RESEARCH REPORT

111

Closing of the Krishna Basin: Irrigation, Streamflow Depletion and Macroscale Hydrology

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International Water Management Institute

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/ river basins / stream flow / hydrology / wetlands / water management / runoff / water allocation / precipitation / rain / water balance / water supply / irrigated farming / environmental effects / water quality / salinity / India / Krishna river /

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Cover Photographs by Trent Biggs show:

- Nagarjuna Sagar Dam on the Krishna River (top left)
- Left bank canal, Nagarjuna Sagar Irrigation Project (top right)
- Worshipers on the banks of the Krishna River at Vijayawada (bottom left)
- Krishna River at Vijayawada (bottom right)

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Contents

Summary

This paper summarizes research on the Krishna River Basin in southern India, including physical and agricultural geography, remote sensing, hydrology, water management, and environmental issues. Discharge from the Krishna into the ocean decreased rapidly from 1960-2003 due to irrigation expansion. Annual runoff to the ocean fell from a pre-irrigation average of 56 cubic kilometers (km^3)(1901-1960) to 13 km^3 (1994-2003), despite no significant change in rainfall. By the late 1990s, the cumulative reservoir capacity in the basin approximated the annual runoff volume. Distributed runoff data shows that this closure happened not only in downstream reaches, but also in upstream tributaries. The basin closure has resulted in interstate disputes over water and an increased need for basin-scale water resources assessment and modeling.

A simple water balance model that uses only the ratio of precipitation to potential evaporation explains 74 percent of the variability in runoff coefficients over the basin, and suggests that the basin has two distinct hydrological regions; the Western Ghats, with high runoff coefficients, and the central and eastern basin, which have low runoff coefficients. The basin has eight hydronomic zones, including water source areas in the Western Ghats, rainfed ecosystems, and a variety of irrigated areas including primary, secondary, tertiary, groundwater, and future irrigated areas. The Western Ghats occupy only 9.5 percent of the basin area, but receive 21 percent of the basin's rainfall and produce 57 percent of the basin's surface runoff due to both high rainfall and high runoff coefficients. Runoff coefficients are low (<10%) for much of the basin due to naturally high evaporative demand and low precipitation. The Western Ghats have high runoff coefficients compared with other rivers in the world with similar climate, likely due to both thin soils and the intensity of precipitation during the monsoon.

A water account of the basin based on agricultural census data, modeled evapotranspiration, and measured basin rainfall and discharge, suggests that evaporation from rainfed ecosystems consumes more water than all agricultural lands combined. Rainfed agriculture consumes more water than irrigated agriculture, but this is based on the assumption that soil moisture does not limit evapotranspiration in rainfed areas. More than 50 percent of the basin's irrigated area is supplied by small tanks and groundwater, which are not currently included in the allocations to the three states. Neglect of this important irrigation sector and its impact on the basin water balance could result in unanticipated shortages of inflow to irrigated projects downstream. Additional water use by other sectors, including urban water demands, are currently a small fraction of total basin water use (<1%), but are potentially important in drought years and during critical irrigation months.

Basin closure, combined with the pending renegotiation of water allocation among the three states that share the basin, has resulted in disputes over the remaining water resources. One consequence of the political and legal dispute is a lack of data availability and transparency, particularly for streamflow, canal flow, and groundwater levels. The restrictions on data access remain a key constraint to further research and planning for water resources in the basin.

Closing of the Krishna Basin: Irrigation, Streamflow Depletion and Macroscale Hydrology

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Introduction: Basin Approach to Hydrology and Agricultural Production

Food production increased markedly in many parts of the world during the twentieth century (Dyson 1999). In India, the rate of growth of food production surpassed the rate of population growth, resulting in increased food per capita, though significant problems of malnutrition and distribution remain (Hopper 1999). Increased food production has required rapid expansion of irrigated area and water diversion to agriculture, which has resulted in groundwater overdraft (Shah et al. 2003; Singh and Singh 2002) and streamflow depletion in some basins (Vörösmarty and Sahagian 2000). Water scarcity resulting from basin closure has numerous implications for water management, including increased competition and an imperative to improve water productivity in order to maintain growth in the agricultural economy (Keller et al. 1998; Molle 2003; Wallace 2000). Basin closure also occurs in the context of global climate change, which may impact water availability and introduce additional uncertainties (Mehrotra 1999).

Water resources analysis in regions experiencing closure should be carried out in a basin context, because uses in one area affect water availability in downstream areas (Molden et al. 2003). The Krishna Basin in southern India is one example of a basin closing to future water resources development following the rapid expansion of irrigated agriculture. The International Water Management Institute (IWMI) has selected the Krishna Basin as a benchmark basin for intensive, continuing studies of basin-scale water management under increasing water scarcity, based primarily on the criteria of basin closure coupled with imminent revisions to basin water allocations. The Krishna Basin is shared by three Indian states (Andhra Pradesh, Maharashtra, and Karnataka), and increasing water scarcity has resulted in water competition among them. A basin tribunal, which resolves interstate water disputes and makes legally enforceable water allocation decisions, was reconstituted in 2004 to revise the allocation decisions made by the first tribunal in 1976. The pending reallocation has resulted in competing claims by each state about the appropriate allocation award, and represents an opportunity for third-party review of allocation rules.

This document summarizes the physical geography, agriculture, land use, hydrology, and environmental issues of the Krishna Basin. Emphasis is placed on the hydrology and irrigation. A map of hydronomic zones is presented using land use derived from satellite imagery (Moderate Resolution Imaging Spectroradiometer - MODIS) and ancillary maps of irrigated command areas. A macroscale hydrological model of the annual water balance that uses only the ratio of precipitation and potential evapotranspiration is parameterized for the basin. The macroscale model is then combined with the hydronomic zones map, which points to the importance of the Western Ghats mountains for runoff generation, and documents low runoff coefficients (<0.10) in a majority of the basin area. A water account based on cropped area is combined with the hydronomic zones, and points to the importance of rainfed ecosystems for the basin water balance. Additional research projects by the International Water Management Institute in the Krishna Basin are included in Appendix 1.

Physical Geography and Climate

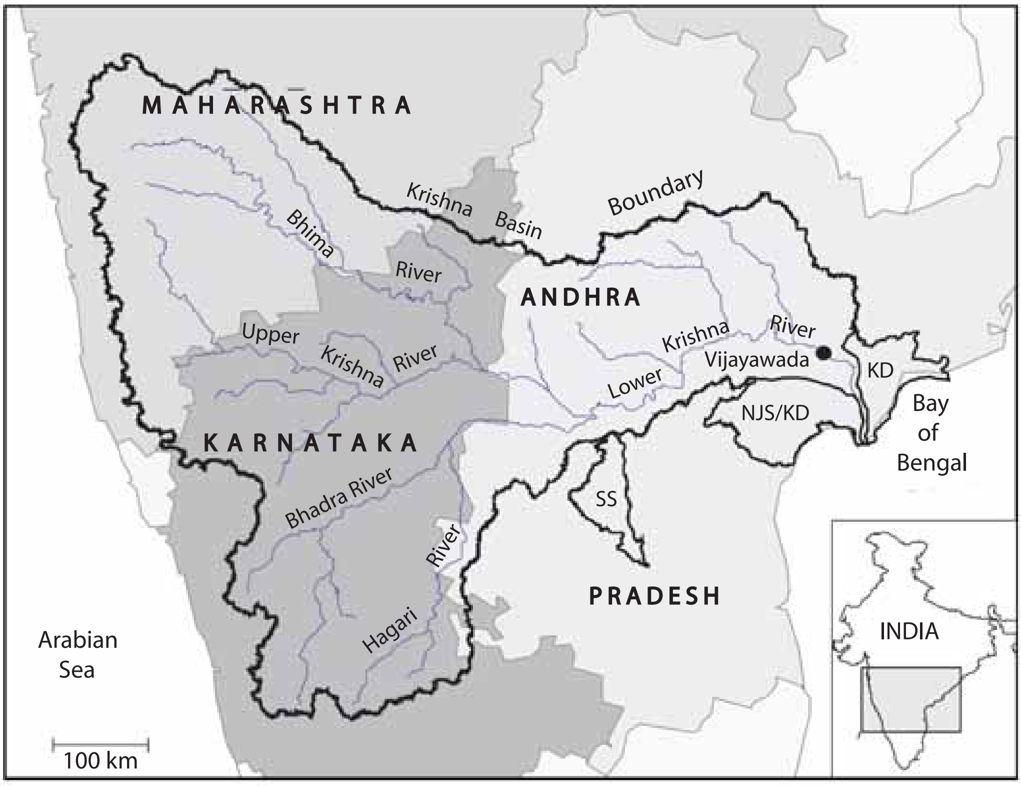
The Krishna River Basin is the fifth largest river system in India in terms of annual discharge and drainage area (Table 1; Figure 1). The basin covers parts of three South Indian states: Karnataka, Andhra Pradesh, and Maharashtra. The river originates as the Upper Krishna River in the Western Ghats of Maharashtra and Karnataka, drains the Deccan Plateau, and discharges into the Bay of Bengal. The main stem of the Krishna River has two major

TABLE 1.
Rivers in India, ranked by annual discharge volume.

Rank	Name	Discharge (km^3/year)	Drainage Area (km^2)
1	Brahmaputra	629	194,413
2	Ganges	525	861,452
3	Godavari	110.5	312,812
4	Indus (to the border of Pakistan)	73.3	321,289
5	Krishna	69.8	258,948

Source: Kumar et al. 2005

FIGURE 1.
Location map of the Krishna Basin. Areas labelled NJS/KD, KD and SS are command areas outside the topographic basin boundary.



Notes: NJS = Nagarjuna Sagar, KD = Krishna Delta, SS = Srisailam.

tributaries, the Bhima River from the north and the Tungabhadra River from the south (Figure 1). Most of the basin is relatively flat (Figure 2a) and 90 percent lies below 750 meters (m) elevation, though elevations in the Western Ghats reach up to 1,900 m (Figure 2b). The basin has been divided into twelve sub-basins for water resources analysis by the National Water Development Agency of India (NWDA)(Figure 3).

The basin has a topographic boundary defined by the area that receives runoff, and a command-area boundary, which includes areas outside of the topographic boundary that receive water from canals that cross the topographic boundary (Figure 1). The irrigated area outside the topographic boundary may be considered to be part of other basins, so water transported to it may be considered an inter-basin transfer; here

FIGURE 2.
(a) Topography of the Krishna Basin. Digital elevation model from the Shuttle Radar Topography Mission (90 m grid resolution); (b) Cumulative area by elevation.

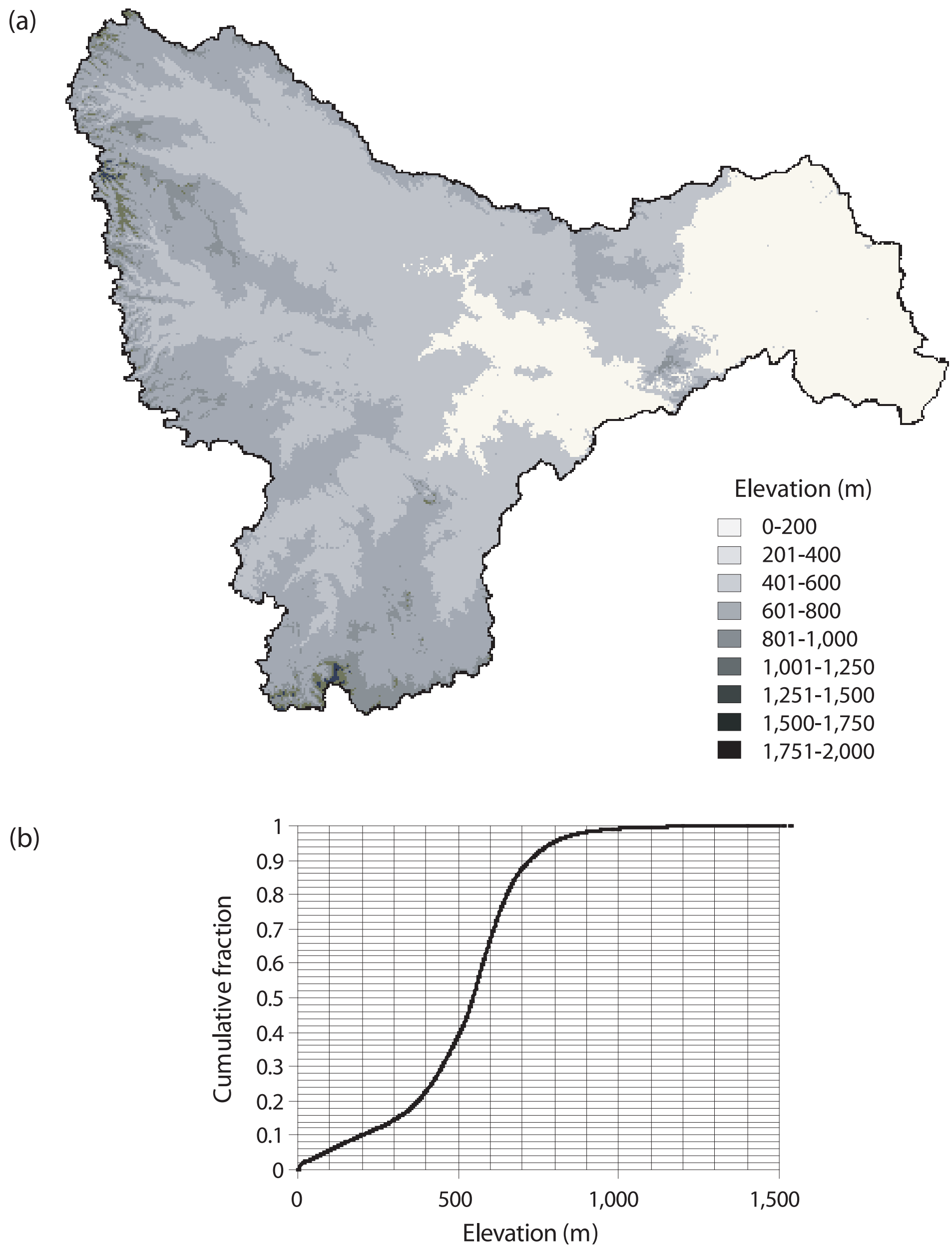
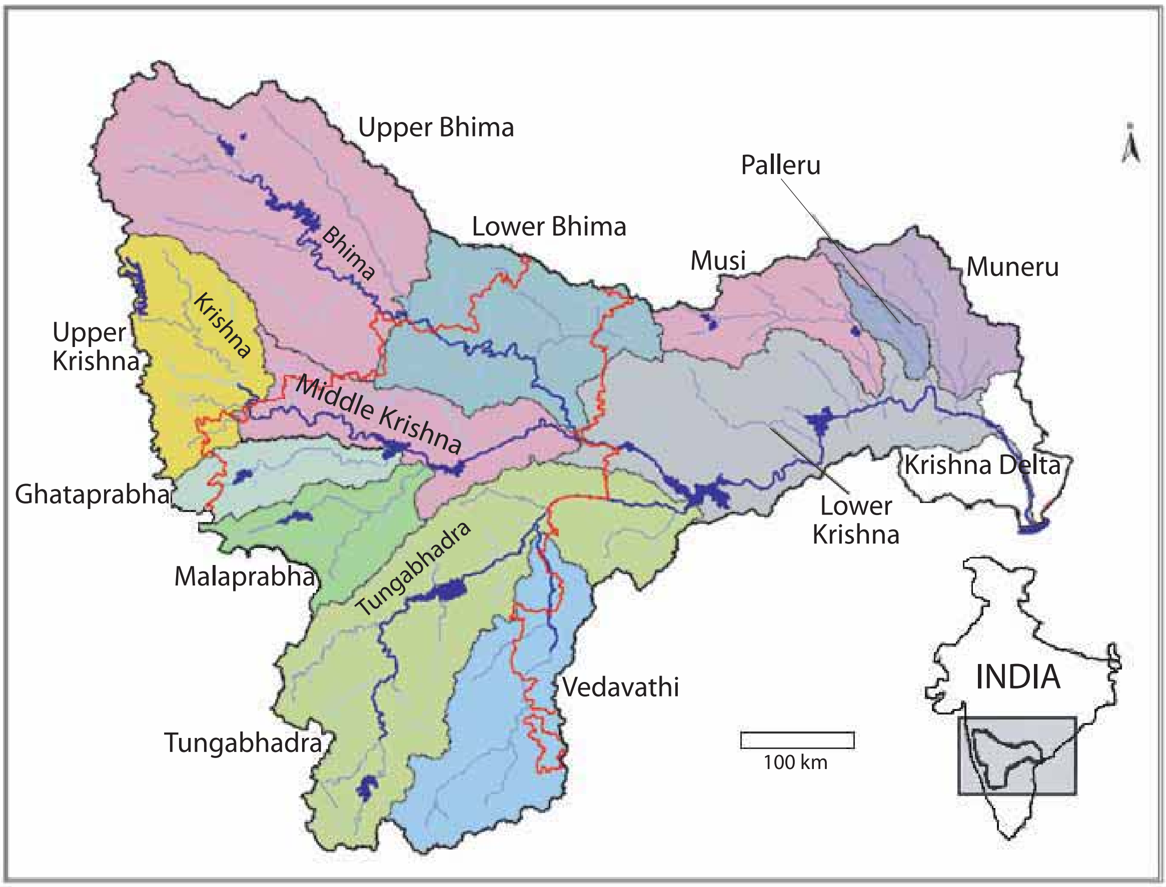


