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URBAN AND INDUSTRIAL WATER USE IN THE KRISHNA BASIN, INDIA†

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ABSTRACT

Regional urbanization and industrial development require water that may put additional pressure on available water resources and threaten water quality in developing countries. In this study we use a combination of census statistics, case studies, and a simple model of demand growth to assess current and future urban and industrial water demand in the Krishna Basin in southern India. Water use in this ''closed'' basin is dominated by irrigation (61.9 billion cubic metres (BCM) yr^{-1}) compared to a modest domestic and industrial water use (1.6 and 3.2 BCM yr^{-1}). Total water diversion for non-irrigation purposes is estimated at 7–8% of available surface water in the basin in an average year. Thermal power plants use the majority of water used by industries (86% or 2.7 BCM yr^{-1}), though only 6.8% of this is consumed via evaporation. Simple modelling of urban and industrial growth suggests that non-agricultural water demand will range from 10 to 20 BCM by 2030. This is 14–28% of basin water available surface water for an average year and 17–34% for a year with 75% dependable flow. Although water use in the Krishna Basin will continue to be dominated by agriculture, water stress, and the fraction of water supplies at risk of becoming polluted by urban and industrial activity, will become more severe in urbanized regions in dry years.

KEY WORDS: Krishna Basin; urban water use; industrial water use; modelling

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RÉSUMÉ

L'urbanisation régionale et le développement industriel demandent de l'eau, ce qui peut augmenter la pression sur les ressources en eau disponibles dans les pays en développement. Dans cette étude nous utilisons une combinaison de données de recensement, des études de cas et un modèle simple de croissance de la demande pour évaluer la demande en eau urbaine et industrielle actuelle et future dans le bassin Krishna en Inde du sud. Les usages de l'eau dans ce bassin « fermé » sont dominés par l'irrigation (61.9 milliards de m^3/an) alors que les usages domestiques et industriels sont modestes (1.6 et 3.2 milliards de m^3/an). L'eau utilisée en dehors de l'irrigation est estimée à 7 –8% de l'eau de surface disponible dans le bassin en année moyenne. Les centrales thermiques utilisent la plus grosse partie de l'eau allouée aux industries (86% ou 2.7 milliards de m^3/an) bien que seulement 6.8% de cette quantité soit consommé par évaporation. Une modélisation simple de la croissance urbaine et industrielle suggère que la demande non-agricole d'eau variera de 10 à 20 milliards de m^3/an d'ici à 2030. C'est 14–28% de l'eau de surface disponible du bassin en année moyenne et 17–34% de l'écoulement garanti à 75%. Bien que l'utilisation de l'eau dans le bassin Krishna continue à être dominée par l'agriculture, la tension sur l'eau peut devenir plus sévère en année sèche dans les régions urbanisées avec en outre le risque d'une pollution par l'activité urbaine et industrielle.

MOTS CLÉS: Bassin Krishna; utilisation urbaine de l'eau; utilisation industrielle de l'eau; modélisation

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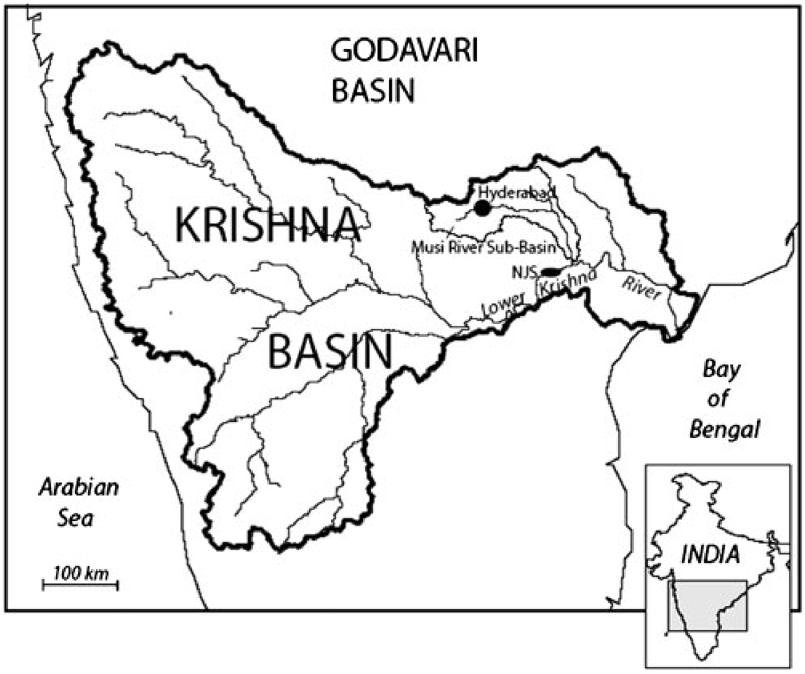

Figure 1. Map of the Krishna Basin

INTRODUCTION

Water demands for rapid industrial development and population growth in many developing countries put increasing pressure on freshwater resources. In a fully allocated basin, this demand can only be met by reallocation away from existing uses, most commonly from irrigated agriculture and by reuse of return flows, including an increased use of urban wastewater in irrigation. The negative impacts of reallocation emerge strongly in dry periods in regions where large industries and urban agglomerations share the same water source as an irrigation scheme, although the scale of impact depends on the size of the water source. The impact of additional urban water use on irrigation depends crucially on the size of the shared source (Van Rooijen *et al.,* 2005). For example, the phased pumping of water from the Nagarjuna Sagar reservoir in southern India to meet projected demands of the city of Hyderabad is large compared to historic water supply patterns, but it remains a relatively low volume when compared to what is allocated to irrigation each year.

