the annual cropping intensity can range up to 200% in areas with double cropping or perennial crops. The same accounting was applied to MODIS data, which included continuous and double-cropped classes. Some municipality boundaries extended outside the NSLC zone boundaries, so cropped areas for each zone (A_C) were determined as the product of the census-reported cropped area and the fraction of the municipality area overlapping the zone boundary. The boundaries of the three main zones were overlaid on the municipality boundaries in a geographic information system (GIS) (Fig. 1), but the command area boundaries for each individual major canal were not available, so it was not possible to determine the cropping intensity for each major canal. Data on the irrigated area (A_I) were available from the ICAD, so irrigation intensity was computed for each major canal. The boundaries of the municipalities and the zones, and therefore the values of A_C and A_G included cropped areas under tank irrigation, groundwater irrigation, rainfed cropping, and natural shrub lands that are not part of the designed irrigated area reported by the ICAD (A_D). Similarly, due to the unavailability of CCA boundaries of major canals, the cropped area estimated by MODIS images also incorporated gross cropped areas, including groundwater and rainfed areas outside of the actual areas served by the canals. The CI of water intensive crops will likely be smaller than the irrigation intensities (I) of water intensive crops because A_G includes areas not served by the canals. Changes in cropping intensity (CI) may be due to variations in rainfall as well as canal deliveries.

Image Analysis

Maps of irrigated and cropped areas were determined by performing unsupervised classification using the ISOCLASS cluster algorithm in ERDAS Imagine 8.7 (ERDAS 2003) on a time-series of 500 m resolution 8-day composite MODIS images for surplus (2000–2001), normal (2001–2002), and deficit years (2002–2003) [see Biggs et al. 2006 for details of the classification method]. Land cover class names were assigned based on the time series of vegetation growth, quantified by the normalized difference vegetation index (NDVI), corroborated by field visits in 2003 and 2004. For instance, the double peak in NDVI series during an irrigation year indicates a double cropped area while a higher peak of NDVI indicates paddy and a lower one indicated grains or rainfed crops. The continuous NDVI series during the year were delineated as sugarcane and orchard based on the threshold values. The irrigated area was estimated from irrigated fractions of each class provided by Biggs et al. (2006). The mapped classes included double-cropped rice grains, continuously irrigated sugarcane, and rainfed crops. The areas under double cropping, sugarcane, and orchard classes were counted twice for annual intensity in order to incorporate the cropped areas during the postmonsoon season.

The irrigated fractions for each class may vary spatially and temporally, so actual irrigated areas at each municipality may differ between the satellite estimate and census data. The main objective of the MODIS classification is to provide a map of changes in vegetation pattern and sowing time and help determine spatial patterns of changes in major crops in the command area.

Results and Discussion

Operation and Canal Releases

The annual inflow to the Nagarjuna Sagar reservoir ranged from 15,000 to 74,000 Mm^3 during 1974–1998, with an average of

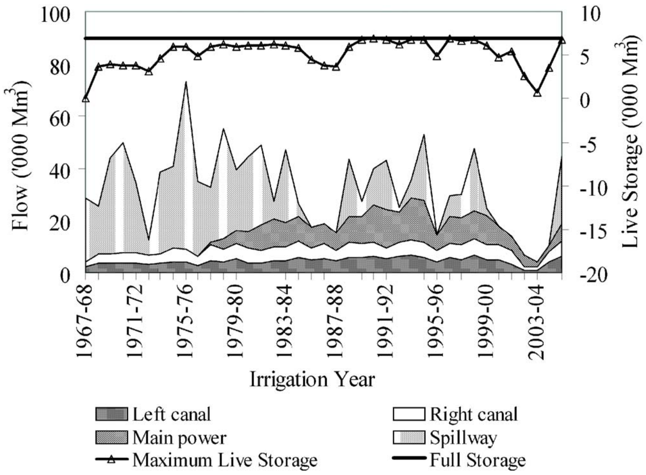

Fig. 2. Annual releases and reservoir storage status in Nagarjuna Sagar Reservoir project