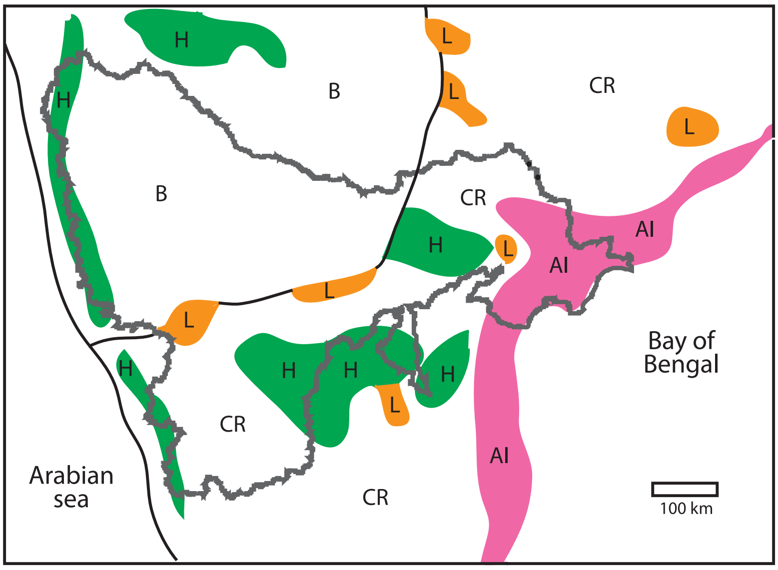
FIGURE 3.
Major sub-basins of the Krishna Basin.



we consider irrigated command areas outside of the topographic boundary to be part of the basin. The area within the topographic boundary was delineated using the digital elevation model (DEM) from the Shuttle Radar Topography Mission (SRTM). It has an area of 258,514 square kilometers (km^2), and is most appropriate for rainfall-runoff analysis. The irrigated command areas outside of the topographic boundary receive water from the Krishna River but do not contribute to runoff to the Krishna River, and hence should not be included in basin-scale analyses of rainfall-runoff relationships. The command-area boundary is more difficult to define than the topographic boundary due to patchy cropping patterns, multiple water sources, and different phases of command area development. The Nagarjuna Sagar and Krishna Delta canals carry water outside of the topographic boundary, increasing the effective basin area to 272,935 km^2. The command-area boundary in the eastern portion of the Krishna Delta is ill-defined, since canals from the Godavari River to the north connect with those from the Krishna River, making the command-area boundary between the Krishna and Godavari dynamic, overlapping, and dependent upon canal releases. Current canal construction for the Telugu Ganga Project at the Neelam Sanjeeva Reddy Dam could extend the effective basin boundary further to 277,226 km^2. One canal provides water to the city of Chennai, which is not considered a part of the basin boundary for this analysis. A large wetland in the northeastern Krishna Delta also has an uncertain hydrologic relationship with water from the Krishna River and canal system, so the boundary of the basin vis-à-vis the wetland is uncertain.

Most of the Krishna Basin lies on crystalline and basaltic rocks that have low groundwater potential, particularly compared with the relatively high-yielding aquifers that occur on

FIGURE 4.
Hydrogeologic map of southern India and the Krishna Basin.



Code	Aquifer system	Yield potential (l/s)
Al	Alluvium	0-40
L	Limestone	5-25
CR	Crystalline rock	1-40
B	Basalt	1-25
H	Hills	<1

Modified from Central Ground Water Board
http://www.cgwber.nic.in/cgwa_profile.htm

deep alluvium of the Indo-Gangetic Plain to the north (Figure 4). The Cretaceous igneous basalts and Precambrian granitic gneiss that underlie most of the basin create hard-rock aquifers that have low porosities and low hydraulic conductivities. The Krishna Delta occurs on deep alluvial sediments that have aquifers with higher potential. Soils in the basin are generally shallow (Figure 5a) and clayey, with some areas of gravelly clay and loam (Figure 5b). Soil types (based on the Soil Taxonomy classification system, NRCS 1999) include Entisols and Vertisols (black cotton soils) in the west and Alfisols (red soils) in the south and east. Soils tend to be deeper in valley bottoms, and are deeper on average in Andhra Pradesh.

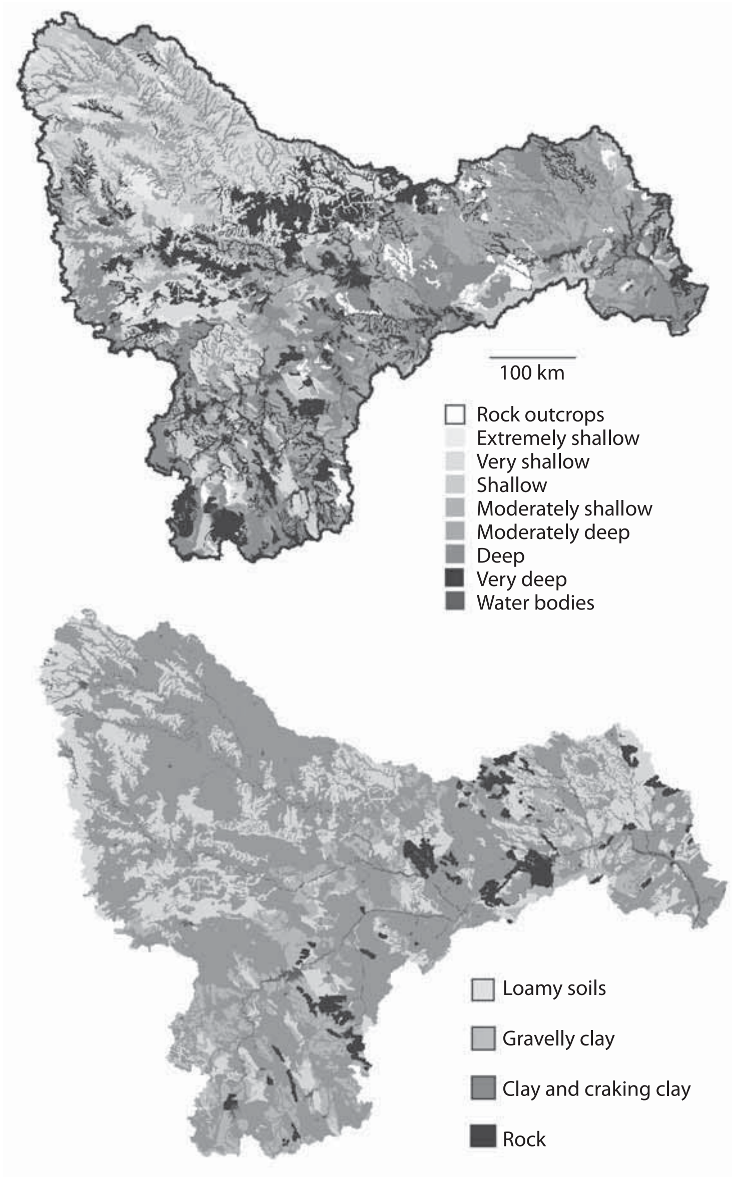
Four monthly rainfall datasets are available for the basin. First, gridded data from the IWMI Climate Atlas is available from 1961-1990 at 0.17 degree resolution (Figure 6a, http://www.iwmi.org, access date September 17, 2006). Second, the global dataset from the Climate Research Unit (CRU) of the University of East Anglia (New et al. 2000) has data available from 1900-2000 at 0.5 degree resolution (Figure 6b). Third, meteorological stations from the Indian Meteorological Department (IMD) have point data at 26 locations, with variable coverage from 1945-2000 (Figure 7). Fourth, the Indian Institute of Tropical Meteorology (IITM) provides precipitation estimates by subdivisions of India from 1871-2006, and makes annual and seasonal forecasts (Figure 7; http://www.tropmet.res.in/, access date September 17, 2006). The IITM data is derived from the IMD meteorological station data and should therefore be similar to the IMD data.

Annual rainfall differs significantly between the two gridded datasets (IWMI Climate Atlas and CRU), particularly in the northwest corner of the basin (Figure 6). The CRU dataset matches the IMD meteorological station data better than the IWMI Climate Atlas from 1961-1990, which

FIGURE 5.
(a) Soil depth; and (b) Soil texture in the Krishna Basin, from 1:500:000 scale maps.

(a)

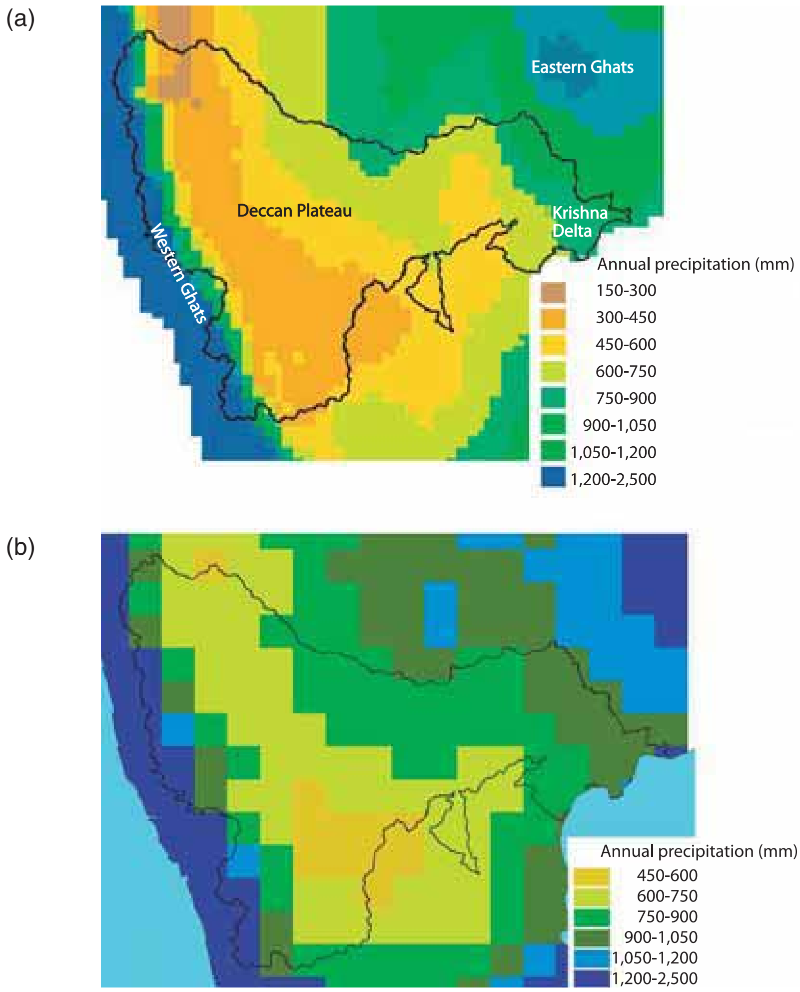
(b)



is the period included in the IWMI Climate Atlas (Figure 8). The CRU dataset has a lower mean bias (+25 millimeters (mm)) and lower root mean square error (RMSE, 82 mm) than the IWMI Climate Atlas (bias -145 mm and RMSE 224 mm). The reasons for the differences among the datasets are not known, but it is suggested that the CRU dataset be used for rainfall runoff modeling given its spatial resolution and agreement with the IMD data. The IITM data are more difficult to compare with the IMD point data; later in the report we compare rainfall-runoff relationships for the CRU and IITM datasets.

The two arms of the monsoon embrace the Indian subcontinent on both sides, the southwest monsoon from the Arabian Sea and the northeast monsoon from the Bay of Bengal. Rain out of atmospheric water during transport inland causes precipitation in the Krishna Basin to decrease with distance inland from both coasts, most dramatically east of the Western Ghats, where precipitation decreases from over 3,000 mm to approximately 500 mm over a distance of 80

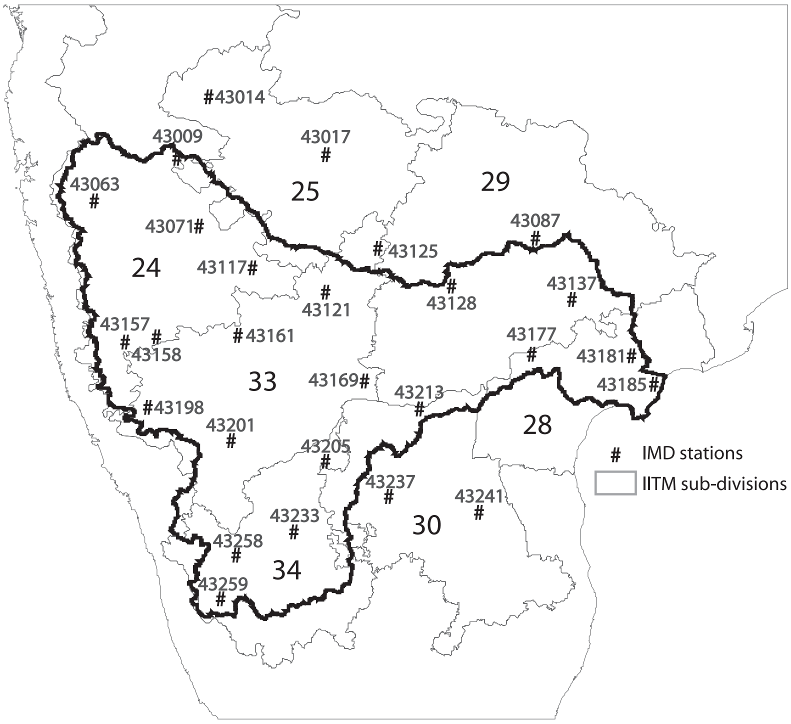
FIGURE 6.
Precipitation for the Krishna Basin from (a) the IWMI Climate Atlas; and (b) the CRU grid.



kilometers (km) (Gunnel 1997). Precipitation decreases more gradually from 850-1,000 mm in the Krishna Delta in the east to 500-600 mm in the northwestern part of the basin. The average rainfall in the basin is 840 mm, approximately 90 percent of which occurs during the monsoon from May to October (Figure 9).