Competition for water between agriculture and the urban–industrial sector may occur at a variety of scales, including the basin scale. The Krishna Basin, in southern India (258 514 km^2), has experienced increasing water scarcity due to rapid irrigation development (see map, Figure 1). The basin faces strong inter-seasonal and spatial variations in rainfall (Biggs *et al.,* 2007), which can cause acute scarcity and competition during dry years. Water availability varies considerably by sub-basin, and large projects that were built to increase water storage capacity have fuelled disputes among the three basin states: Karnataka, Andhra Pradesh and Maharasthra. Industrial development, urbanization and water pollution contribute to making available water scarcer and the chance of conflicts higher. Tensions among farmers have emerged when additional water, originally intended for irrigation, has been withdrawn for Hyderabad (Lakshimipathi, 2001). As a first step to mitigate water scarcity in the basin, it is necessary to know the scale and concentration of current non-agricultural water use. In order to better understand the dynamics of water use in the basin, it is necessary to map spatial concentrations and temporal peaks of water use in relation to dry areas or drought periods. When these dynamics are better understood, more integrated regulation of water use and reuse can contribute to creating a more sustainable future for water users in the basin.

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Table I. Industry water use and productivity for a selection of countries

Country	Industrial value added (IVA):[a] 2001 (in billion constant 1995 US$)	Industrial water use: 2000 (km3 yr^{-1})	Industrial water productivity (IWP) (US$ IVA m^{-3})
Japan	1890	16	119.62
Korea, Republic	286	3	93.66
UK	340	7	47.28
The Netherlands	120	5	25.17
Germany	748	32	23.43
USA	2148	221	9.73
China	594	162	3.67
India	120	35	3.42

[a] IVA is the estimated total money spent on industrial production.

Source: United Nations Educational Scientific and Cultural Organization (UNESCO) and World Water Assessment Programme (WWAP) (2006).

Even though overall urban growth rates for India are expected to decrease (Government of India, 2006), securing sufficient and reliable water supplies is emerging as a big challenge. Water use and wastewater disposal are increasingly unrestricted due to a lack of clear environmental policies and a fragmented responsibility and control over water used for industrial purposes (Centre for Science and Environment, 2004). Water use by water-consuming sectors is likely to increase faster than population growth. The World Bank expects that demand for water for industrial uses and energy production in India will grow at an annual rate of 4.2% to 2025 (World Bank, 1998a), compared to a projected population growth rate that will decline from 1.4 to 0.9% between 2006 and 2025 (Government of India, 2006). This future demand will inevitably increase pressure on the available freshwater resources, both due to water consumption and water pollution. On top of this, India scores poorly in terms of industrial water productivity (US$3.42 m^{-3}), which is among the world's lowest at between 2 and 40 times lower than those in developed countries (Table I). Current effluent standards use concentration as the measure of contamination, encouraging the practice of dilution until acceptable norms are met, rather than control at source and limitation of the total load exported. Relatively clean or reusable water polluted by industrial effluents renders it unfit for irrigation or other consumption and effectively represents a consumptive loss.

At present, the Krishna Basin is home to approximately 68 million people, of which about two-thirds live in rural areas (derived from Government of India, 2001). In addition to population growth, urbanization and economic growth amplify domestic water demands as urban areas consume more water per capita than rural areas (Madras Institute of Developing Studies, 1995). In India, the process of urbanization has resulted in a high percentage of the urban population residing in class I cities (population greater than 100 000), which rose from 25% of the urban population in 1901 to 64% in 2001. Population growth was higher in class I cities than in towns (size range 20 000–100 000), and this gap further increased during the 1990s (Government of India, 2001). The water consumption rates of these different populations differ markedly due to the establishment of water supply infrastructure. Piped water distribution systems supply 69% of households in large cities, 45% in smaller cities and towns, but only 9% of rural households in India (McKenzie and Ray, 2004). Hand pumps are the predominant source of drinking water in rural areas, which decreases per capita water use significantly. In 1998–99, the percentage of households that had piped water supply was 43.8 for Andhra Pradesh, 55.6 for Karnataka and 68.9 in Maharasthra, whereas in rural areas this was only 9.3, 10.4 and 22.5% respectively (McKenzie and Ray, 2004). The rising rate of urbanization in India has strong implications for the magnitude and spatial distribution of urban water demand.