37,000 Mm^3. Of this, $12,928 \pm 3,821$ Mm^3 was utilized between NJS and Krishna delta (Prakasam Barrage) and the rest spilled over Prakasam barrage to the Bay of Bengal (Fig. 2). The majority of inflow (70–90%) occurs during the monsoon season and the reservoir is normally full by October. Since completion of the reservoir in 1974 and the year 1999, the full supply level (179.83 m) was achieved each year except in 1985–1988 and 1995–1996, when water levels dropped to 54–72% of live storage (Fig. 2). There has been normally 5–19% of live storage as carry-over of water from one surplus year to the next year (Fig. 2). From 1999 to 2004, the inflow into the reservoir reduced year after year. Consequently, the reservoir storage fell to a maximum of only 11% of its live storage capacity in 2003–2004.

On average, 60% of the water supplied by NJS and Krishna Delta canals was delivered through NJS canals. The fraction of total water supplied through NJS canals fell to 40% during 2002–2003. Prior to 2000, both the NJS canals delivered 40% more than their allocations (3,738 Mm^3).

Spatio-Temporal Pattern of Canal Flow Deliveries and Timing

The water supply at the head regulator of NSLC was roughly double the sum of the releases into major canals across all zones prior to 2002, indicating conveyance loss, seepage loss, and unaccounted flows of more than 40% (Table 2). During the deficit year, 2002–2003, the difference between main canal flow and sum of releases into main canals was only 17% of the release from the main canal which indicates lower conveyance loss and unaccounted withdrawal during low flows. During 2002–2004, the inflow into the reservoir was also delayed, which in turn delayed canal releases by more than a month (Fig. 3) and changed the spatial allocation pattern (Table 3). The water supply from the main canal to individual zones was similar to normal supply (1995–2000) during 2000–2001, but reduced steadily to 19% of normal supply from 2001–2002 to 2003–2004 (Table 2). During the water surplus year, the total water release from Zone 1 was more than the allocated supply, while water supplies to Zones 2 and 3 were almost half of the allocated values. During the deficit year, Zone 1 experienced the largest reduction (23% of allocation)

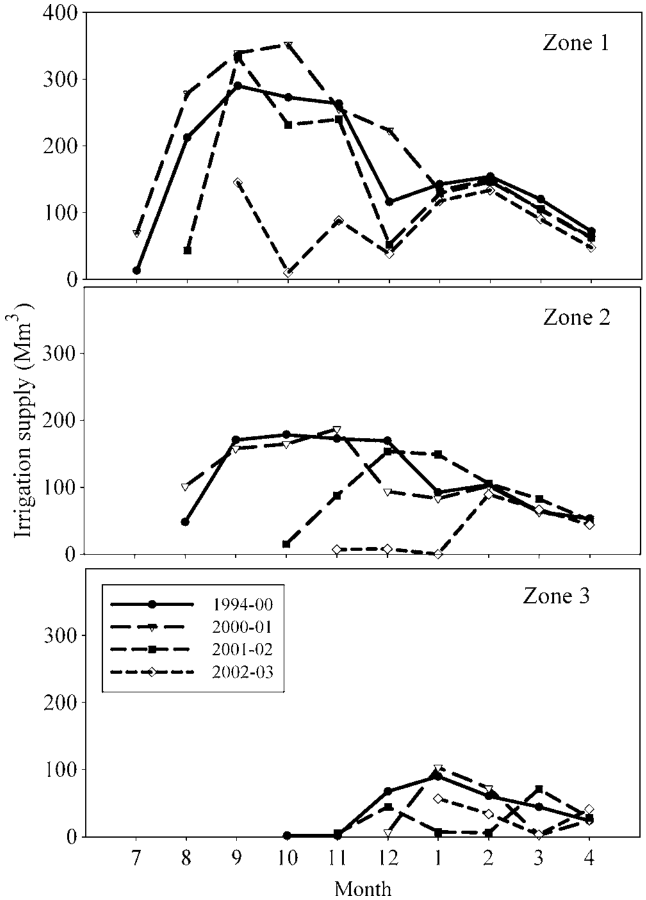

Fig. 3. Canal flow schedule in three zones for four different periods: average (1994–2000), water surplus (2000–2001), normal (2001–2002), and deficit (2002–2003)