The climate of the basin, as quantified by the aridity index (potential evaporation divided by precipitation), is dominantly semi-arid with some dry, sub-humid areas in the Krishna Delta, Western Ghats, and Eastern Ghats, and a narrow humid band in the Western Ghats (Figure 10). The potential evaporation (E_p) data used to calculate the aridity index and the climate classification scheme are from the United Nations Environment Programme (Ahn and Tateishi 1994). The climate classification has three subdivisions of the semi-arid category (Deichmann and Eklundh 1991). E_p exceeds precipitation in all but three months of the year during the peak of the monsoon (Figure 9), highlighting the need for irrigation during the non-monsoon seasons.

FIGURE 7.
Meteorological stations from the Indian Meteorological Department (IMD), and subdivisions of the Indian Institute for Tropical Meteorology.



Note: The large bold numbers indicate the IITM subdivision codes, which correspond to:

24 - Madhya Maharashtra, 25 – Marathwada, 28 - Coastal Andhra, 29 – Telangana, 30 – Rayalaseema, 33 - N. Interior Karnataka, and 34 - S. Interior Karnataka

FIGURE 8.
Comparison of annual rainfall from meteorological stations (IMD) and interpolated grids from the IWMI Climate Atlas and CRU rainfall dataset, 1961-1990. The dashed line is the 1:1 line.

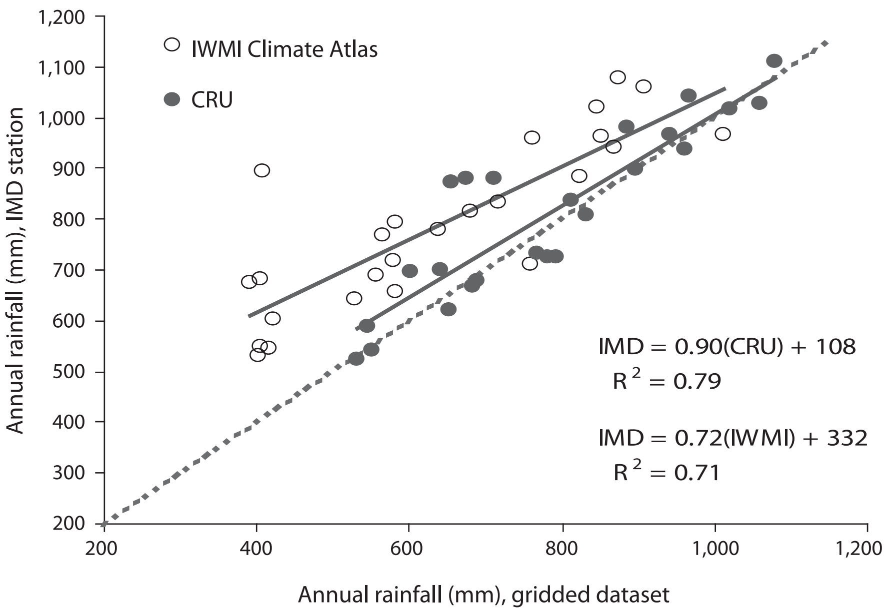


FIGURE 9.
Rainfall and potential evapotranspiration in the Krishna River Basin above Vijayawada station, with the dry and cropping seasons.

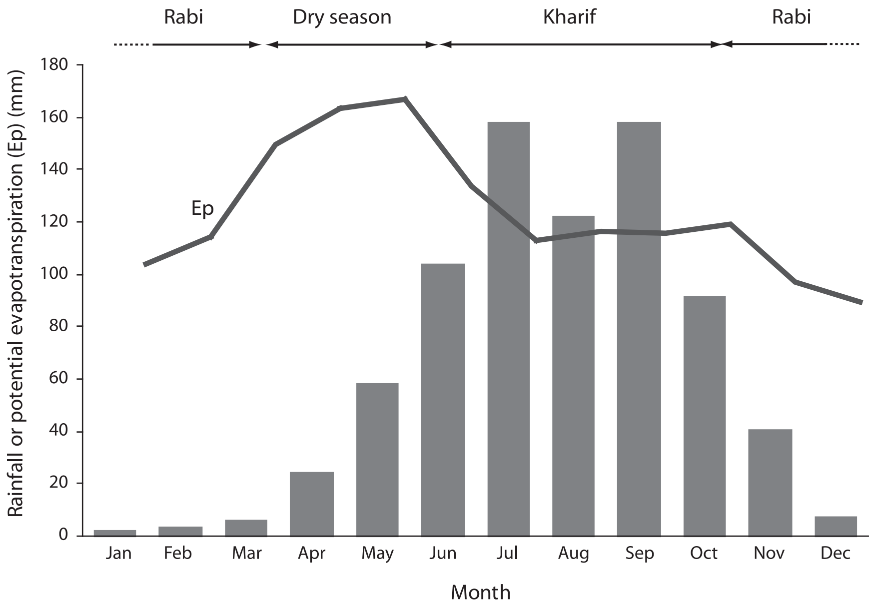
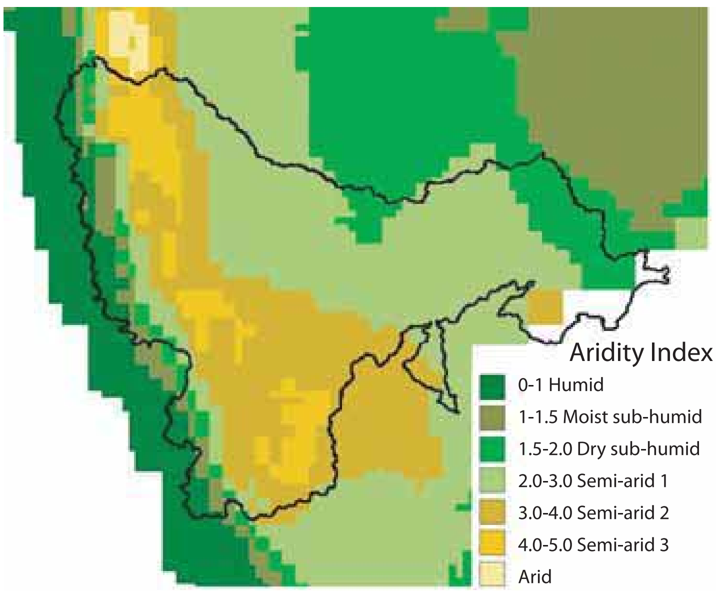


FIGURE 10.
Aridity index map of the Krishna Basin. The rainfall data was from the IWMI Climate Atlas, and potential evaporation was from UNEP.



Sources: Ep data: Ahn and Tateishi 1994; Precipitation data from the IWMI Climate Atlas.

Agriculture and Population

All three states that overlap the basin have diverse cropping patterns (Neena 1998) including rice, jowar (sorghum), corn, sugarcane, millet, groundnut, grass fodder, and a variety of horticultural crops. Based on the Agricultural Census of 1998, the basin has five cropping regions (Figure 11): (1) Rice-grains and cash crops in the eastern basin, including the Krishna Delta, Nagarjuna Sagar command area and groundwater irrigated areas; (2) Grains-rice-sugar dominate in the northwest. Most rice-sugarcane irrigation occurs in command areas at the base of the Western Ghats; (3) Grains-rice-oilseeds in the center and central-south; the Tungabhadra Command Area contains most of the rice production in this part of the basin; (4) Oilseeds-grains in the southwest, with minimal irrigated area; (5) Rainfed rice and cash crops in the Western Ghats. The annual cropping cycle consists of three periods (Figure 9): the *Kharif* or monsoon season (June to October), the *Rabi* or post-monsoon (November to March), and the dry season (April to May). Aquaculture occurs in the delta, especially in the wetlands at the boundary of the Krishna and Godavari deltas. Three major cropping patterns occur in the canal irrigated systems, including double cropping (rice-grains, 4.6% of total basin area of 258,912 km^2), continuous irrigation of long-cycle crops (sugarcane and agroforest, 3.4%), and irrigated dry crops (3.0%) (Figure 12; Table 2). According to both remote sensing and census data, groundwater and minor irrigated areas, which are composed mostly of small irrigated patches (<0.1 km^2) in rice, groundnut, corn, cotton, and horticulture, represent a larger fraction of the basin irrigated area than all major canal irrigated areas combined (Table 2).

Expansion of irrigated areas has changed the basin-average normalized difference vegetation index (NDVI) from 1982-1999 (Figure 13). NDVI increased the most in the Upper Bhima and Upper Krishna, which experienced rapid growth in both groundwater and surface water irrigated area. A detailed analysis of land cover change mapped at 8 km pixels may be found in Thenkabail et al. (2007).

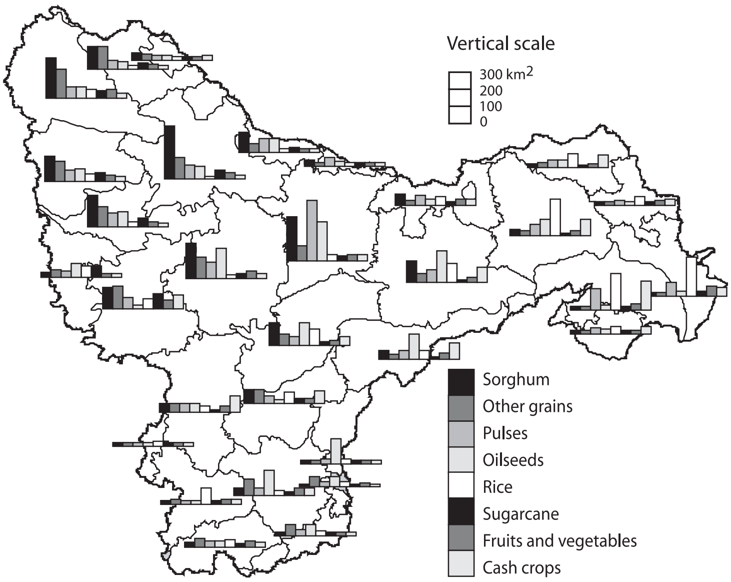
In 2001, the basin contained a total of 67 million people, with 45 million in rural areas (Government of India 2001). The rural population density is highest in the Krishna Delta and central-west Alamatti Basin, and lowest in the center and southwest (Figure 14). Of the twelve major sub-basins, the Musi has the highest total population density due to the large urban center, Hyderabad (~7 million).

Irrigation and Hydronomic Zones

Water has been managed in the Krishna Basin for centuries. Water management originated with the construction of small earthen dams, or tanks (Shiva 1991). In the sixteenth century, the Vijayanagar Empire sponsored the construction of irrigation canals and small reservoirs (tanks) on the Tungabhadra River in Karnataka, and the urban reservoir Hussain Sagar was constructed in Hyderabad.

Beginning with British engineers in the 1850s, the irrigation strategy in southern India has emphasized “light irrigation” of irrigated dry crops like cotton and sorghum, versus “heavy irrigation” of water-intensive crops like rice and sugarcane (Wallach 1984). With the exception of the Krishna Delta, most of the irrigation schemes in the Krishna Basin, including the Tungabhadra, Bhadra, and Nagarjuna Sagar were

FIGURE 11.
Area of major crops in the Krishna Basin by district, and generalized cropping regions.



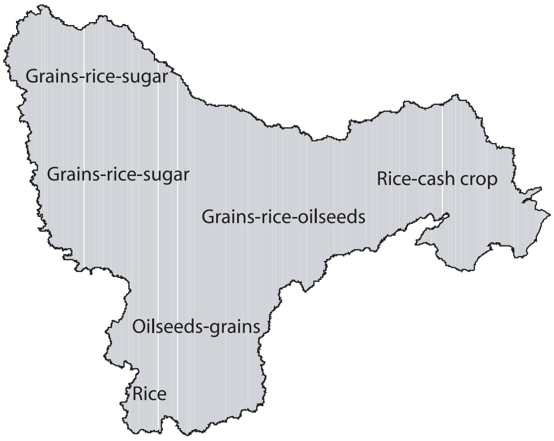


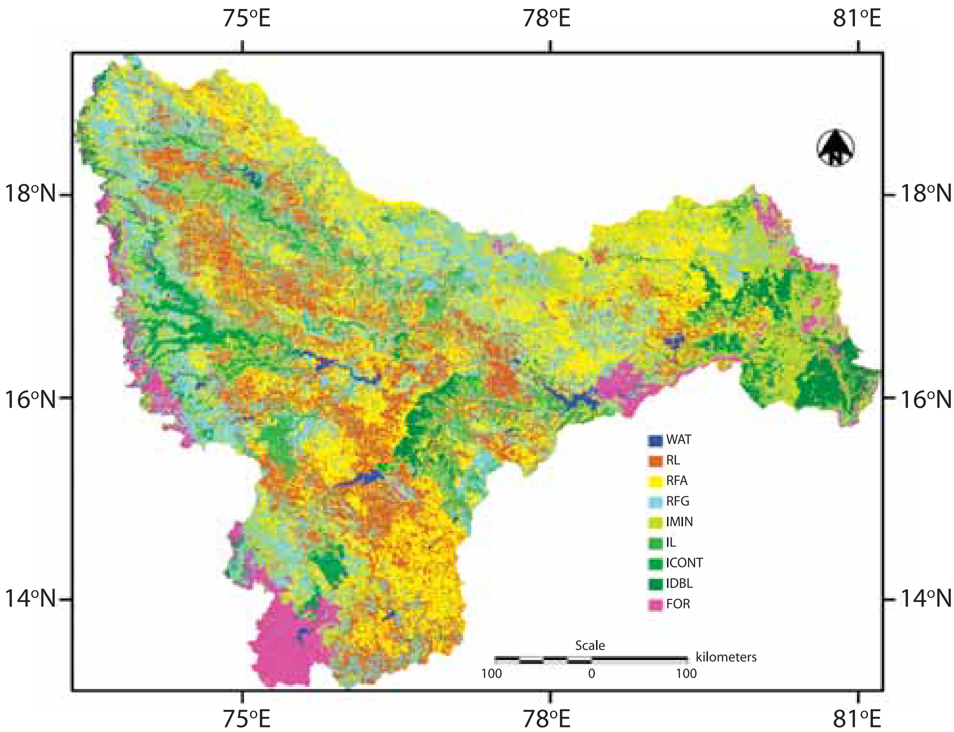
TABLE 2.
Land cover and irrigated area by source in 2002, corresponding to Figure 12, in km². Groundwater and surface water irrigated areas were determined using combined census data and satellite imagery. See Biggs et al. 2006 for discussion of error rates and ranges using different methodology for determining irrigated areas.

Class name	Map code	Total area of class (km²)	Groundwater irrigated	Surface water irrigated	Total irrigated area
Water	WAT	2,508	0	0	0
Rangeland	RL	63,143	0	0	0
Rainfed agriculture	RFA	51,162	0	0	0
Rainfed + groundwater irrigation	RFG	62,944	15,740	0	15,740
Minor irrigation	IMIN	35,788	3,220	0	3,220
Irrigation low NDVI	IL	7,702	0	3,770	3,770
Continuous irrigation (sugarcane)	ICONT	8,600	0	4,390	4,390
Irrigated double crop	IDBL	11,775	0	9,300	9,300
Forest	FOR	15,290	0	0	0
Basin Total		258,912	18,960	17,460	36,420

Source: Biggs et al. 2006

Note: NDVI = normalized difference vegetation index

FIGURE 12.
Land cover map of the Krishna Basin from MODIS, corresponding to the classes in Table 2.