Water used in cooling in power generation requires a significant proportion of total industrial water allocation in India. In both India and the Krishna Basin, most of the power is generated by coal-fuelled thermal power plants that need water for cooling, mostly using a once-through-flow system. Water use rates per unit of power generated are high in thermal plants, namely 80 m^3 per megawatt hour (MWh^{-1}), but in theory only a small fraction of the water is actually consumed through evaporation and the balance is returned to the environment, possibly causing thermal pollution.

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Industries in India have insufficient incentive to treat their effluents, or to reuse their water (Centre for Science and Environment, 2004). Urban wastewater reuse in irrigated agriculture is already taking place on a large scale, and increases in the wastewater volume generated by urban agglomerations will continue to provide a significant source of water for irrigation in the absence of any treatment, though one of different water quality (Van Rooijen *et al*., 2005). A study of the twin city of Hubli-Darward in the Indian state of Karnataka shows that secure wastewater flow allows irrigation of fields devoted to agro-forestry, vegetables and fodder production, especially in the dry season (Bradford *et al*., 2003). Water quality in relation to recycling is an additional concern in closed basins with increasing allocation to urban areas and industry.

Integrated water resources planning requires accurate determination of current water use patterns and an estimation of future growth in different sectors. A few government institutes in India have made efforts to estimate water use by all sectors in the Krishna Basin. An early attempt was made by the Central Pollution Control Board to quantify water use of the most important sectors for the entire Krishna Basin (Central Pollution Control Board, 1989). In a separate study, the Central Water Commission (CWC) compiled water balances for some of the 12 sub-basins in the Krishna Basin. However, a detailed estimate of water use for non-agricultural purposes is lacking. The government of Andhra Pradesh published a comprehensive vision for water management with estimates and strategies for future water use by the different sectors, but only for Andhra Pradesh and without a basin-wise perspective (Government of Andhra Pradesh, 2003). The Upper Bhima Water Partnership has prepared a similar vision for one sub-basin, the Upper Bhima (Upper Bhima Water Partnership, 2002). Revised water accounts and projections of future water use are necessary, especially those that distinguish among different sectors including domestic, industrial and thermal power generation.

In order to support integrated water resources management, we provide estimates of population, rural and urban domestic water use, and industrial and agro-industrial water use in the Krishna Basin. The goal is to identify the major urban and industrial features of the basin that are likely to dominate non-agricultural water demand now and over the next few decades. For example, the role of rural areas, towns, cities, industries, and thermal power production is determined. Urban water use in four cities has been analysed in detail to assess their impact on irrigated agriculture. The research results may be useful for policy makers involved in water resource planning and allocation in the Krishna Basin and can contribute to development of a formalized and transparent allocation policy within and across the three states. Results of this research will be of importance to the research on water productivity that is currently being conducted by the International Water Management Institute (IWMI) Hyderabad in the Krishna Basin. The work is intended to have broader resonance with more generic issues of urbanization and industrialization that are relevant in other basins and other developing countries.

RESEARCH OBJECTIVES

The research objectives were to:

- understand the spatial and temporal dynamics of non-agricultural water use in a closed basin;
- assess the impact of urban water use on irrigated agriculture for the largest urban and industrial settlements in the basin.

METHODS

Two approaches have been followed during this research. First is the basin and sub-basin assessment of water use by urban areas and industry. Population and water use rates by industry were combined with projected growth rates to model future water use dynamics within the basin. Second, four cities (Hyderabad, Pune and Vijayawada and Raichur) in different parts of the basin were used as case studies to understand the current and potential impact of urban water use on irrigated agriculture.

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Urban domestic water use

Domestic water use was estimated at the basin and sub-basin level by multiplying population (N_i) with a water use rate per capita (ω) for each settlement size class (i):

$$I_{\mathrm{dom}} = \sum N_{\mathrm{i}}\omega_{\mathrm{i}} \tag{1}$$

where I_{dom} = domestic water use ($\mathrm{m}^3\,\mathrm{yr}^{-1}$), N_i = population, ω_i = gross per capita daily water use ($\mathrm{m}^3\,\mathrm{d}^{-1}$) and i = settlement size class.

District-wise population data from the India Census (2001) were used to calculate N_i by sub-basin. The rural population (in settlements with fewer than 20 000 inhabitants) is relatively uniformly distributed in each district, so the district-wise rural population data were aggregated into basin and sub-basin-wise population using the area-percentage method. If one district has 80% of its area in the basin, we assume that 80% of the rural population in the district is living in the basin. Most of the urban population resides in cities with 100 000+ inhabitants that are much less uniformly spread over the basin. Accordingly, urban settlements of more than 20 000 people were located sub-basin-wise using a geographic information system (GIS).

Per capita water use (ω_i) is often higher in urban areas than in rural areas. Per capita water use is related to the water supply infrastructure, which clearly differs between rural and urban areas. Rural areas in India tend to rely on pumped groundwater, often from hand pumps in village centres. Urban agglomerations more commonly have surface water supplies, including the delivery of piped water. The Indian government uses a norm of 40 litres per capita per day (lpcd) for rural water supply systems. Urban areas that have piped water supply but no underground sewerage use considerably more water than rural areas, 70 lpcd. These values are norms and actual water use rates vary greatly per city and depend on city-specific characteristics of water infrastructure, management and availability. For example, actual net water use is much lower in Hyderabad (80 lpcd) compared to Pune (180 lpcd). Per capita water use (ω_i) can change with infrastructure development, which in turn is stimulated by economic growth. Water use rates were derived from various literature sources and specified by settlement size (Table II).