Table 2. Annual Canal Releases (Mm^3) from Nagarjuna Sagar Left Canal Head and Water Distribution from Major Canals in Its Three Zones

Water year	Left main canal head (*A*)	Zones					Unaccounted water (%) $[(A-B)/A^*100]$
		Zone 1	Zone 2	Zone 3	Pumping schemes[a]	Total (*B*)	
Water allocated (Mm^3)	—	1,387	1,147	353	611	2,887	—
Average (1995–2000)	5,229	1,535	1,057	278	611	3,481	33
Surplus year (2000–2001)	5,142	1,722	558	197	611	3,088	40
Normal year (2001–2002)	3,277	1,059	475	60	611	1,205	47
Deficit year (2002–2003)	982	326	291	198	0	815	17

[a]Assumed formal pumping allocation during normal and surplus years and zero pumping during deficit year.

Table 3. Rainfall and Irrigation Application during Surplus, Normal, and Deficit Years

Water year	Parameters	Zone 1	Zone 2	Zone 3	Left main canal command	Coefficient of variation (%)
	Average rainfall (mm) (1994–2003)	689	772	887	800	—
Surplus year (2000–2001)	Rainfall (Mm^3)	250	218	423	892	25
	Irrigation (Mm^3)	1,722	558	197	2,477	96
	Total inflow (Mm^3)	1,972	776	621	3,369	84
	Percent of total water inflow	*59*	*23*	*18*	*100*	—
Normal year (2001–2002)	Rainfall (Mm^3)	202	163	321	686	26
	Irrigation (Mm^3)	1,059	475	60	1,594	94
	Total inflow (Mm^3)	1,261	638	381	2,280	80
	Percent of total	*55*	*28*	*17*	*100*	—
Deficit year (2002–2003)	Rainfall (Mm^3)	123	130	230	483	21
	Irrigation (Mm^3)	326	291	198	815	24
	Total inflow (Mm^3)	449	421	428	1,298	17
	Percent of total water inflow	*35*	*32*	*33*	*100*	—

in supplies while Zone 3 saw no change in supply. Twenty canals out of a total of 52 canals that connected directly to the main canal were closed in water scarce years.

All the canals in Zone 2 operate during the monsoon season in a normal year, but only 52% of canals operated in the deficit year (2002–2003). Zone 3 does not receive any water during the monsoon season because it is designed to irrigate ID crops during the postmonsoon season. All the canals (ten) in Zone 3 flowed in the postmonsoon season during 1998–2002, but during the water deficit year, only one third of the canals supplied water to farmers.

In addition to reducing the number of working canals, water scarcity also impacted the timing of canal deliveries. During the normal year, supplies began in July in Zone 1, and in August in Zone 2 (Fig. 3). After 2001, water supply for the monsoon season crops was delayed by 1 month. During the postmonsoon season, Zone 1 suffered a delayed start of deliveries, and received water in January instead of December. Zone 2 received water in February and Zone 3 received it in January but in a reduced quantity (Fig. 3).

Interannual water supply fluctuated most in Zone 1 and least in Zone 3. Zone 1 received 60% more water during the surplus year and 70% less during the deficit year (Table 3) compared to the normal year. Zone 2 received 17% more and 40% less during surplus and deficit years respectively. Zone 3 received less water during the normal year compared with Zones 1 and 2 but received similar quantities during both surplus and deficit years. Zone 3 gets very limited supply which is made possible by the irrigation department by putting extra efforts to push water to the tail end. During the water deficit year, all the zones received similar quantities demonstrating an equitable water distribution by the irrigation department in response to pressure from tailend farmers. The coefficient of variability was 24% as opposed to 96% in a surplus year (Table 3).

During the water surplus year, the ratio of total water available (irrigation+rainfall) in Zones 1, 2, and 3 was 59:23:18 compared to 35:32:32 during water crisis years (Table 3). Both rainfall and irrigation amounts during the water deficit year reduced to 34% of total water available during the surplus year.