Source: From Biggs et al. 2006.

FIGURE 13.
Change in a vegetation index (NDVI) for two years with similar rainfall (~760 mm), 1999 and 1982. Positive numbers indicate increases in vegetation and biomass.

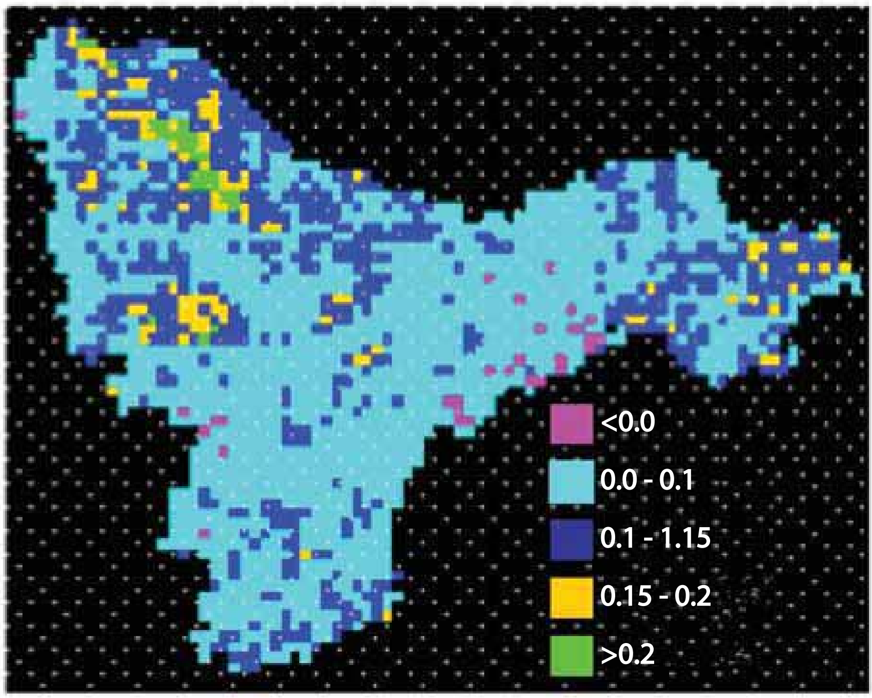
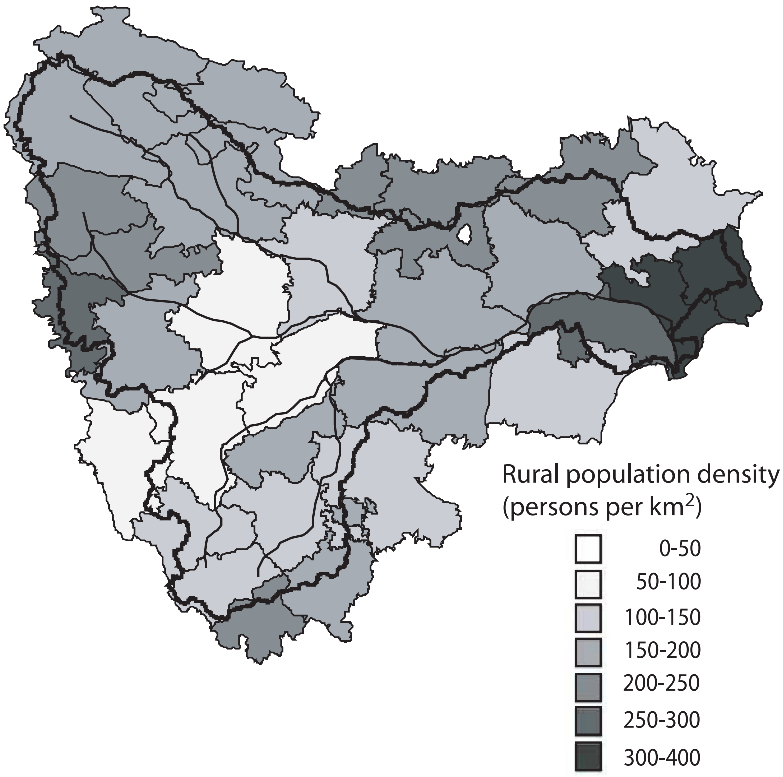


FIGURE 14.
Rural population density in the Krishna Basin, 2000 census.



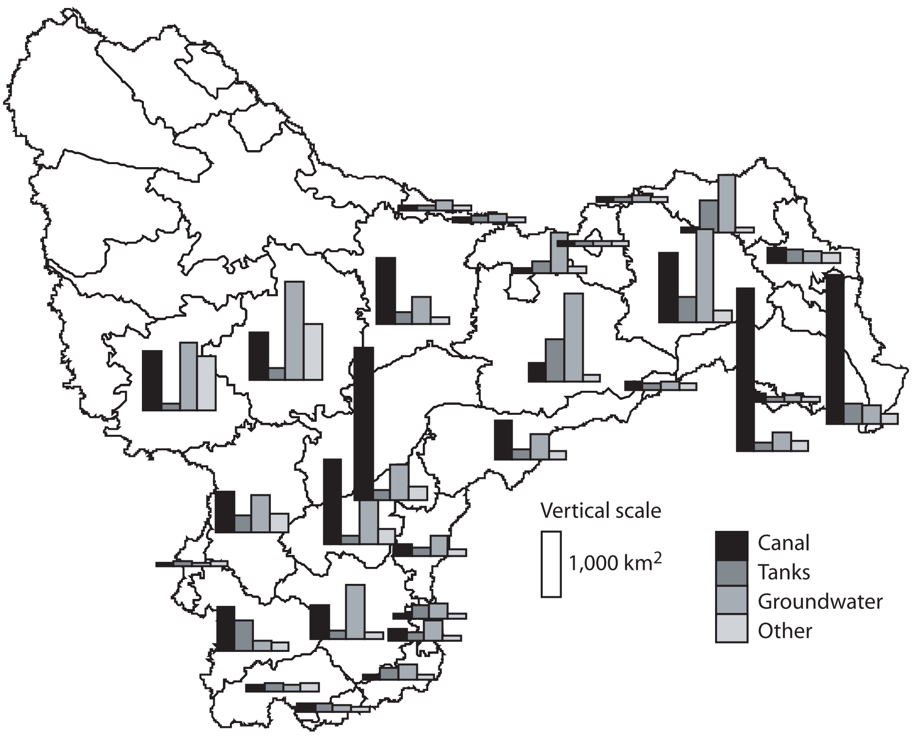
designed for light irrigation with some heavy irrigation at the head-ends of canals on heavy clay soils. However, planned limits to rice and sugarcane cultivation ("localization") have proven nearly impossible to enforce, resulting in heavy water use at the head-ends and water scarcity at the tail-ends of major command areas (Mollinga 2003). Additionally, an irrigation setback distance surrounding village settlements was planned for malaria control purposes, though in practice, farmers in head-end villages irrigate virtually all available land. As a result, water shortages occur at the tail ends of canals, and irrigated agriculture often covers only one-half or less of the planned command area (Wallach 1984). Economic simulation studies suggest that this inequitable distribution may result in a 37 percent reduction in the production potential of the Tungabhadra irrigated command area (Janmaat 2004).

In the early 1990s, the Government of Andhra Pradesh initiated irrigation reforms designed to improve water management in the State and to devolve decision-making authority from the State to district and sub-district levels. The policies focus on decentralizing water resource control to local levels through the creation of Water User Associations (WUAs) and Distributary Committees (Mollinga et al. 2001). Management interventions in irrigation project command areas focus on maintenance and repair of existing irrigation infrastructure. In upland areas, interventions focus on rainwater harvesting, which includes the construction of Kolhapur type weirs and small tanks designed to intercept storm runoff and store it as either surface water or groundwater (Batchelor et al. 2003). Other local management projects include bunding of small drains, land shaping, afforestation and pasture development. In urban areas, building laws mandate collection of water from rooftops for groundwater recharge. The net effect of these new management interventions on the basin-scale water balance, particularly their implications for downstream users, is not well understood (Batchelor et al. 2003).

Typology of Irrigation Projects

In India, irrigation projects are classified by the size of the command area into Major (>10,000 ha), Medium (2,000–10,000 ha) and Minor (<2,000 ha). Minor irrigation projects include tanks, dug wells, and tube wells. Major irrigation projects in the basin began with the Krishna Delta Project at Vijayawada in 1852, which was designed to irrigate 530,000 ha (Government of Andhra Pradesh 2005). In the 1920s, two reservoirs were established near Hyderabad, the regional capital, for flood control and urban water supply. Extensive irrigation and hydropower development began in the 1950s with the construction of several large reservoirs including the Tungabhadra (1953), Nagarjuna Sagar (1974) and the Srisailam projects (1987). Today, the basin has a large number of water management structures, ranging from runoff harvesting check dams and small tanks with earthen dams (<1 ha surface area) to the mega-projects like the Nagarjuna Sagar Dam on the Krishna main stem. Andhra Pradesh alone contains 66,000 tanks, of which 90 percent irrigate less than 40 ha, and 10 percent irrigate between 40 and 2,000 ha (Government of Andhra Pradesh 2003b). Small tanks are also common in Karnataka (Shiva 1991). Data on gross irrigated area by source for Karnataka and Andhra Pradesh in 1994 suggests that the area irrigated by tanks (11,100 km^2) is approximately equal to the area irrigated by groundwater (12,100 km^2). The relative importance of different sources varies spatially (Figure 15), and many tanks outside of irrigated command areas are used primarily as groundwater recharge structures.

FIGURE 15.
Irrigation by source in the Krishna Basin, 1994. Districts with no bar charts indicate no data.



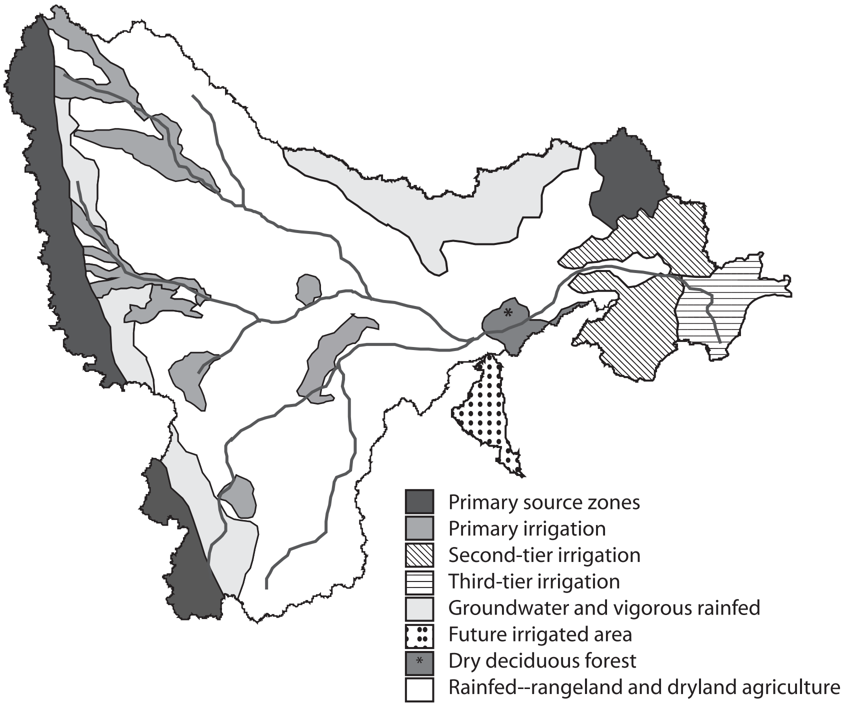
Major irrigation projects created a total of 32,000 km^2 of potentially irrigated command area by 1987, with another 43,000 km^2 under construction in 1987. The actual irrigated area is significantly less than the designed area due to heavy irrigation at the head-ends of projects and insufficient water for tailenders (Wallach 1984). Over 100 medium and major projects have been built in the basin, with a total reservoir capacity of 54 km^3 (Appendix 2, after Abbasi 2001; Government of Andhra Pradesh 2005; Government of Maharashtra 2005).

Hydronomic Zones

Hydronomic zones describe the interaction of hydrology with human water use, and help define the range of management challenges likely to be experienced in a basin (Molden et al. 2001). The delineation of hydronomic zones is somewhat subjective and can change depending on the criteria used, especially in heterogeneous irrigated landscapes like the Krishna Basin. For example, groundwater irrigation zones could include areas 10 or 25 percent irrigated. Delineation of crisp zones is especially problematic in patchy groundwater and minor irrigated areas, and the zones will vary as a function of scale. Nonetheless, based on satellite imagery from the Moderate Resolution Imaging Spectroradiometer (MODIS), precipitation maps, and knowledge of basin hydrology, eight hydronomic zones may be delineated for the Krishna Basin. The map provides a departure point for future discussions of hydronomic zoning of the basin (Figure 16; Table 3).

1. The primary water source areas in the Western Ghats and Eastern Ghats have high annual precipitation (>900 mm), high runoff coefficients, and are dominated by forests and mixed agricultural-forest land uses.
2. Primary irrigated areas receive water flowing from primary source areas, and do not depend on reservoir releases from upstream. In the Krishna Basin, these areas are dominated by sugarcane and rice, especially in the Upper Krishna and Upper Bhima sub-basins.
3. Second-tier irrigated areas depend on reservoir releases and return flow from upstream. In the Krishna Basin, this includes the Nagarjuna Sagar (NJS) command area and some irrigated areas in the Bhima basin. The NJS command area has experienced fluctuating and generally declining canal releases, in part due to upstream irrigation development. Defining the division between primary and second-tier is somewhat flexible and scale-dependent, since even small tanks often have other tanks above them. Here we define second-tier areas as those that have regulated reservoirs upstream.
4. Third-tier irrigated areas depend on reservoir releases and return flow from more than one upstream reservoir, and are typically delta areas with a range of environmental challenges. The Krishna Delta has some unique environmental challenges, including some areas of saline intrusion, which threaten both irrigation water quality and mangrove ecosystems.
5. Groundwater and vigorous rainfed vegetation, delineated using the MODIS land cover classification, occurs mostly where precipitation is greater than 650 mm. The irrigated fraction in these areas is less than 25-40 percent, and irrigation occurs along valley bottoms (see Biggs et al. 2006, for a detailed discussion).
6. Future irrigated areas. The Telugu Ganga Project, under construction in 2005, extends outside of the basin's topographic boundary and adds to the basin's command-area boundary. Other areas of future irrigation from both expansion of existing canal networks, establishment of new reservoirs and construction of new minor and medium irrigation projects could be delineated, but detailed data on the location and extent of those projects were not available at the time of publication.
7. Dry deciduous forest. Rainfall less than 650 mm. Due to rugged topography and poor soils these areas were not converted to agriculture

FIGURE 16.
Hydronomic zones of the Krishna Basin based on MODIS land cover, precipitation, and location in the river system.



and remain in deciduous forest. Though no water balance data is available for these forests, their low rainfall and high evaporation rates (Bouwer et al. 2007) suggest that they contribute relatively little to runoff.

8. Rainfed ecosystems with little or no irrigated area have an average rainfall of 500 mm, and include a mix of shrublands, grasslands, rocky areas, and rainfed agriculture. Satellite imagery and census statistics suggest that approximately 2-10 percent of these areas have minor and groundwater irrigation at some point in the annual cropping cycle.