The settlement size defining urban and rural settlements (i.e. the boundaries defining the size classes) would ideally be based on water supply infrastructure, which is a primary determinant of consumption rates. Due to a lack of data on the supply infrastructure, we used a size threshold of 20 000, which yields comparable estimates to those based upon the district-wise urban population data from the Census of India (Government of India, 2001). Observed differences between the calculated sum of 20 000+ cities and the urban population from the district-wise census (Table III) can be explained by a different definition of the urban population. The Census defined and applied the following criteria to define rural and urban settlements: (1) a size threshold of at least 5000 inhabitants; (2) >75% of the male working population engaged in non-agricultural economic pursuit; (3) and a population density of

Table II. Population and estimated per capita water use in the Krishna Basin by size class

City size class	No. settlements (Census 2001)	Population (Census 2001)			Per capita water use	Domestic water use	
		million	%	% of urban use	(lpcd)	MCM	%
Million plus: Hyderabad/Pune	2	9.6	14.1	41.2		412	25
	Hyderabad	6.0	8.8	25.8	80[a]	175	11
	Pune	3.6	5.3	15.5	180[a]	237	14
Cities (>100 000)	28	9.5	14.0	40.8	120[b]	416	25
Towns (20 000–99 999)	96	4.2	6.2	18.0	100[b]	153	9
Villages (<19 999)	1617	44.8	65.8	—	40[c]	654	40
Total/average	—	68.1	100		66	635	100

[a] Estimations are based on case studies.
[b] Central Pollution Control Board (2003).
[c] Estimation based on Gleick (1996) and Government of Andhra Pradesh (2003).

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Table III. Distribution of urban and rural population in the Krishna Basin by sub-basin in 2001

Code	Sub-basin	Population (millions)					Area ('000 km^2)	Density (no. km^{-2})
		Total	% Urban	Rural	Urban	Cities[a]		
K1	Upper Krishna	5.4	23	4.1	1.3	1.9	17.6	304
K2	Middle Krishna	3.1	25	2.3	0.8	0.2	17.8	174
K3	Ghatabrabha	2.2	27	1.6	0.6	0.6	8.7	251
K4	Malaprabha	2.0	34	1.3	0.7	1.0	11.6	172
K5	Upper Bhima	13.4	41	8.0	5.5	5.5	45.3	296
K6	Lower Bhima	5.3	30	3.7	1.6	1.1	25.0	212
K7	Lower Krishna	10.4	21	8.2	2.2	2.7	35.4	295
K8	Tungabhadra	7.5	31	5.2	2.3	2.0	47.7	157
K9	Vedavathi	4.5	23	3.5	1.0	1.2	23.4	194
K10	Musi	7.2	70	2.1	5.0	7.0	11.3	641
K11	Palleru	0.6	16	0.5	0.1	0.0	2.9	212
K12	Muneru	4.8	27	3.5	1.3	0.2	10.3	462
K13	Krishna Delta							
Total	Basin	66.4	34	44.0	22.4	24.0	256.9	258

[a] Cities represents the sum of urban agglomerations having a population >20 000 inhabitants.

>400 km^{-1} (Bhagat, 2005). The threshold separating rural from urban water supply regimes could be refined by determining the size required for replacement of hand pumps with piped water supply.

Population growth rates for domestic water use estimates were set to be the same for all scenarios. The average annual population growth rates, derived from state-wise urban and total population projections, are 1.89 and 0.71 for urban and rural areas for the period 2001–26 (Government of India, 2006).

Industrial water use

Estimating current water use by industries is difficult due to restricted data access. District-wise data on the number of factories by sector were available, but were only published for medium and large industries or in terms of the number of factories. These units are difficult to use as input for estimating industrial water use, as it is not known how much water a particular industrial unit or factory consumes.

We use two alternative methods to estimate industrial water demand: domestic water use as a proxy for industrial water use, and industrial production data combined with per unit water use. Industrial water use (I_i) in million cubic metres per year (MCM yr^{-1}) can be estimated as a percentage of rural (f_r) and urban (f_u) domestic water use, as done previously by the Central Pollution Control Board (1989) with Equation (2a).

$$I_{ind} = I_{rd} f_u + I_{ud} f_r \tag{2a}$$

where I_{ind} = industrial water use (MCM yr^{-1}), I_{rd} or I_{ud} = rural or urban domestic water use (MCM yr^{-1}) and f_u or f_r = rural or urban water use factor (dimensionless).