Depth of Water Supply

The allocated amount of 3,738 Mm^3 serving a command of 359,200 ha in NSLC would be equivalent to an average supply depth (or duty) of 1.04 m, if there were no conveyance losses and water were applied evenly over the command area. The total depth of water delivered in major canals (volume divided by crop area) of the NSLC decreased with distance from the reservoir, from 2 to 0.04 m. Within each zone, the major canals designed for water intensive irrigation had priority over the smaller branch canals in terms of priority for water supply and amount. Canals at the tail end of Zone 1 received less water than canals in the upper half of the system during the deficit year. Zone 2 had less variability in both rotations (interannual) as well as depth of water supply compared with Zone 1. The water supply depth in the tail end (0.07 m) is less than one irrigation (with normal surface irrigation methods) indicating that either supplemental irrigation is practiced, or large parts of the nominal area are not in fact supplied.

During the normal year (2001–2002), the water supply depths were 0.52 ± 0.22, 0.43 ± 0.07, and 0.23 ± 0.17 m in Zones 1, 2, and 3, respectively (Table 4). During the surplus year (2000–2001), the overall depth over the NSLC command area was 69% larger than in the normal year, and only 15% of the normal depth during the deficit year. The spatial coefficient of variation in irrigation depth was largest in Zone 3 followed by Zone 1 and Zone 2 (Table 4). The spatial variability of irrigation depths in each zone increased during water surplus and water deficit years, which was more pronounced in Zones 1 and 3. The head and tail commands were more subjected to variability in canal flows or inequitable water distribution (see coefficients of variation in Table 4).

Irrigation and Cropping Intensities

Irrigation intensity (I) was 80–120% (Fig. 4) in the NSLC command during 1980–2001 compared to a design intensity of 91%. The irrigation intensities of both water intensive (WI) and irrigated dry (ID) crops varied between 40 and 60% compared with design potential of 51 and 40%, respectively. During the water scarce year, the area of ID crops exceeded that of WI cultivation

Table 4. Annual Depth of Water Supply in Different Zones Including Monsoon and Postmonsoon Season Irrigations

Water year		Zone 1	Zone 2	Zone 3	Left main canal command
Surplus year (2000–2001)	Average (m)	1.23	0.33	0.17	0.74
	SD (m)	0.90	0.15	0.12	0.78
	COV[a] (%)	73	45	70	105
Normal year (2001–2002)	Average (m)	0.52	0.42	0.23	0.44
	SD (m)	0.22	0.07	0.17	0.18
	COV (%)	42	17	73	41
Deficit year (2002–2003)	Average (m)	0.09	0.05	0.04	0.07
	SD (m)	0.06	0.02	0.05	0.05
	COV (%)	69	47	104	73
Change 100*(Deficit/Reference[b])	% of reference year	16.7	14.6	26.5	9.0

[a]Coefficient of variation.

[b]2001–2002 for Zone 1 and 2000–2001 for Zones 2 and 3.

due to canal closures. The WI irrigation intensity reduced drastically in 2002–2003 (from an average of 52 to 5%) while no record was available for canal water use by ID crops (Fig. 4). During 2002–2003, 40% of the average cropped area was left barren. There was no canal irrigated WI crop during 2003–2004 and the rainfed crops have been reported as ID crops in Fig. 4, which probably received supplemental irrigation after October.

Cropping patterns varied widely across the three zones of the NSLC according to both the municipality-level census data (Fig. 5) and MODIS classification. The NSLC irrigated command is 43% of the geographical area of the zones, and covers 55, 42, and 36% of the geographical area of Zones 1, 2, and 3, respectively.

Zone 1 had predominantly paddy (CI=30% of A_G) and chickpea near the main canals while cotton and chickpea dominated towards the tail ends of the major canals in Zone 1. The total CIs in Zone 1 calculated from census data were 49 and 26% during the surplus (2000–2001) and deficit (2002–2003) years, respectively (Table 5). The reduction in CI was primarily due to a decrease in paddy area from 30 to 11% of the area of Zone 1. Though the cropping intensities interpreted by MODIS were larger than reported in municipality level census data (Tables 5 and 6), the relative comparisons indicated similar trends in Zone 1. The relative difference between cropping intensities during reference and deficit years was similar and indicated that almost half of the cropped area was left fallow (Tables 5 and 6). The MODIS images indicated that farmers shifted from a double to a single rice crop (late paddy), rainfed grains, or fallow during the deficit year (Fig. 6).