TABLE 3.
Summary of hydronomic zones in the Krishna Basin, with rainfall from the IWMI Climate Atlas, runoff modeled from the Budyko-Zhang relation (Figure 23), and the aridity index (Figure 10). Aridity index and runoff coefficients are dimensionless. The percentages are the percent of total rainfall or runoff occurring in each hydronomic zone. Note that irrigated zones may only be partially irrigated, so the basin irrigated area is less than the sum of the zones with irrigation.

Name	Area	Rainfall			Runoff			Aridity	Runoff
	(km^2)	mm	km^3	%	mm	km^3	%	index	coefficient
Primary source areas	23,964	1,616	39	21	1,228	29	57	0.7	0.76
Primary irrigation	16,948	451	8	4	90	0.8	2	3.2	0.10
Second-tier irrigation	18,316	742	14	7	263	2.5	5	1.9	0.18
Third-tier irrigation	7,935	838	7	4	323	1.4	3	1.6	0.22
Groundwater irrigation	35,398	683	24	13	236	5.9	12	2.1	0.25
Future irrigation	4,291	543	2	1	144	0.2	0	2.8	0.10
Deciduous forest	9,182	820	8	4	386	3.5	7	1.7	0.47
Rainfed/rangeland	168,274	497	84	46	123	7.3	14	3.0	0.09

Hydrology: Basin Closure and Runoff Production

The Krishna Basin began closing rapidly with the inception of large irrigation projects in the 1960s (Figure 17). Mean annual runoff to the ocean was 57 km^3 (29% of rainfall) from 1901-1960 as measured by the stream gage at Vijayawada, which is downstream from the diversion to the Krishna Delta and 105 km from the river's outlet to the ocean (Figure 1). Dam construction and irrigation expansion continued rapidly, and by 2005 total reservoir storage (54.5 km^3) was nearly equal to annual discharge (Figure 17). This resulted in a decrease in annual average discharge to less than 13 km^3 or ~7 percent of rainfall by 1990-2001, despite no significant decrease in rainfall. The 13 km^3 of annual discharge to the ocean was only 21 percent of the pre-irrigation flow of water to the ocean, and 79 percent of the river discharge was consumed by irrigated agriculture in the basin by 1990-2001. Evapotranspiration, which balances the decrease in streamflow, increased by 20 percent from 1901-1960 and 1990-2000. Discharge at Vijayawada decreased for all probability levels (Figure 18). The 50 percent dependable flow decreased from 56 km^3 during 1901-1960, to 17 km^3 during 1975-2003. Approximately 8 percent of the years had zero flow over 1975-2003. Modeling studies suggest that the depletion is due mostly to irrigation development (Bouwer et al. 2007).

Dam construction and irrigation development have significantly changed the rainfall-runoff relationship at the basin-scale. Annual precipitation in the basin correlated closely with discharge from 1900 to 1960 (Figure 19). This rainfall-runoff relationship was significantly disrupted in the 1960s, resulting in significantly less runoff for a given rainfall depth. Measured runoff coefficients also decreased for some of the major sub-basins, indicating that basin closure also occurred at the tributary level (Table 4). The measured runoff coefficient from the Upper Krishna fell from 0.68 in the 1960s, to 0.52 from 1971-1975, and to 0.45 during 1996-2001. Similarly, the runoff coefficients for the Upper Bhima sub-basin decreased from 0.33 to 0.27 between 1971-1974 and 1996-2001. Basin closure, then, has happened at numerous scales and was not due to a few projects but resulted

FIGURE 17.
Runoff and reservoir storage at Vijayawada station on the Krishna River.

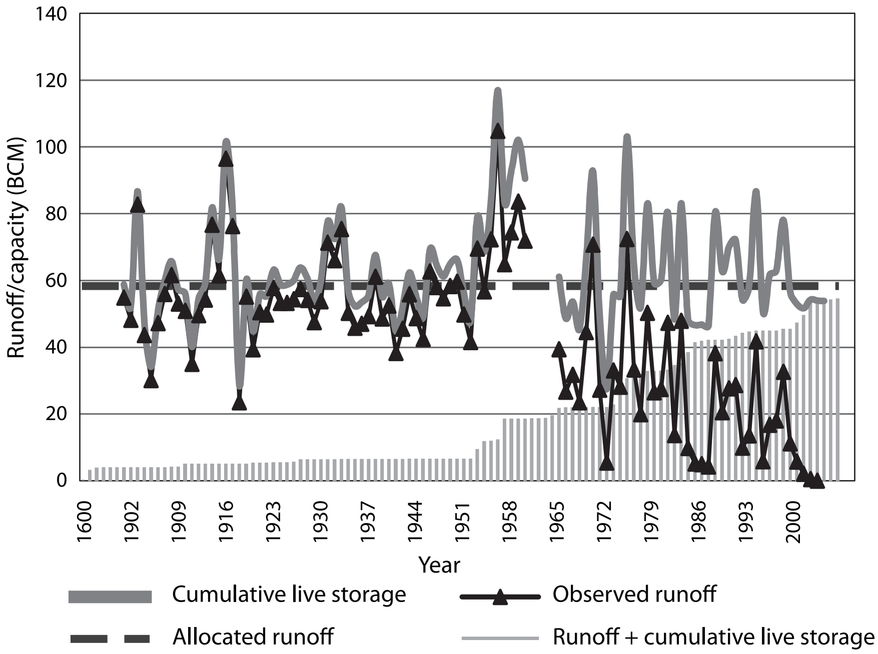
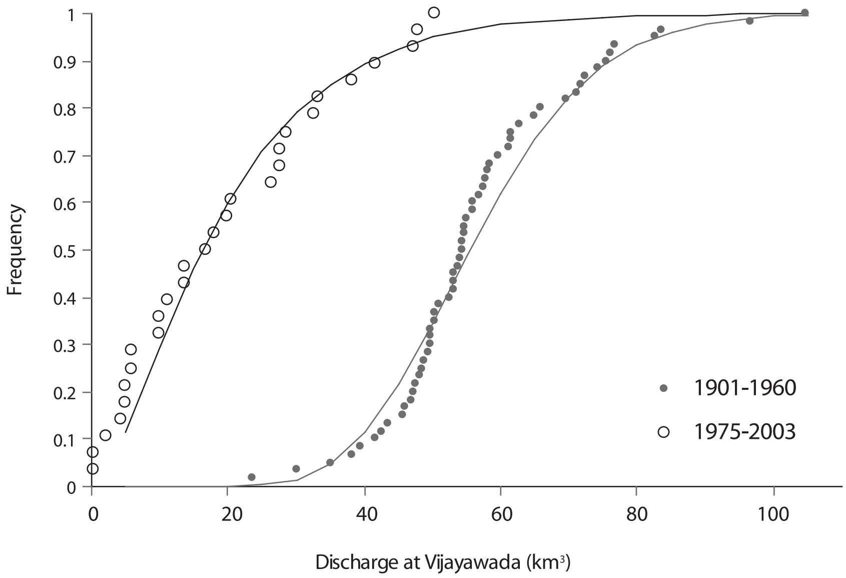


FIGURE 18.
Cumulative probability distributions of discharge at Vijayawada, fit to Gamma distributions.



from the cumulative impact of irrigation expansion in numerous locations in the basin.

The parameters and fit of the rainfall-runoff relationship depend on which precipitation dataset is used, the Indian Institute of Tropical Meteorology (IITM) dataset, or the CRU dataset (Figure 19a). The IITM dataset extend further back in time (1871-2005) than the CRU dataset (1901-2000), have a higher R^2, and are available in near real-time and for seasonal forecasts. The reason for the better overall performance of the IITM rainfall data for predicting runoff may be due to the use of more rainfall stations by the IITM compared to the CRU. Estimation of rainfall in watersheds smaller than several tens of thousands of km^2 remains problematic due to lack of data. Mandal-level rainfall data are available for Andhra Pradesh and Karnataka, but not Maharashtra. Overall, the IITM data are most useful for whole-basin analysis and forecasting, while the CRU data can be used for sub-basins.

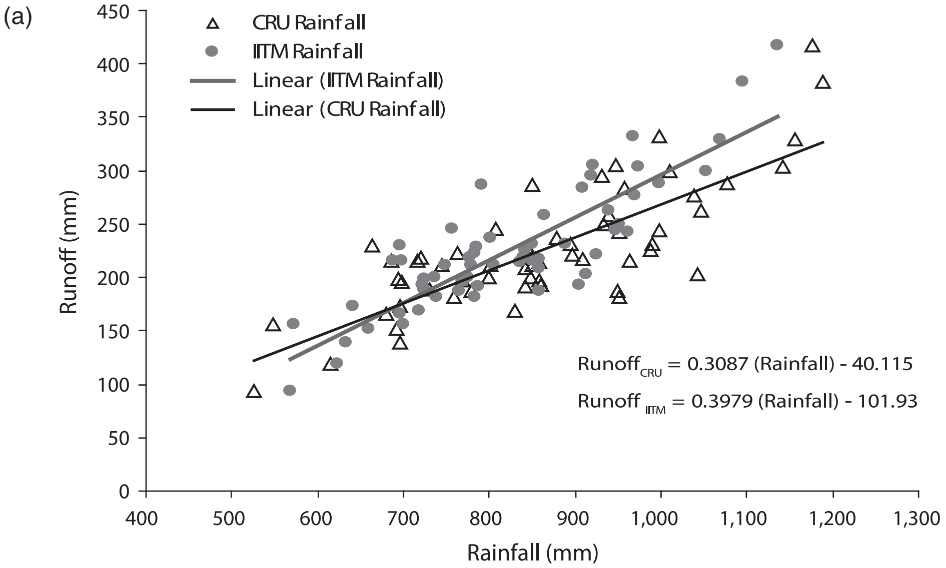
Approximately half of the decrease in inflow to the Lower Krishna at Deosugur over 1971-2001 was caused by reduction in the flow of the Upper Bhima River (-3.63 km^3), which had intensive

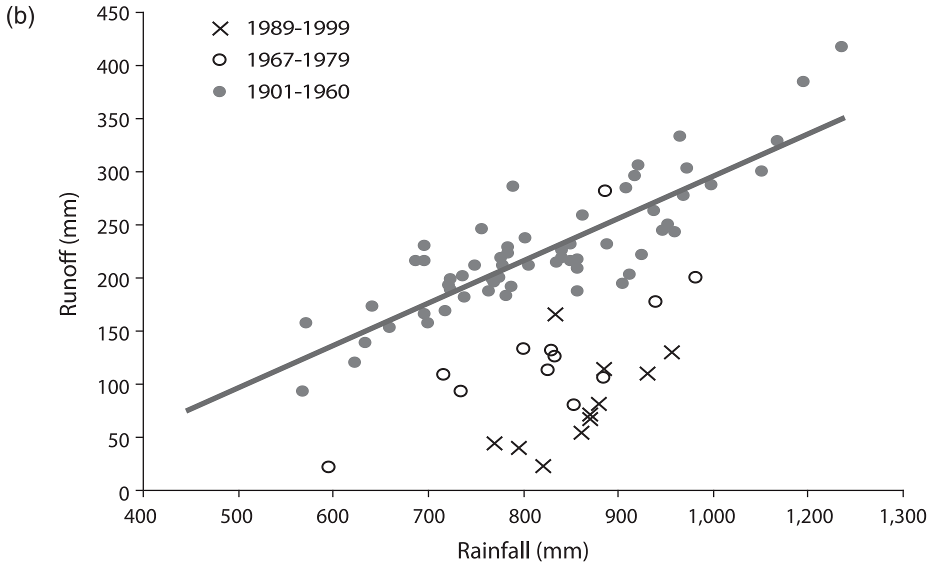
TABLE 4.
Change in rainfall, runoff, and runoff coefficients for two time-periods, 1971-1974 and 1996-2001. The areas include the whole catchment area above the gauging station.

Sub-basin	Station	Area	Rainfall (mm)		Runoff (mm)		Rainfall: Runoff		Change in
		(km^2)	71-74	96-01	71-74	96-01	71-74	96-01	runoff (km^3)
Upper Bhima	Takali	33,916	652	751	201	94	0.31	0.13	-3.63
Lower Bhima	Yadgir	69,863	655	769	146	96	0.22	0.12	-3.47
Middle Krishna	Alamatti	36,286	920	964	477	456	0.52	0.47	-0.78
Lower Krishna	Deosugur	129,500	834	882	228	163	0.27	0.18	-7.94
Tungabhadra	Bawapuram	67,180	730	792	71	71	0.10	0.09	0
Krishna	Vijayawada	251,360	728	817	93	53	0.13	0.07	-10.09

Source: Central Water Commission 2004

FIGURE 19.
(a) Rainfall-runoff relationship for the Krishna Basin at Vijayawada, 1901-1960, using CRU rainfall (open triangles) and IITM data (black circles); (b) Rainfall-runoff relationship for the Krishna Basin at Vijayawada, using IITM rainfall data, by 3 time-periods.





irrigation development upstream over the 1980s and 1990s (Figure 13). The other half of the decrease to the Lower Krishna was due to decreased flow from the Upper Krishna River. The values are somewhat difficult to interpret given the low rainfall during 1971-1974; the apparent water consumption in the Bhima River and Upper Krishna River would be lower if a wetter period were used to calculate the baseline discharge.

Water Accounting

Agriculture and Ecosystems

Water accounting identifies activities that consume water in a river basin and provides the basis for water productivity assessment (Molden 1997). A surface water account was constructed for the Krishna Basin for the period 1994-2003 using data on precipitation, runoff, agricultural census statistics, and crop evapotranspiration estimates (Figure 20; Table 5). Ideally, changes in groundwater volume would be included in the basin water account, but limited data made direct determination of groundwater volume difficult. For the surface water accounting, total annual evapotranspiration (ET) in the basin was calculated as the difference between observed precipitation and observed runoff, which assumed no annual net change in soil or groundwater storage. ET from irrigated agriculture was calculated using two methods: first, as the difference between mean runoff from 1901-1960 and mean runoff from 1993-2004, and second, as the product of the district-wise cropped area from the agricultural census (http://www.indiaagristat.com), the area fraction of the crop that was irrigated, and potential evapotranspiration (E_p) from the Penman-Monteith equation and crop coefficients (Allen et al. 1996) (Table 6). The irrigated fraction was determined from census data, which separate crops into irrigated and non-irrigated at either the district or state level. ET from rainfed crops was calculated as the product of E_p, the fraction of the cropped area under rainfed conditions (=1-irrigated fraction) and the district-wise gross cropped area. ET from rainfed ecosystems and other low-beneficial ET (e.g., reservoirs, soil) was the difference between basin total ET and the sum of ET from rainfed and irrigated crops.

The accounting suggests that rainfed ecosystems account for more than half of annual ET, and that rainfed agriculture consumes more water than irrigated systems (Figure 20). It is important to note that these estimates assume that rainfed crops do not experience water stress, and further simulation or field studies will be required to establish a crop water balance under soil moisture stress.

Urban Water Supply

Of the 67 million people living in the basin in 2000, 22 million lived in cities as defined by the Indian Census. Using the UN Agenda 21 target of 40 liters per capita per day, the domestic water requirement of these 67 million people would be 0.98 km^3, and 0.32 km^3 for the urban population. Assuming a return flow of 80 percent, this gives 0.20 km^3 of depletion over the basin, which is much smaller than the agricultural sector. The city of Hyderabad is the largest in the basin, and has begun drawing water from nearby irrigation projects (Van Rooijen et al. 2005), though the net impact is less than 15 percent of the annual

FIGURE 20.
Water account of the Krishna Basin for 1994-2003, using agricultural census statistics, observed precipitation, and observed runoff at Vijayawada.