The Central Pollution Control Board of India estimated that, on a basin scale, industries take about 20% of the total water volume that is annually diverted to non-agricultural use (Central Pollution Control Board, 1989). The cities of Hyderabad, Pune and Vijayawada yield numbers of the same magnitude that are comparable between cities (25%). Industrial water use in rural areas is significantly lower, as most industries are concentrated in urban areas. In the most rural districts in the basin, Mahboobnagar and Nalgonda (respectively 11 and 13% urban), only 4.4 and 3.0% of the water not allocated to irrigation was used by industries (Central Pollution Control Board, 1989). In the model, we assume that industrial water use in urban and rural areas accounts for 25 and 5% of total non-agricultural water use respectively.

Table IV. Area and number of factories of the states and of the state areas in the Krishna Basin.

State	Area (km^2)			Number of factories (Census 2001)		
	State	In basin	%	State	In basin	%
Andhra Pradesh	275 068	76 131	28	14 029	6 387	46
Maharasthra	301 690	69 398	23	28 324	10 486	37
Karnataka	191 791	113 419	59	9 440	1 852	20
Total/average	768 549	258 948	33	51 793	18 725	34

The second method for estimating industrial water use involves multiplying industrial production ($P_{\rm i}$) with specific water use rates ($\beta_{\rm i}$):

$$I_{\rm i} = \sum P_{\rm i}\beta_{\rm i} \tag{2b}$$

where $I_{\rm i}$ = industrial water use ($m^3\,yr^{-1}$), P_i = industrial production ($t\,yr^{-1}$) and β_i = water use rate ($m^3\,t^{-1}$).

Industrial production data have been translated from the state level to the Krishna Basin level, based on the percentage of factories in the state that are located in the basin, using data from the 2001 Census (Table IV). For the future scenarios, annual growth rates are based on sector-wise recorded values averaged for the period 1997–2006 derived from the Ministry of Commerce and Industry, Government of India (2007).

Water use for thermal power generation

Global scale estimates and country reports of industrial water use do not differentiate between water for manufacturing and water for thermal power generation (Vassolo and Döll, 2005). This is a serious oversight, especially if a distinction between types of pollution is to be made or where effective industrial water conservation measures need to be designed. Current power generation strategies in India do not foresee rapid changes in the balance of energy sources, so water demand for thermal energy generation is expected to grow at a rate that is comparable with overall power demand.

One megawatt hour (MWh) of energy requires an estimated 80 m^3 of water (Table V), of which a small fraction is lost as evaporation from cooling towers (Centre for Science and Environment, 2004). The ‘‘water productivity’’ of thermal power plants differs by plant; badly managed plants could use 200 $m^3\,MWh^{-1}$. In this assessment, we use the standard value of 80 $m^3\,MWh^{-1}$, though this is lower than the global average of 180 $m^3\,MWh^{-1}$ used by Vassolo and Döll (2005) and therefore represents a lower bound on water use by thermal power. Examination of the performance indicators of the thermal power plants in the Krishna Basin could refine water use and consumption estimates.

Water use by thermal power plants in the basin was estimated by multiplying basin thermal power production with a per unit water use rate (Equation 2b), as for the other industrial sectors. Hereby, basin thermal power production is the summation of power generation of all thermal power plants that are located in the basin.

Agro-industrial water use

Agro-industrial water use refers to water that is used for processing of harvested crops into a desired product, and does not include water consumption by crops during plant growth. It may not always concern food processing, and can also be for non-edible products like cotton. It is assumed that agro-industrial activity is mostly concentrated in rural areas in the vicinity of the areas of production. The products that are dealt with here are: cotton, sugar and rice, which are the main agro-industries in the basin. Agro-industrial water use ($I_{\rm a}$) is estimated by multiplying the amount of processed goods (P_i) with a specific water use rate (ω_i), using the following equation:

$$I_{\rm a} = \sum N_{\rm i}\omega_{\rm i} \tag{3}$$

where $I_{\rm a}$ = agro-industrial water use ($m^3\,yr^{-1}$), $P_{\rm i}$ = processed amount ($t\,yr^{-1}$) and $\omega_{\rm i}$ = water use rate ($m^3\,t^{-1}$).

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Table V. Water use by major water-consuming industries in the Krishna Basin

Sector	Production P_i (t)[a]	Water use rate ω_i ($m^3\ t^{-1}$)		Water use (I_{ind})		
		India average	Global best practice	MCM	% (excl. power)	%
Textiles (cotton yarn)	57 475	225 (200–250)[b]	<100[c]	12.9	3.1	0.4
Paper (and paper products)	250 000	150 (150–200) (wood)*b* (75–100) (waste paper)[b]	50–75 (wood)[c] 10–15 (waste paper)[c]	37.5	8.9	1.1
Iron and steel	7 000 000	50 (10–80)[b]	5–10[b]	350	83.2	10.2
Distilleries	1 050	150 (75–200)[d]	No data	0.2	0.0	0.0
Fertilizers	1 331 794	15 (1.4–20)[b]	1.5*c*	20	4.8	0.6
Thermal power generation	38[e]	80 m3 MWh^{-1} [b] (withdrawal)	<10 m3 MWh^{-1}[b] (withdrawal)	3 016	—	87.8
Total						
Thermal power excluded				421	100	—
Thermal power included				3 437	—	100

[a] Based upon most recent available production data average for 1996–2005.
[b] Centre for Science and Environment (2004).
[c] World Bank (1998b).
[d] Uttar Pradesh Pollution Control Board (2001).
[e] In 10^6 MWh, based on the sum of annual station-wise power generation in the Krishna Basin, in the years 2003–04.