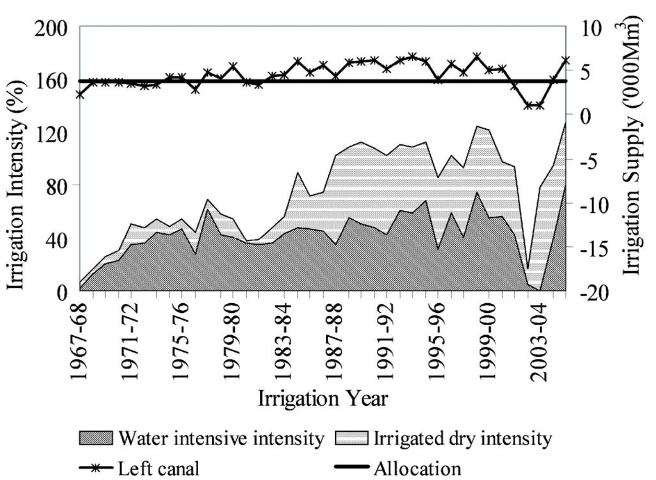

Fig. 4. Annual irrigation intensity in left canal command. During years 2002–2004, rainfed crops have been assumed as irrigated dry crops.

Zone 2 had mainly paddy (25%), cotton (10%), grains (4.5%), and chili (3%) during the water surplus year, 2000–2001. The WI and ID cropping accounted for similar areas in 2000–2001 (Table 5). Similar to Zone 1, the water scarcity impacted the paddy crop which decreased from 25% in a surplus year to 9% in a deficit year. Part of the paddy was replaced by ID crops toward the head reach of major canals (Fig. 5). The overall CI decreased from 56% in the surplus year to 38% in the deficit year (Table 5) due to a decrease in paddy. Due to water scarcity, one third of the cropped area was left fallow by the farmers.

The MODIS classification indicated a similar decrease in the WI cropped area but an increase in the area of ID crops. In contrast to the census data, the MODIS classification demonstrated no significant change in total cropping intensity (Table 6) of Zone 2 from the surplus to the deficit year. This is likely due to some shrub lands and grasslands being classified as ID cropped areas. Census data suggest that a groundwater irrigated area increased from 14 to 17% during the water deficit year but the tank irrigated area decreased from 13 to 6% of A_G (Table 1). The shift to groundwater irrigation suggests that Zone 2 farmers are already used to uncertainty in irrigation supplies and have alternative water sources to irrigate ID crops. By contrast, the groundwater irrigated area did not change in Zone 1, suggesting that farmers there may not have installed wells for use during deficit years. Zone 2 farmers were better equipped with alternative sources and crop choices than Zone 1 farmers and were able to respond to water scarcity by shifting the cropping pattern according to canal flow and rainfall availability. A considerable area shifted from WI to ID crops between 2000–2001 (surplus) and 2002–2003 (deficit year, Figs. 5 and 6).

Zone 3 had a total CI of 60% in the normal year, predominantly paddy (18%), mangoes (12%), cotton (7%), chickpea (10%), sugarcane (2%), and turmeric etc. Although Zone 3 does not have water allocation for WI crops, the WI crops, paddy, and sugarcane are grown at the head of major canals or next to the tanks and on the bank of the Krishna river or close to Krishna Delta command (Figs. 5 and 6). The proportion of area of ID crops decreased significantly from 41 to 28% due to no cotton during the deficit year. A similar trend in the ID cropped area was