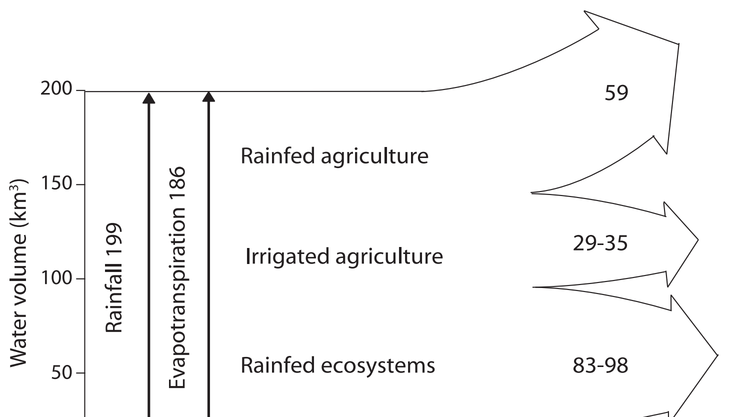


TABLE 5.
Variables and equations used for the basin-scale water accounting. E_p is potential ET determined from the Penman-Monteith equation and crop coefficients are from Allen et al. 1996. Alpha is the fraction irrigated.

Variable	Data source or equation
Precipitation (P)	CRU dataset
Runoff (Q)	Measured at Vijayawada (1993-2004)
Gross cropped area (A)	Indian Agricultural Census 1998
Irrigated fraction (α)	Indian Agricultural Census 1998
Potential ET (E_p)	Penman-Monteith Equation and Crop Coefficients
Total ET in the basin (ET_b)	P – Q (1993-2004)
ET irrigated agriculture (ET_{irr})	
1. Runoff method	Q (1900-1960) – Q (1993-2004)
2. E_p method	αAE_p
ET rainfed agriculture (ET_{rfa})	$(1-\alpha)AE_p$
ET rainfed ecosystems (ET_{rfe})	$ET_b - ET_{irr} - ET_{rfa}$

TABLE 6.
Gross cropped area and estimated water consumption of major crops in the Krishna Basin, 1998-1999 as calculated from district statistics and the Penman-Monteith equation for potential ET. Potential ET is the ET for a single cropping season. Data on gross area were downloaded at the district level from http://www.indiaagristat.com, August 2005. For sugarcane, ET values are included for a 14-month crop but for the basin water balance, all sugarcane was assumed to be 11-month due to a lack of data on crop durations.

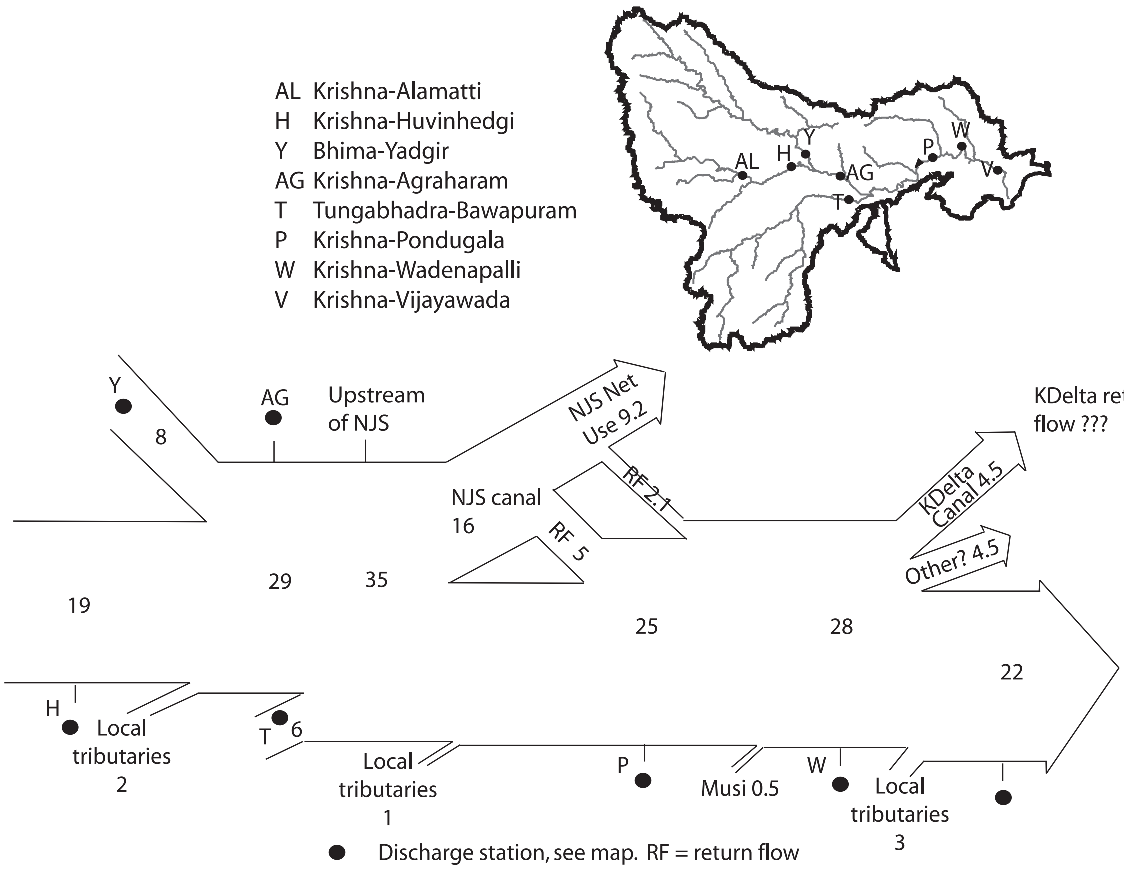
		Gross area (km^2)	Potential ET (mm)	Total ET (km^3)	Fraction irrigated	ET irrigation (km^3)	ET rainfed (km^3)
Food crops	Rice	21,608	608-818	13.1-18.3	0.84	11.0-15.4	2.1-2.9
	Sorghum	33,033	406	13.4	0.08	1.1	12.3
	Pearl millet	8,540	457	3.9	0.07	0.3	3.6
	Pulses (gram)	22,030	590	13	0.04	0.5	12.5
	Wheat	4,613	650	3.0	0.70	2.1	0.9
	Corn	3,584	530	1.9	0.38	0.7	1.2
	Finger millet	2,565	351	0.9	0.10	0.1	0.8
	Small millets	2,296	479	1.1	0.07	0.1	1
	Oilseeds	26,689	525	14	0.17	2.4	11.6
Cash crops	Sugarcane						
	11 month	4,844	1,239-1,672	6.0-8.1	1.00	6.0-8.1	0
	14 month	-	1,970	9.5	1.00	-	-
	Cotton	10,134	819	8.2-8.4	0.17	1.4	6.9
	Spices	3,153	825	2.5	0.62	1.55	0.95
	Tobacco	848	1,003	0.70	-	0	0.70
Fruit	Mango	1,165	3,482	0.70	0.25	0.2	0.5
	Banana	359	625	1.25	0.25	0.3	0.9
	Citrus	384	821	0.24	0.25	0.1	0.2
	Grapes	134	631	0.11	0.25	0	0.1
	Guava	111	606	0.07	0.25	0	0.1
	Sapota	132	1,724	0.08	0.25	0	0.1
	Papaya	29	628	0.05	0.25	0	0
	Other	478	633	0.30	0.25	0.1	0.2
Vegetables	Eggplant	199	633	0.12	0.25	0	0.1
	Tomato	521	688	0.33	0.25	0.1	0.2
	Onion	1,149	565	0.79	0.25	0.2	0.6
	Others	1,293	406	0.73	0.25	0.2	0.5
Total		149,891	-	76-83	-	29-35	58-59

water supply for each irrigation project involved. Future growth could impact some irrigation projects during dry years. Water supply to Hyderabad from the largest irrigation project in the basin (Nagarjuna Sagar) is forecast at 5-10 percent of total releases from the project's reservoir by 2030. Most of the urban water supply (50-70%) returns to streams as wastewater, which is used in irrigated agriculture near cities. The continued expansion of cities may result in increased local conflict over irrigation water, though agriculture is by far the largest water consumer in the basin (Figure 20).

Towards a Node-by-Node Water Account

Basin-wide water resources planning and comparison of water productivity across the basin will require establishing a project-based water account. For this report, sufficient data was available to establish a nodal water account for the Lower Krishna in Andhra Pradesh (Figure 21). The Upper Krishna at Huvinhedgi contributes more than 50 percent of the runoff to the lower basin, and 47 percent of the irrigation inflow to the Nagarjuna Sagar (NJS) returns to the Krishna River. Other studies on parts of the NJS also show high return flow percentages (Gosain et al. 2005), which contrasts with the value of 7.5-10 percent used by previous water tribunals to allocate water among the states. The return flow from the NJS is equivalent to more than 80 percent of the Krishna Delta's water requirement, which points to the necessity of accounting for high return flows for accurate water assessment and management. Future studies could establish return flow percentages for other projects in the basin, such as in the Bhima Tributary, pending data availability.

FIGURE 21.
Water account of the Lower Krishna Basin, May 1989 - May 1996.



Note: Question marks indicate uncertain quantities or processes.

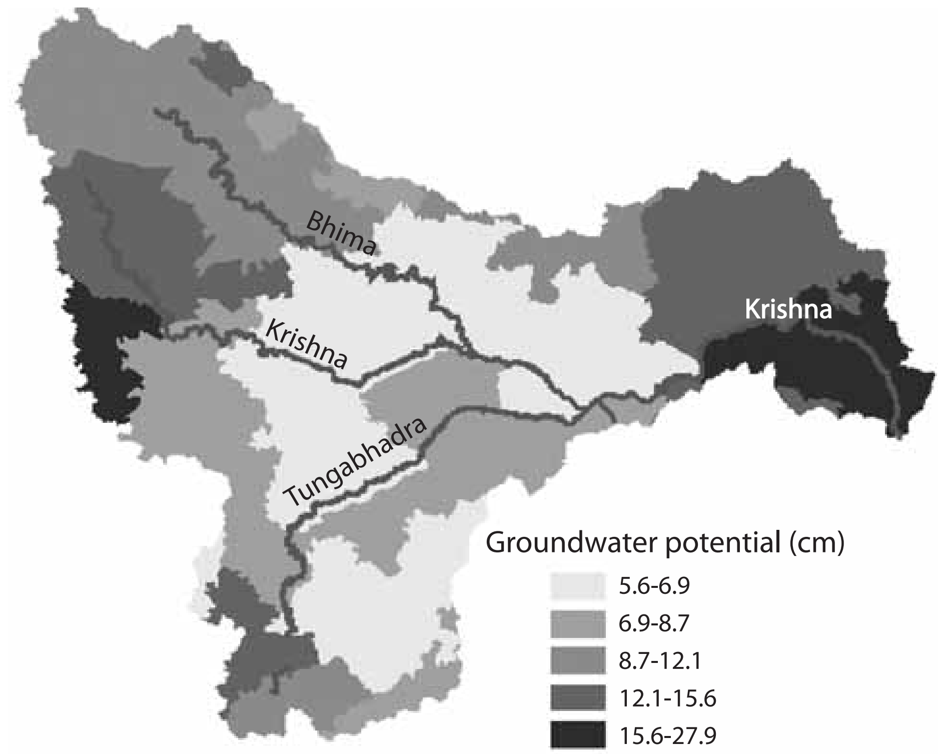
Groundwater Status

The water account established above included the contribution of groundwater irrigated areas to ET, since the ET calculations were based on cropped areas that include both groundwater and surface water irrigated crops. However, the account does not explicitly track groundwater abstraction or make a water balance on the basin's groundwater volume or depletion rates. On average, there is 26.4 km^3 replenishable groundwater in the basin (Kumar et al. 2005). Areas of the highest precipitation, including the Upper Bhima, Upper Krishna near the Western Ghats, and the Krishna Delta, have the largest groundwater potential due to high recharge rates (Figure 22). The Middle Krishna has very little replenishable groundwater due to low precipitation and hard rocks with poor aquifer properties.

Groundwater use increased markedly in India from the 1970s, and particularly in the 1990s (Deb Roy and Shah 2002). In the Krishna Basin, groundwater irrigated area equals surface water irrigated area (Figure 12; Table 2; see also Biggs et al. 2006). The number of shallow tube wells in the basin increased from 35,000 in 1987 to 137,000 by 1994 (Ministry of Water Resources 2001). The real boom in groundwater expansion, as indicated by rural electrical connections, occurred in the late 1990s for which there is little data available. Recharge and abstraction rates are not well quantified. The role of groundwater irrigation in decreasing the Krishna River discharge to the ocean or to different projects in the basin is also not known.

In a survey of groundwater irrigation in watersheds of Andhra Pradesh, the Andhra Pradesh Groundwater Department estimated

FIGURE 22.
Groundwater potential in the Krishna Basin, by district.



Sources: Ministry of Water Resources 1997; Ministry of Water Resources 1998; and Government of Andhra Pradesh 2003a.

TABLE 7.

Characteristics of the thirteen Krishna sub-basins and other watersheds with available runoff data. The catchment area for Group A sub-basins is the area between the gauging station and the nearest upstream gauging stations, and does not include the entire catchment area. The area for Group B sub-basins includes the entire sub-basin area.

Code	Sub-basin	Length (km)	Area (km^2)	Total population 2001 (millions)	Population density 2001 (persons/km^2)	Annual rainfall runoff (P) (mm)	Annual rainfall runoff (P) (km^3)	Annual runoff (Q) (km^3)	Runoff coefficient (Q:P) Observed	Runoff coefficient (Q:P) Predicted	Runoff coefficient (Q:P) Curve[a]	Potential evaporation (Ep)[b] (mm/yr)	Aridity index (Ep/P)
GROUP A: 13 SUB-BASINS[b]													
K1	Upper Krishna	306	17,972	5.93	304	1,099	27.1	18.3	0.68	0.62	LM	1,291	1.2
K2	Middle Krishna	483	17,558	2.5	174	462	9.9	0.93	0.09	0.08	BZ	1,522	3.3
K3	Ghataprabha	283	8,829	2.18	251	718	8.1	3.6	0.45	0.38	LM	1,385	1.9
K4	Malaprabha	306	11,549	2.25	172	528	7.8	1.6	0.20	0.11	LM	1,468	2.8
K5	Upper Bhima	515	46,066	13.46	296	570	31.1	10.3	0.33	0.24	LM	1,360	2.4
K6	Lower Bhima	346	24,548	4.82	212	678	16.2	2.4	0.15	0.12	BZ	1,651	2.4
K7	Lower Krishna	611	36,125	10.87	295	641	26.0	3.6	0.14	0.13	BZ	1,492	2.3
K8	Tungabhadra	531	47,827	7.17	157	668	42.3	12.2	0.29	0.14	BZ	1,446	2.2
K9	Vedavathi	391	23,590	4.65	194	411	13.4	1.4	0.11	0.07	BZ	1,479	3.6
K10	Musi	267	11,212	9.11	641	669	8.4	1.3	0.16	0.14	BZ	1,512	2.3
K11	Palleru	153	3,263	0.55	212	781	2.6	0.45	0.17	0.19	BZ	1,353	1.7
K12	Muneru	196	10,409	3.66	462	901	9.9	2.2	0.22	0.23	BZ	1,355	1.5
K13	Krishna Delta	-	9,386	5.61	598	1,200	11.3	-	-	-	-	-	-
	Total	-	268,334	72.8	258	808	214.1	58.28	0.29	-	-	-	-
GROUP B: OTHER STATIONS													
	Jewangi[d]	-	1,862	-	-	590	1.1	0.13	0.12	0.10	BZ	1,642	2.8
	Halia[d]	-	3,245	-	-	799	2.6	0.24	0.09	0.18	BZ	1,466	1.8
	Wyra[d]	-	1,833	-	-	1,000	1.8	0.70	0.38	0.27	BZ	1,300	1.3
	Vijayawada[e]	-	251,355	-	-	797	200.3	57	0.28	0.18	BZ	1,453	1.8
	Yadgir[e]	-	69,863	-	-	719	50.2	10	0.20	0.35	LM	1,457	2.0
	Bawapuram[e]	-	67,180	-	-	768	51.6	4.8	0.09	0.17	BZ	1,450	1.9
	Takali[e]	-	33,916	-	-	691	23.4	7.5	0.32	0.39	LM	1,318	1.9
	Deosugur[e]	-	129,500	-	-	913	118.2	29	0.43	0.51	LM	1,402	1.5
	Alamatti[e]	-	36,286	-	-	1,003	36.4	18	0.48	0.57	LM	1,347	1.3
	Ramapuram[e]	-	23,500	-	-	696	16.4	0.9	0.05	0.15	BZ	1,461	2.1

Notes: [a] Indicates the curve used to predict the runoff coefficient. BZ indicates Budyko-Zhang model with w=0.8 (for basins that do not intercept the Western Ghats), and LM indicates the linear model (for basins that intercept the Western Ghats). Both curves are in Figure 23.