Basin-wise production was estimated with cropped areas from the census data. Water use rates for processing (ω) were taken from the literature. Annual growth rates of agro-industrial production have been assumed as being the same as industrial production; 5% for the ‘‘business as usual’’ and ‘‘water savings’’ scenario and 7% for the ‘‘accelerated growth’’ scenario.

Impact assessment of urban water use on irrigated agriculture

Four cities serve as case studies of the impact of urban water use on irrigated agriculture. The case studies span the whole basin (Raichur) and include the two largest cities (Hyderabad, Pune), a city in the Krishna delta (Vijayawada), and a city in the central basin with high water use from industry and thermal power generation. Data on the location of urban water sources and agricultural users of those sources were extracted from the available literature and visits to the local water supply authorities. The impact assessment was carried out by comparing urban and industrial water use with agricultural water use from shared sources.

RESULTS

Population and domestic water use

The rural population was estimated at 44.8 million people who are assumed to use approximately 40 litres per capita per day (Gleick, 1996; Government of Andhra Pradesh, 2003). Urban areas in the basin include 96 towns in the size class of 20 000–100 000 people and 30 cities with a population of over 100 000 (Table II). The basin has 33 districts. The district capital is usually the largest city in the district, often having more than 100 000 inhabitants. Two cities with million-plus inhabitants (Hyderabad, Pune) account for the majority of the urban population in their respective sub-basins. Table II gives an impression of the distribution pattern of population by settlement size and estimated water use per category. Per capita water consumption in urban areas of the Krishna Basin (115 lpcd) was higher than the global norm (80 lpcd).

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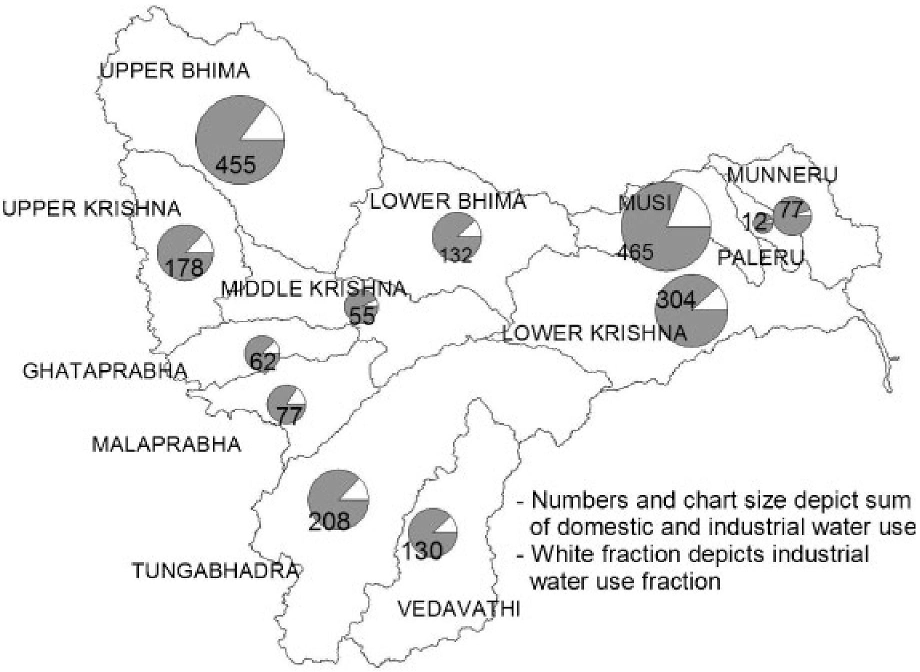

Figure 2. Totals for domestic and industrial water use by sub-basin and fractions for urban and rural areas in the Krishna Basin

Figure 2 presents the distribution of domestic and industrial water use for the urban and rural areas by sub-basin. Total domestic water use (rural and urban) in the basin is 1.6 billion cubic metres (BCM) based on population data from the Census of 2001. This number compares well with estimates of the World Bank for 1997 (1998). Their national estimate of 25 BCM gives 2.0 BCM when multiplied with the Krishna Basin area percentage of India (7.8%) and 1.6 BCM when multiplied with the percentage of India's population living in the Krishna Basin (6.5%). The urban population currently represents 34% of the total, but uses almost three times more water per capita, which is reflected in a 60% share of total water use. Both the million plus and 100 000+ population categories each represent 14% of the total population, but each accounts for 25% of basin domestic water use. Adding the two categories shows that the people living in cities (>100 000) represent 28% of the total population but account for half of domestic water use in the basin. Table II shows that, given expected urbanization patterns, more domestic water will be demanded in the Krishna Basin as a result of increasing average per capita water demand, apart from mere population growth.