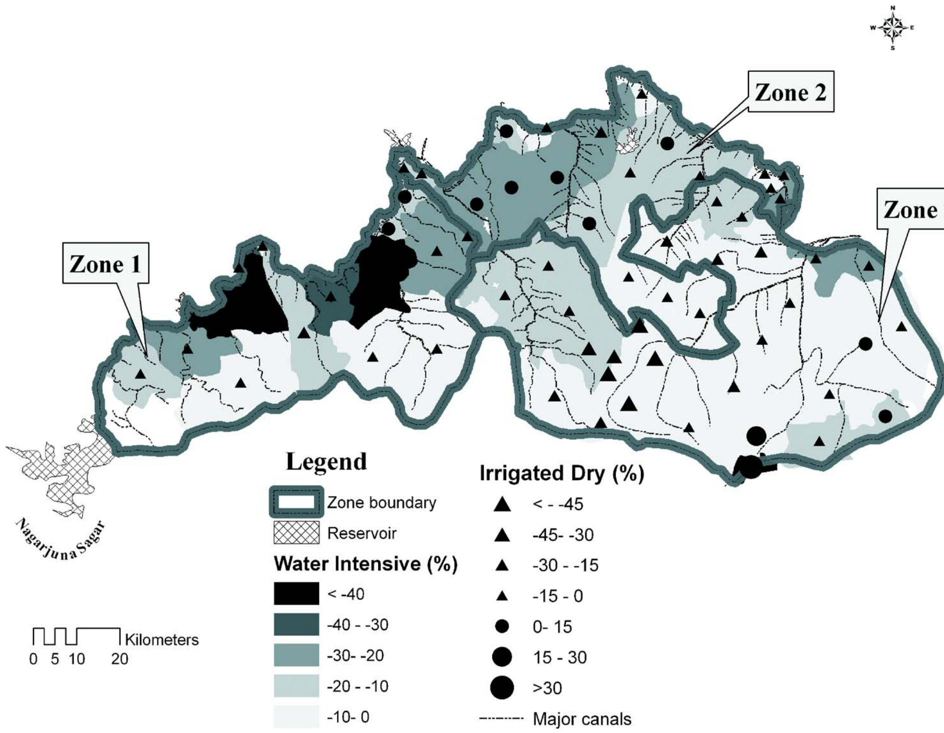

Fig. 5. Change in annual cropping intensity (census) from 2000–2001 to 2002–2003 in three zones of Nagarjuna Sagar left canal command

observed by MODIS away from canals. The cropping intensity of WI crops in Zone 3 declined from 18 to 12% during the deficit year. There were no major changes in total canal supply during water surplus and deficit years and the cropping changes were more likely due to lower rainfall (Table 3) than changes in canal water supply from NSLC. Another dominant crop, mangoes, did not show any change, as it is primarily dependent on rainfall and groundwater and does not respond to annual water supply fluctuations unless drought is severe enough to kill the trees. In contrast to census data, MODIS data showed an increase in the WI cropped area. This reverse trend can be attributed to mixing of orchard, paddy, and other vegetation within one 500 m^2 MODIS pixel.

Both MODIS and census statistics indicated a large impact of irrigation supplies on land use: primarily a decline in the WI cropped area in Zones 1 and 2. MODIS identified areas with changes and delays in the WI cropped area, which is critical in assessing the impact of canal operations. The WI cropped area was more concentrated at the head of each major canal or closer to tanks and balance reservoirs in Zones 2 and 3. Zone 1 had relatively large WI cropped areas (60% of total cropped area in a surplus year) therefore shift from WI cropping to fallow was the largest in Zone 1 due to variability in canal supplies and low precipitation. Large canals operated more frequently and supplied more water than small major canals taking off from the main canal. All the performance parameters documented in our study indicated that the major impact fell on Zone 1 and less on Zone 2. Zone 3 is less dependent on canal flows and is more governed by rainfall patterns and secondary or local sources.

Summary and Conclusions

Continued rapid development of surface and groundwater throughout the Krishna Basin in southern India resulted in histori-

Table 5. Cropping Intensities (CI) by Zone from Municipality-Level Agricultural Statistics

Water year	Crop	Zone 1	Zone 2	Zone 3	Left main canal command
Geographical area (ha)		276,990	219,815	421,012	917,817
Reference year[a]	Water intensive	30	28	18	24
	Irrigated dry/rainfed	19	28	41	31
	Total	49	56	60	56
Deficit year (2002–2003)	Water intensive	11	11	12	11
	Irrigated dry/rainfed	15	27	28	24
	Total	26	38	40	35
Change (deficit-reference)	Water intensive	–20	–17	–6	–13
	Irrigated dry/rainfed	–3	–1	–14	–8
	Total	–23	–18	–20	–20

[a]2001–2002 for Zone 1 and 2000–2001 for Zones 2 and 3.