[b] Ahn and Tateishi (1994).

[c] Precipitation from Government of India, Krishna Water Disputes Tribunal (1973). Runoff is naturalized, corrected for irrigation diversions.

[d] Observed runoff data, not corrected for irrigation diversions. Precipitation data from Andhra Pradesh State Water Data Center. Both runoff and rainfall data cover 1989-1996.

[e] Observed runoff data, not corrected for irrigation diversions. Precipitation data from CRU dataset, University of East Anglia. Both runoff and rainfall data cover 1971-1979.

that 38 percent of the watersheds in the State had unsustainable rates of groundwater abstraction, and 15 percent were overexploited in 2004 (AP Groundwater Department, unpublished report). The most severe groundwater overdraft occurred inland where recharge rates and aquifer yields are low. No comparable analyses were available for Maharashtra or Karnataka. The relationship between groundwater abstraction and streamflow is highly uncertain and remains a major gap in understanding of the basin. The groundwater-surface water relationship is particularly crucial for the interstate allocation, as the current allocations assume no interaction between the two.

Runoff Coefficients and the Budyko-Zhang Curve

Runoff volumes and the ratio of runoff to rainfall (the annual runoff coefficient) vary as a function of climate. Annual runoff coefficients in the Krishna Basin ranged from greater than 0.68 at the base of the Western Ghats to less than 0.05 in the semi-arid central plateau (Table 7; Figure 10). While complex models may be calibrated to fit observed runoff coefficients, an alternative "downward" approach to hydrologic modeling uses simple relationships and accepts some lack of fit in exchange for using simple measurements and better conceptual understanding of basin hydrology (Sivapalan et al. 2003). Such approaches are particularly suited to data-scarce regions like the Krishna Basin, since they do not require the application of highly parameterized models to ungauged locations. The Budyko model uses only climate as measured by the ratio of potential evaporation (*Ep*) and precipitation (*P*) to predict the annual water balance. It has been used to model global river discharge and to predict annual evaporation and runoff coefficients. Zhang et al. (2001) proposed a formulation of the Budyko relation that includes a single adjustable parameter (*w*), and is written as:

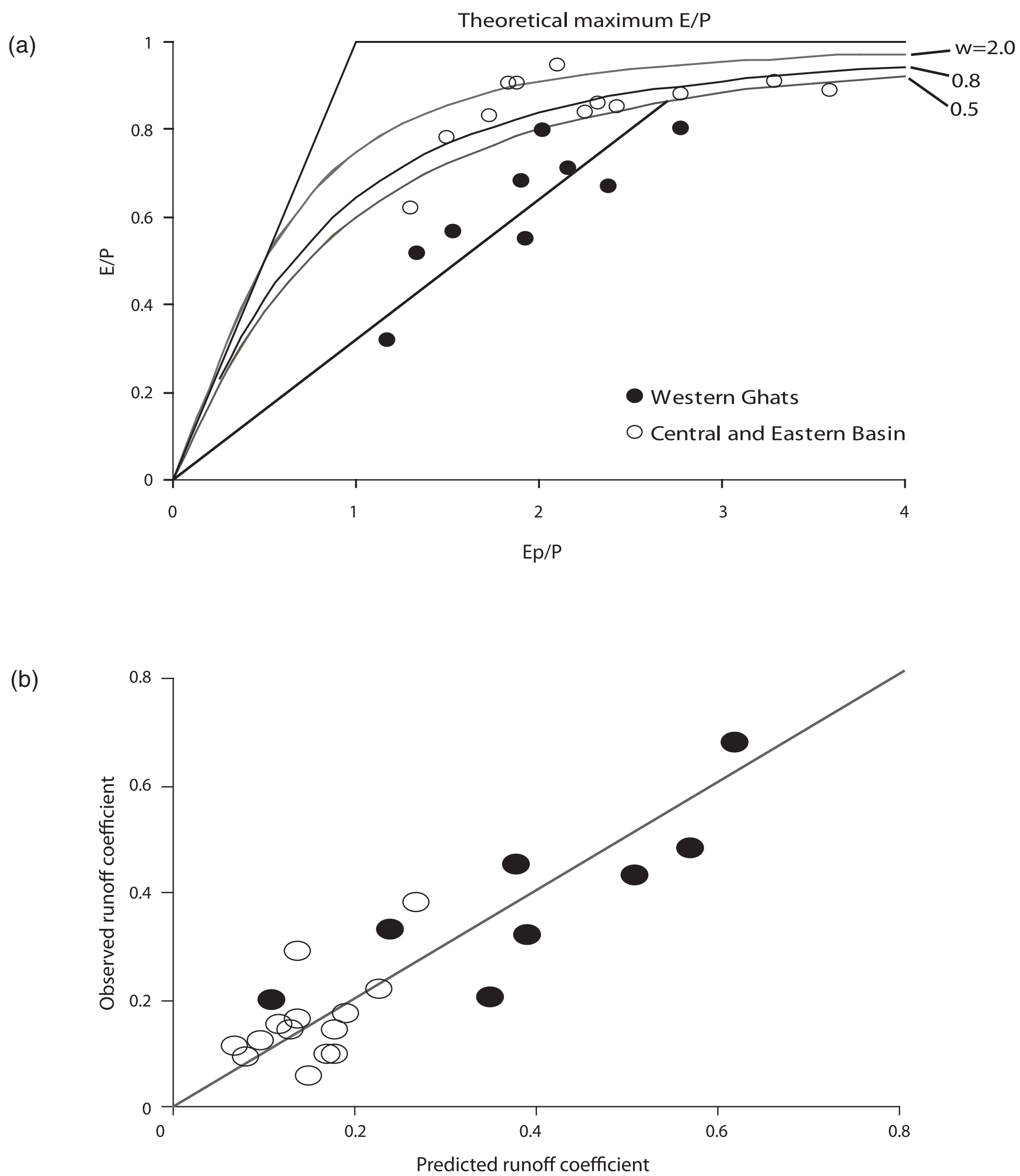
$$E/P = \frac{1 + w\frac{Ep}{P}}{1 + w\frac{Ep}{P} + \frac{P}{Ep}} \qquad (1)$$

where *E* is annual evaporation (mm), *P* is annual precipitation, *Ep* is annual potential evaporation, and *w* is a coefficient that relates to plant-available water (dimensionless). The runoff coefficient is 1-*E/P*. *Ep* was taken from Ahn and Tateishi (1994). Zhang et al. (2001) compiled values of *w* for global rivers, and found that catchments covered with grasses have lower evaporation and higher runoff than catchments covered with forests for a given climate (Figure 23).

A single Budyko-Zhang (BZ) model gives a poor fit to the data (R^2 0.42-0.49). Splitting the data into streams draining the Western Ghats and streams draining exclusively the central and eastern basin gives a much better fit to the data (R^2 = 0.74) and a lower root mean square error (0.06). The best-fit value of *w* for the central and eastern Basin is 0.8, which is intermediate between grass (*w*=0.5) and forest (*w*=2) in the BZ model (Figure 23). Rivers draining the Western Ghats fit a straight linear regression better than a strict BZ curve, and have lower evaporation coefficients and higher runoff coefficients compared with other global rivers covered in grass and forest. The high runoff coefficients in the Western Ghats and the remaining scatter around the BZ curves could be due to thin soils, high seasonality and intensity of precipitation, land use, or water management (Farmer et al. 2003; Milly 1994). The BZ curve tests for the effect of climate alone on runoff coefficients, and other, more highly parameterized models that incorporate land use and soil type will certainly produce runoff estimates that more closely match the observed values. More detailed models will be required to produce seasonal or monthly runoff values, but the BZ model shows that climate alone explains more than 70 percent of the spatial variability in annual runoff coefficients (Figure 23b).

The Budyko-Zhang (BZ) model may be used to estimate annual runoff from each of the hydronomic zones (Table 3). The narrow Western Ghats zone occupies only 9.5 percent of basin area (Figure 16), but accounts for 21 percent of the basin's annual rainfall volume, and generates 57 percent of the basin runoff due to high runoff coefficients.

FIGURE 23.
(a) Evaporation coefficients for the Krishna Basin, with Budyko-Zhang (BZ) curves and the observed values of E/P.
(b) Predicted versus observed runoff coefficients from the BZ relations in (a).



Notes: Values of w are for equation (1), and represent the evaporation coefficients for grass (w=0.5), forest (w=2), and the best-fit for the central and eastern Krishna Basin (w=0.8).

The legend is the same for both graphs.

Water Allocation: The Krishna Tribunal

Water in India is managed by State authorities. The lack of permanent interstate management institutions has led to interstate disputes. In response, the Krishna Water Disputes Tribunal was established in 1969 to allocate water among the three states that share the Krishna Basin. The Tribunal used the annual flow at Vijayawada from 1894 to 1972 to determine the flow at 75 percent dependability (58 km^3, the flow that is exceeded 75% of the years).

The major intra-basin transfers occur from the Upper Krishna, where ~50 percent of the basin's discharge originates, to the Middle and Lower Krishna (Table 8; Figure 24). Allocation to the Lower Krishna exceeds the volume of water generated in the sub-catchment by ~13 km^3, while the Upper Krishna is allocated 6 km^3 but generates ~18 km^3. Most other sub-basins have a balance between water availability and water allocation, and therefore would contribute only marginally to flow downstream if all allocation were used.

Despite these State-wise allocations from the Tribunal, water development and irrigation projects have continued to the point where basin-wide water demand is roughly double the total volume of water allocated by the Tribunal (Table 9; Shiva 1991). While this may not generate conflicts in surplus years, it may generate significant deficits for downstream projects during years at or near the 75 percent dependable flow. The increasing demand for water creates significant and continuing conflicts between states, including controversy over newly planned projects. The Alamatti Dam on the Upper Krishna, in particular, generates conflict, since the Upper Krishna provides more than 50 percent of the annual discharge to the Lower Krishna Basin and the Nagarjuna Sagar and Krishna Delta projects located there (Figure 21).

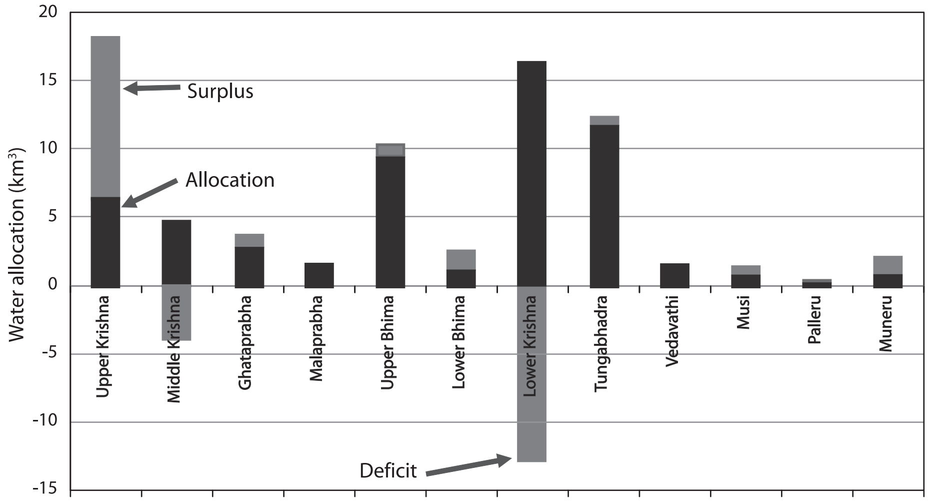
The initial Krishna Water Disputes Tribunal (KWDT) for interstate allocation expired in 2000. The new KWDT was constituted in April 2004 and is expected to provide a report with revised allocations between 2008 and 2010. It is to be noted that the first tribunal was formed in 1963 and the final decision on water allocation was made in 1976, so current reallocation negotiations could last longer than a decade. Negotiations for additional water release to downstream states are

TABLE 8.
Rainfall, available yield, and allocation for the 13 major sub-basins (all values are in km^3).

	Sub basin	Rainfall	75% Runoff dependable	Runoff allocation				Surplus
				MH	KT	AP	Total	
K1	Upper Krishna	27.10	18.31	6.43	0.13		6.57	11.74
K2	Middle Krishna	9.92	0.93		4.74		4.74	-3.82
K3	Ghataprabha	8.13	3.62	0.12	2.71		2.83	0.79
K4	Malaprabha	7.79	1.58		1.61		1.61	-0.03
K5	Upper Bhima	31.14	10.30	9.26	0.02		9.28	1.02
K6	Lower Bhima	16.23	2.41	0.04	1.18	0.16	1.39	1.02
K7	Lower Krishna	26.05	3.57		0.05	16.26	16.30	-12.74
K8	Tungabhadra	42.28	12.17		8.20	3.57	11.77	0.40
K9	Vedavathi	13.40	1.44		1.17	0.35	1.53	-0.08
K10	Musi	8.39	1.30			0.97	0.97	0.33
K11	Palleru	2.64	0.45			0.32	0.32	0.14
K12	Muneru	9.93	2.21			1.03	1.03	1.18
	Total	203	58.3	15.9	19.8	22.7	58.33	

Notes: MH = Maharashtra; KT = Karnataka; AP = Andhra Pradesh.

FIGURE 24.
Water allocation and transfer for 12 NWDA sub-basins, according to the 1973 Krishna Tribunal Award.



currently ad hoc; Chief Ministers of downstream states like Andhra Pradesh approach officials of other states (Karnataka) in what amount to personal pleas for additional water (The Hindu 2003). Both inter- and intra-state conflicts are likely to continue as irrigation development continues. In Andhra Pradesh, farmers in the Krishna Delta region have staged hunger strikes to secure assurances of additional releases from upstream dams within the State, and farmers in the Tungabhadra projects have stormed irrigation offices demanding immediate water release (The Hindu 2002).