Industrial water use

Total industrial water use in the Krishna Basin in 2001 is estimated at 0.30 BCM using a fixed percentage of domestic water use and without considering thermal power (Equation 2a). Total domestic and industrial water use varies strongly by sub-basin due to large variations in population by sub-basin (Table VI). Based on state-level industrial production data, weighted by the number of state factories in the basin, total industrial water use in the basin was 2.74 and 0.42 BCM in 2005, respectively with and without thermal water use, which is estimated as 88% of total use (Equation 2b). Table V shows the most important industrial sectors in terms of water consumption and an estimate of per unit and total annual water use. The largest manufacturing use of water is in the iron and steel sector with an estimated annual consumption of 0.35 BCM yr^{-1}. The sector that has the highest water use rate per unit of production is textiles, but total consumption is still modest, relative to iron and steel, with an estimated annual consumption of 12.9 MCM yr^{-1}. Industrial water use is dominated by the thermal power generation sector (3.02 BCM, Table V). Without considering thermal water requirements, the two methods of industrial water use estimation compare reasonably well (0.30 versus 0.42 BCM).

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Table VI. Domestic and industrial water use in the Krishna Basin by sub-basin in 2001 and comparison with 75 and 50% dependable flow in each sub-basin. Does not include water use for thermal power production

Sub-basin		Industrial water use[a] (MCM)			Domestic and industrial water use	Percentage of runoff		Runoff (75%)[b]	Runoff (50%)[b]
Code	Name	Rural	Urban	Total	(MCM)	75	50	(MCM)	(MCM)
K1	Upper Krishna	3.8	19.8	23.6	178	1.2	1.0	14 819	17 315
K2	Middle Krishna	2.1	2.1	4.2	55	7.9	3.0	697	1 821
K3	Ghatabrabha	1.5	6.3	7.8	62	1.5	1.4	4 039	4 492
K4	Malaprabha	1.2	10.4	11.6	77	4.1	3.3	1 857	2 350
K5	Upper Bhima	7.2	60.5	67.7	455	4.9	4.3	9 262	10 602
K6	Lower Bhima	3.4	12.3	15.7	132	2.0	1.8	6 658	7 249
K7	Lower Krishna	7.5	29.4	36.8	304	5.8	4.1	5 213	7 500
K8	Tungabhadra	4.7	21.7	26.4	208	1.9	1.7	10 867	12 180
K9	Vedavathi	3.2	12.6	15.8	130	10.2	8.2	1 280	1 583
K10	Musi	2	84.5	86.5	465	54.4	38.8	854	1 197
K11	Palleru	0.5	0.4	0.9	12	2.6	2.0	449	602
K12	Muneru	3.2	2.2	5.4	77	6.1	3.7	1 271	2 092
Total	Basin	40.2	262.2	302.4	2 155	8.6	6.1	57 266	68 983

[a] Industrial water use is 25% of urban domestic plus 5% of rural domestic.

[b] Data from the National Water Development Agency, for 75 and 50% dependable flow over the period 1901–96 for most sub-basins, derived from Sajjan (2005).

Estimates of total industrial water use in India range between 40 (Central Pollution Control Board, 2002) and 67 BCM (World Bank, 1998a). The World Bank estimates that current demand for water for industrial uses and energy generation will rise from 67 BCM (1998) to 228 BCM by 2025. Assuming that industrial water demand is uniformly spread over India, the Krishna Basin (7.9% of the country area) would have a water demand ranging between 3 and 5 BCM in 2001 and increasing to 18 BCM by 2025. This compares well with our detailed assessment from production data of 2.7 BCM in 2001.

Thermal energy

Our best estimates give 3.0 BCM of water use for thermal power generation, of which we assume that a small fraction (<10%) is consumed via evaporation. Total generated electricity in India in 2003 is estimated at 557 billion kilowatt hours (BkWh) of which 468 BkWh (84%) is produced by thermal installations[1]. Per capita total primary energy consumption in India doubled in the period from 1980 to 2003 from 1800 to 3800 kWh per capita yr^{-1}. Per capita electricity consumption (580 kWh yr^{-1} in 2005) is expected to exceed 1000 kWh yr^{-1} in the next 10 years, but will remain low compared to world average of over 10 000 kWh yr^{-1} (IndiaCore, 2005). The energy generated by thermal power plants has quadrupled since 1980 from 103 to about 440 kWh per capita yr^{-1} in 2003. Growth of electricity consumption may continue at a slower rate than gross domestic product (GDP), possibly due to an increasing contribution by the service sector (which does not consume much power at all), a lag in increasing capacity, or improvements in the efficiency of transmission and use. However, India is expected to have the fastest-growing energy consumption in the world after China, at 3.3% yr^{-1}until 2025 (Energy Information Administration, 2005). Coal consumption is expected to rise 2.5% yr^{-1} over the same period, so water use for thermal power generation is expected grow at the same rate, if coal continues to be used and per unit water use remains constant. Changes in per unit water use or water efficiency are expected to remain constant or improve, but to what extent is very uncertain and would require more in-depth analysis of environmental policy development for thermal power plants. In the analysis, an annual increase in efficiency of 2 and 0.5% m^{-3} was chosen for the water savings and accelerated development scenarios respectively, compared to a constant rate for the business as usual scenario (BAU).