Table 6. Zone Wise Cropping Intensity Interpreted by MODIS Images

Parameters	Crop type	Zone 1	Zone 2	Zone 3	Main canal command
Geographical area (ha)	—	276,990	219,815	421,012	917,817
Surplus year (2000–2001)	Water intensive	46	48	30	39
	Irrigated dry/rainfed	42	44	68	54
	Total	87	92	98	93
Normal year (2001–2002)	Water intensive	46	56	26	39
	Irrigated dry/rainfed	45	60	64	57
	Total	91	117	90	97
Deficit year (2002–2003)	Water intensive	27	37	33	32
	Irrigated dry/rainfed	34	58	48	46
	Total	61	96	80	78
Change (deficit-reference year)[a]	Water intensive	*−19*	*−11*	*3*	*−7*
	Irrigated dry/rainfed	*−10*	*14*	*−20*	*−8*
	Total	*−29*	*4*	*−17*	*−15*

Note: Numbers indicate percentage of geographical area of each zone in each crop type.

[a]Reference year is 2001–2002 for Zone 1 and 2000–2001 for Zones 2 and 3.

cally low inflows during a recent drought event, particularly in lower Krishna reservoirs. The study demonstrates how data on canal flows, census data on cropped areas, and satellite imagery can be used to document spatial variations in water supply and its consequences for land use in a large irrigated command area in the lower Krishna basin. The integrated approach was used to assess changes in the spatial equity of canal flow and land use with water supply shocks in the head, middle, and tail reaches of the left main canal command (359,200 ha) of Nagarjuna Sagar during water surplus (2000–2001), normal (2001–2002), and deficit (2002–2003) years. In normal and surplus years, the water distribution was highly inequitable with very large flows in the head zone (1,722 Mm^3) and very low flows (198 Mm^3) in tail reaches. During surplus and normal years, 33–40% (1,990 Mm^3) of water supplied from the head regulator of the main canal was lost through the canal distribution network, which reduced to 17% during the deficit year. Contrary to expectation (and hypothesis), the spatial distribution of canal flows among the three major zones of the command area was more equitable during the low-flow year. This was due to decreased flow in the headreach of the canal and less canal distribution losses, which reduced the skewed water use of normal and surplus years. During the water deficit year, a 60% reduction in water availability resulted in 40% of the cropped area being fallowed in the left canal command. MODIS images identified areas impacted by low canal releases and showed a widespread shift from double to single cropping, particularly in the head and middle zones during the deficit year; from normal sowing paddy variety to late sowing paddy variety and to rainfed crops or fallow. The head reach of the command (Zone 1) had larger spatial and temporal variability in canal sup-