The Tribunal Award, Groundwater Irrigation and Return Flow

Both intra- and inter-state water management could be significantly complicated by groundwater irrigation and small watershed development, which are not included in the current allocations. Though an estimate of replenishable groundwater has been made by the Tribunal, groundwater use is not considered to be linked to streamflow and is decoupled from the surface water allocation award. Neglect of the groundwater-streamflow interactions could lead to significant

TABLE 9.
Water allocation to the three states sharing the Krishna Basin, and current water demand from existing irrigation systems.

	Percentage of basin area (%)	Water allocation (km^3)	Water demand 1991 (km^3)	Ratio Demand: Allocation
Maharashtra	25	15.9	23.4	1.48
Karnataka	42	19.8	40.5	2.05
Andhra Pradesh	33	22.7	56.9	2.51
Total	100	58.4	120.8	2.07

Source: Adapted from Shiva 1991.

over-estimation of available surface water, particularly as groundwater irrigation continues to expand.

The Tribunal award assumed that 7.5-10 percent of water diverted to an irrigation system returned to streams as return flow, which could be allocated to downstream users. Actual return flow in irrigated areas may be much higher than this; the return flow from part of the Nagarjuna Sagar system in Andhra Pradesh has been estimated at more than 50 percent (Gosain et al. 2005), which is consistent with the lower-basin water budget (Figure 21). High return flows probably occur because high water duty and flooded crops, mainly rice, are being grown instead of the intended irrigated dry crops. Though many farmers already take advantage of return flows by installing informal lift irrigation schemes downstream of major projects (Mollinga 2003), more accurate estimation of return flows could result in more efficient management of the total water available in the basin.

Inter-basin Transfers

The Krishna is linked to adjoining basins, particularly the Godavari in the delta region and Pennar to the south, which includes a pipeline for urban water supply to Chennai. The Government of Andhra Pradesh plans a Godavari-Krishna inter-basin transfer through a major aqueduct lift in the middle reaches to augment urban water supplies to Hyderabad City and the Nagarjuna Sagar reservoir by 2020, though this date could change to suit political imperatives. Additionally, the national River Linking mega-project identifies Mahanadi-Godavari-Krishna links which would be targeted to meet irrigation demand.

Data Limitations and Future Hydrologic Research

Basin closure and the pending reallocation of water to the three states have resulted in intense competition over remaining water resources, among States, irrigation projects, and sectors. One consequence of the competition is restriction to data access, both among the three states and with third-parties. As a consequence, the actual water availability, use, and productivity of different irrigation projects remain difficult to determine rigorously and consistently. Such lack of data transparency represents a significant problem for water resource allocation and management in the basin and limits the ability to develop innovative solutions. Though the river basin tribunal assesses water availability and allocation rules every 20-30 years, there is a need to update water resources assessment more frequently while the hydrology of the basin is changing rapidly due to irrigation and urban development. Models of expected water yield linked to decision support systems could facilitate the water managers to operate the basin with updated hydrology. That can only happen if the data was made publicly available. The real-time operation would help the water mangers and would empower farmers and other water users to deal with changes due to climate or upstream withdrawals.

In 1991, the International Law Commission established the Law of the Non-Navigational Uses of International Watercourses, which outlines principles for containing conflict generated by shared water resources (Gleick 1993). One central principle was the requirement for regular sharing of data and agreement to a common database among potential stakeholders. Interstate conflict over water in India is a recurring problem in other basins, including the Cauvery Basin, and negotiations in federal Tribunals can last decades. Principles outlined by the International Law Commission could be applied to water resources conflicts among Indian States, and may prevent the escalation of conflict and lead to more rapid resolution of interstate conflicts. Agreement over the amount and spatial and temporal distribution of water resources via established principles of regular data exchange would be an important first step in resolving water allocation in water-scarce basins like the Krishna.

Environmental Issues

The magnitude of streamflow depletion, a large human population and rapid urbanization might be expected to have strong impacts on environmental and water quality conditions in the basin. Information on the environmental impacts of irrigation development in the Krishna is limited; here we provide a preliminary summary of available literature and past IWMI research.

Sedimentation of reservoirs is a recurring challenge to the maintenance of tanks and reservoirs, though the relatively low relief and a geologic substrate resistant to erosion (granitic gneiss and basalt) result in total sediment loads that are low compared with basins draining the Himalaya. The Tungabhadra reservoir has some problems with siltation, possibly exacerbated by iron and manganese ore mining (Shiva 1991). Sedimentation problems may be more severe in the Bhima River system, which has the highest erosion rates of the major tributaries, and in small watersheds compared with large river systems (Ramesh and Subramanian 1988).

Problems with soil salinity appear limited in the NJS command area and the wastewater irrigated area near Hyderabad. Most salinity in NJS appears to be due to primary, or natural, salinity (Dwivedi et al. 1999). Simple simulation studies of the Tungabhadra Command Area suggest that salts could be accumulating and causing yield reduction (Janmaat 2004), though no data was used to validate the model or verify the presence of high soil salinity. In the wastewater irrigated area near Hyderabad, salinity has been blamed for low rice yields and may have encouraged farmers to grow more salt-resistant crops such as paragrass; however, the links between wastewater irrigation, salinity, crop yields, and farmer cropping decisions have not been conclusively demonstrated.

Water Quality

The Krishna River and its tributaries receive effluent and wastewater from a number of large cities, including Pune, Satara, Kolhapur, Hyderabad, Kurnool and Vijayawada, among others. More than 500 important industrial units operate from the Krishna Basin, 200 of which are large-scale industrial units (Centre for Science and Environment 2006). Water quality problems in the region are concentrated in the wastewater irrigated areas of Hyderabad and other large urban areas (Jayashree 2000), though water quality may limit groundwater irrigation in other parts of the basin, and chemical mass balance suggests that irrigated areas contribute significantly to pollutant loads in irrigated parts of the basin (Hiremath 2001; Madhurima 2000; Purandara et al. 2004). River pollution has resulted in fish kills in some major tributaries near urban areas (Kulkarni and Gupta 2001), and has altered solute concentration, microbal populations, and faunal biodiversity along the Musi Corridor outside Hyderabad (Ensink et al. 2006). In a regional survey by the Central Pollution Control Board, the majority of streams were critical in terms of biochemical oxygen demand (BOD) and Fecal Coliforms during 2002 and 2003 (Central Pollution Control Board 2002). The Musi River downstream of Hyderabad (18.9 mg/L) and the Bhima River downstream of Pune (33.3 mg/L) had high BOD compared with the other rivers against the acceptable value of 6 mg/L. The Fecal Coliform was higher (17,000 per 100 ml) at Wadenapalli after the confluence of the Musi River. The highest value of total dissolved solids (18,899 mg/L) was observed in the Krishna Delta due to backwater effect. Parts of Nalgonda District in Andhra Pradesh have high fluoride contents, which mainly affects drinking water use and not irrigation.

The waters and soils of the Musi wastewater irrigated area have relatively high salinity and limited heavy metal contamination. Surveys of water and soil salinity (Jiang et al. 2004) suggest that high salinity contributes to compromised rice yields in the wastewater irrigated areas, and paragrass is grown in areas with high soil salinity instead. Surveys of heavy metals show relatively low risk of contamination, and the background soil stock of lead is high compared with the flux from the wastewater (Gerwe et al. 2004).

Some saline groundwaters occur in the Krishna Delta, likely due to seawater intrusion, which may have been exacerbated by groundwater pumping (Saxena et al. 2004; Saxena et al. 2003). Whether the reduction in flow into the delta at Vijayawada (Figure 17) will increase saltwater intrusion is not known. Pollution of shallow hard-rock aquifers has been documented in areas with sugarcane processing (Pawar et al. 1998), though the extent and impact on water productivity is not known.

Mangrove Ecosystems and Fisheries

Mangroves occur in the Krishna Delta (Selvam 2003). Decreased flow at Vijayawada caused by irrigation has likely changed the mix of freshwater and saltwater in the mangroves, potentially altering community structure. Very limited information is available on the mangrove systems and their response to the hydrologic changes in the delta.

Extensive aquaculture occurs in the Krishna Delta and its wetlands. The shrimp industry depends on mangrove ecosystem services for hatcheries, and there are signs that current mangrove area is insufficient to maintain the shrimp industry in the neighboring Godavari Delta (Rönnbäck et al. 2003). Kolleru Lake, a RAMSAR wetland, has been significantly impacted by aquaculture and agriculture (Malneedy 2003). Andhra Pradesh also has important fisheries in many of its tanks (Sugunan 1995). The rapidly changing hydrologic regime in the basin will result in a changing mosaic of aquatic environments.

Conclusion

The broad conclusions and water related issues in the Krishna Basin include:

1) The basin is 80 percent closed due to irrigation development, and streamflow to the ocean from 1995-2005 was only 20 percent of pre-irrigation discharge (1900-1960). Total reservoir capacity is approximately equal to annual average runoff, and total demand exceeds sanctioned allocations by nearly double. Basin closure is happening in tributaries as well as at the outlet to the ocean, resulting in interstate conflicts over scarce water resources.

2) Groundwater irrigated area exceeds surface water irrigated area in the basin. Rapid groundwater irrigation development will likely decrease surface water availability by drawing down regional aquifers and enhancing infiltration along streams. Current water allocation policy considers groundwater and surface water separately, which could lead to over-estimation of surface flow volumes and over-allocations of surface water.

3) A majority of the basin area has very low runoff coefficients (<10%). The Western Ghats dominate runoff in the basin due to high precipitation and high runoff coefficients, so upstream development on tributaries draining the Ghats has particular significance for downstream areas.

Future research in the hydrology of the basin could emphasize:

1) Monthly estimates of precipitation and evaporation, and how these affect runoff, soil moisture, and crop production in rainfed and irrigated areas. This would require a more elaborate model of evaporation, soil moisture, and runoff in the basin.

2) Techniques to define hydronomic zones in basins more quantitatively with a complex mosaic of irrigated areas. The present map is useful for initiating dialogue about how hydronomic zones should be defined.

3) For water allocation policy, a project-by-project water accounting of irrigation systems in the basin is required. Interstate competition for water has restricted access to data to both the other states and third-party research on streamflow and irrigation diversions in the basin. The potential outcome of this lack of transparency includes inappropriate timing and volume of allocation of water in the basin. The resulting errors will likely have severe impacts on the amount and reliability of water supply, and thereby on farmer livelihoods in this water scarce basin. Priorities of the current tribunal should include mandatory transparency of data collection and analysis methods.

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Appendix 1.

Research Projects in the Krishna Basin at IWMI, 2006.

1. "Basin water management for increased water productivity", funded by the Australian Centre for International Agricultural Research (ACIAR). Contact: Anju Gaur (email: a.gaur@cgiar.org)

2. "Water poverty mapping in Andhra Pradesh". Contact: Madar Samad (email: m.samad@cgiar.org)

3. "Agrarian change in the water scarce Krishna Basin". Ph.D. research thesis. Contact: Jean-Philippe Venot (email: jphvenot@yahoo.fr)

4. The "RUAF-CFF (Cities Farming for the Future)" program is a global initiative (http://www.ruaf.org) that aims to contribute to urban poverty reduction, urban food security, improved urban environmental management, empowerment of urban farmers and participatory city governance by capacity development of local stakeholders in urban agriculture and facilitating participation in multi-stakeholder policy formation and action planning on urban agriculture, including safe reuse of urban organic wastes. The project is funded by the International Development Research Center (IDRC) and the Dutch Directorate-General for International Cooperation (DGIS) and is for a duration of four years (2005-2008) involving 20 cities in 14 countries over 5 continents. IWMI is the South Asia and Southeast Asia Regional Coordinator of the RUAF-CFF project. The Hyderabad office of IWMI will focus on Hyderabad. Contact: Robert Simmons (email: r.simmons@cgiar.org)

5. "Ensuring health and food safety from wastewater irrigation in South Asia" is a three-year project supported by the German Federal Ministry for Economic Cooperation and Development (BMZ) (starting August 2005). The goal of this project is to improve health and safeguard wastewater dependent livelihoods of resource poor urban, peri-urban farmers and consumers in developing countries by developing and promoting the uptake of a set of risk mitigation options based on a comprehensive assessment of risks and benefits associated with wastewater irrigation in Hyderabad (India) and Faisalabad (Pakistan). Contact: Robert Simmons (email: r.simmons@cgiar.org)

Completed research projects include:

- "Water Swap" - Examined proposed transfer of freshwater from agricultural users in the Godavari Basin to urban users (Hyderabad), in exchange for urban wastewater from Hyderabad. Contact: P. Narayana (email: PN@iwmiin.exch.cgiar.org)
- "WENEXA - Water Energy Nexus Activity". Determined the feasibility of regulating groundwater use via energy supply pricing and rationing. Contact: P. Narayana (email: PN@iwmiin.exch.cgiar.org)
- "LEAD - Livestock-Environment Interactions in Watersheds". Examined the relationship between the hydrological context and socioeconomics in controlling livestock stocking rates, carrying capacity, and land degradation. Contact: R. Puskur, International Livestock Research Institute (ILRI).
- "Wastewater use and livelihoods in urban and peri-urban areas." Contact: S. Buechler (email: stephbuechler@yahoo.com)
- "Karnataka integrated water resource management in a sub-basin context." Looked at inter-linkages among watershed development, tanks, and drinking water. Contact: Ved Arya.
- "Pro-poor irrigation interventions in canal irrigation systems". Examined poverty and irrigation linkages in Krishna Delta System and Nagarjuna Sagar Left Bank Canal. Contact: Sivamohan (email: m.sivamohan@cgiar.org)

Appendix 2.

Reservoirs with more than 200 million cubic meters (MCM) live storage in the Krishna Basin.

Name	State	Gross storage (MCM)	Live storage (MCM)	Year of completion
Srisailam	AP	8,716	8,288	1984
Nagarjuna Sagar	AP	11,550	6,920	1972
Tungabhadra	KT	3,736	3,307	1953
Koyna	MH	2,797	2,640	1967
Bhadra	KT	2,023	1,785	1953
Ujjani	MH	3,320	1,440	1980
Nira Deodhar dam	MH	156	1,508	2001
Hidkal dam	KT	1,444	1,317	1977
Narayanpur	KT	1,071	869	1961
Alamatti	KT	1,194	841	2002
Malaprabha	KT	1,068	867	1973
Vanivilas Sagar	KT	850	797	1908
Warna	MH	974	779	1991
Dudhganga	MH		680	1992
Bhatghar	MH	673	666	1927
Dimbe	MH	382	354	1998
Dhom dam	KT	382	331	1977
Osman Sagar project	AP	329	318	1920
Manikdho dam	MH	308	283	1984
Vir Baji Pasalkar	MH	374	275	1993
Kanher dam	MH	286	272	2002
Veer	MH	278	266	1965
Panchshet dam	MH	303	256	1973
Radhanagari	MH	237	220	1955
Chaskaman	MH	242	211	2000
Himayat Sagar project	AP	217	204	1926
Total		42,910	35,694	

Notes: AP = Andhra Pradesh
KT = Karnataka
MH = Maharashtra

Research Reports

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101. *Carbon, Land and Water: A Gobal Analysis of the Hydrologic Dimensions of Climate Change Mitigation through Afforestation/Reforestation.* Robert J. Zomer, Antonio Trabucco, Oliver van Straaten and Deborah A. Bossio. 2006.

102. *Informal Irrigation in Urban West Africa: An Overview.* Pay Drechsel, Sophie Graefe, Moise Sonou and Olufunke O. Cofie. 2006.

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