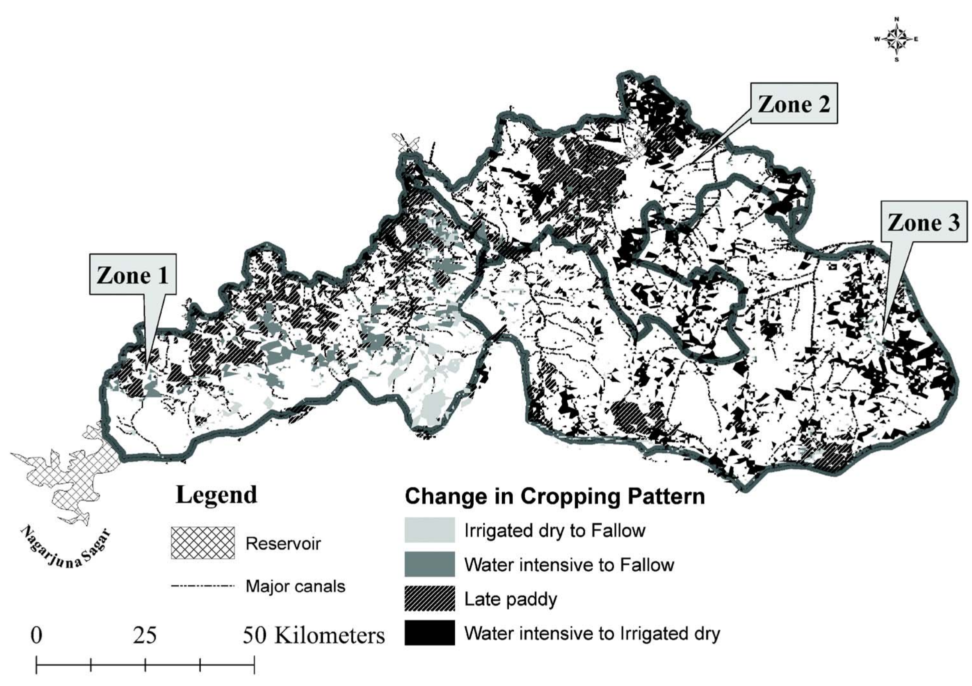

Fig. 6. Change in cropping pattern interpreted by MODIS images during surplus (2000–2001) and deficit (2002–2003) years

plies and land use than Zone 2 (middle) and Zone 3 (tailend). Historically, Zone 3 had chronically low water supply, designed for irrigated dry (ID) crops only, so farmers depended more on precipitation and local water sources than on the canal flows, while Zone 1 and 2 farmers depend heavily on canal flows for WI crops and were highly affected by canal flow shortages.

The study identified areas susceptible to decreases in water supply that could help in decision-making processes for equitable water allocation and distribution. The findings primarily suggested improving the water distribution efficiency of the irrigation network during normal years and conjunctive water use and crop diversification during water shortage years. The large impact of canal flows on cropping patterns in head reaches suggests that adaptive strategies for water scarcity need to be developed to supplement canal flows during times of shortage. Recent field surveys and anecdotal evidence suggests that some head reach farmers have now developed alternative plans, which was evident in 2003–2004 when they switched to irrigated dry crops and now some have developed shallow wells and bores. However, a better understanding of the surface-groundwater interaction is required, since groundwater levels are highly responsive to canal flows.

The equitable allocations can be evolved to share water shortage through diversification in cropping pattern supported by economical incentives. However, further investigation is needed to maximize the productivity and value of these alternatives, which currently compare very poorly with rice and sugarcane cultivation. Anticipation of these changes could help irrigation departments to develop extension strategies designed to meet farmer needs under fluctuating water supply, and help farmers more rapidly adapt to both chronic and episodic shocks in canal supplies. For example, in 2002–2003, farmers planted paddy in anticipation of water supply despite warnings of shortage by the irrigation department.

Other, additional water stressors for the area are also noted. The upstream reservoir, Srisailam irrigation command, and increase in domestic and industrial water supply may further impact water supply during water deficit years. More initiatives are required to allow a measured and planned response in water short years, including use of tools to predict rainfall and excess runoff in the key (upper) part of the basin such as ENSO type procedures; predictive allocation announcement based on likely water availability and mechanism for real-time integrated operation of reservoirs in lower Krishna in response to return flows or improved efficiency; and formal consultative procedures between users and the irrigation department concerning actual allocation and availability. Similar changes in water supply and cropping pattern may occur in other large irrigation systems located in basins experiencing water shortages from drought and upstream development. Future work could investigate the relationship between water shortages and crop yield, and agricultural production and farmer incomes in both the Nagarjuna Sagar command area and other large irrigated systems in downstream reaches of large river basins. The lessons learnt from the study could be used in other major irrigated projects experiencing water supply shocks and inequitable distribution.

Appendix

Canals: Nagarjuna Sagar Left Canal: NSLC, Nagarjuna Sagar Right Canal: NSRC.

Crop classes—water intensive (WI) crops: paddy, vegetables, and sugarcane; irrigated dry (ID) crops (with supplementary irrigation): cotton, chili, grains, orchard, wheat, spices.

Crop intensities—I: irrigation intensity; CI: cropping intensity.

Cropping seasons—Monsoon season: June–October; Postmonsoon season: November–February; Summer season: March–May.

Irrigation or water year: June–May.

ICAD: Irrigation and command area development:

Lift irrigation: systems where water is pumped from a surface source into a gravity canal network for delivery to the fields at higher elevations (out of command).

Nagarjuna Sagar reservoir: NJS.

Census data: In the manuscript, it refers to the data for cropped area collected by the Government agencies at a scale of municipal boundaries ranging from village to district.

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