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Table VII. Actual thermal power generation in the Krishna Basin for selected months in 2003 and 2004, system-wise and state-wise

Plant by state	April 2003	April 2004	May 2003	May 2004	Oct 2003	Oct 2004	Nov 2003	Nov 2004	Average annual 03–04		Water use
									GWH	10^6 MWh	MCM
Andhra Pradesh											
K'gudem	383	389	418	432	316	480	302	447	4 751	4.8	380
K'Gudem New	331	371	359	362	253	291	363	357	4 030	4.0	322
Vijaywada	800	895	883	868	882	743	761	838	10 004	10.0	800
Kondapali	180	183	197	184	195	190	196	204	2 293	2.3	183
Total (56% of KB area)	1 694	1 838	1 857	1 846	1 646	1 704	1 622	1 845	21 078	21.1	1 686
Karnataka											
KPCL Raichur	992	1 052	956	1007	917	825	948	985	11 523	11.5	922
Torangallu IMP Jindal	72	64	72	50	70	22	68	37	683	0.7	55
Belgaum	16	36	14	3	7	–	8	6	135	0.1	11
Total (33% of KB area)	1080	1152	1042	1060	994	847	1024	1028	12 341	12	987
Maharashtra											
Parli	407	282	296	243	349	437	387	480	4 322	4.3	346
Total (11% of KB area)	407	282	296	243	349	437	387	480	4 322	4.3	346
Total Krishna Basin	3181	3272	3195	3149	2989	2988	3033	3354	37 742	37.7	3 019

Source: Numbers derived from Central Electricity Authority. Operation and Monitoring Division.

Table VII identifies all thermal power plants in the Krishna Basin, with actual power production numbers given for the months April, May, October and November in 2003 and 2004. Data could only be found for these months in both years. It is assumed that power generation in the four months is representative of the whole year. This assumption will be most problematic during the irrigation season, when farmers use pumps for groundwater irrigation; however, our data include some months of active pumping (April, October, November) and the four months should be representative of a yearly average. The table shows that 37.7 million MWh yr^{-1} were generated on average for the years 2003 and 2004, of which 60% of the thermal power was in Andhra Pradesh, 30% in Karnataka and 10% in Maharasthra. This gives an annual thermal water use of 3.02 BCM (Equation 2b). State-level calculations of water use in power generation give lower values; 29 million MWh using and consuming 2.32 and 0.16 BCM of water. The average per capita thermal power use in India gives alternative values of 2.08 and 0.14 for thermal water use and consumption respectively. A comparison of results from using the three different estimation methods is displayed in Table VIII. The first method is considered best as it is based upon data of (all) thermal power that is produced in the basin while the other two methods are inevitably less reliable as extrapolation took place either from state- or India-level data to the basin.

Agro-industrial water use

Table IX gives the most important agricultural industries that have been identified in the basin. They are cotton, sugar and rice. The full amount produced is assumed to be processed as well. At present, the total volume of water used in processing sugarcane, cotton and rice is estimated at around 0.4 BCM. This amount is considerable when compared with domestic (1.6 BCM) or industrial water use (2.7 BCM), but it accounts for only 1% of average annual basin available water. Agro-processing is now regarded as the sunrise sector of the Indian economy in view of its large potential for growth and likely socio-economic impact on employment and income generation (Kachru, 2007).

Non-agricultural water use scenarios in the Krishna Basin

As the basin is considered nearly closed, average annual basin water availability can be determined as annual average runoff, which is around 58.3 BCM (Biggs *et al.*, 2007). The 75 and 50% annual dependable flow of water in

Table VIII. Results of industrial and domestic water use with different methods

Method	Equation	Domestic water use (MCM)			Industrial water use (MCM)		
Industrial water use		Urban	Rural	Total	Urban	Rural	Total
Fixed percentage of domestic use	(2a)	1 049	643	1 692	262	40	302
Production * water use rate	(2b)	–	—	—	—	—	2,739 (421)[a]
Domestic water use							
Population * lpcd per size class	(1)	981	654	1 635	—	—	—
Thermal water use		Power generation (million MWh)	Water use (MCM)	Water consumption (MCM)			
State%-production * water use rate	(2b)	29	2 318	158			
SUM (plant-wise production* water use rate)	(2b)	38	3 016	205			
Per capita thermal power use * pop	(4)	—	2 078	141			

[a] Number between brackets excludes thermal use.

the basin is respectively 57.3 and 69.0 BCM, derived from reports from the National Water Development Agency (NWDA) by sub-basin that include runoff time series for the period 1901–96, for most of the sub-basins. Non-agricultural water use as a fraction of 75 and 50% dependable flow gives a good indication of the fraction in dry and median years. Inter-annual variations in basin water availability may have consequences for sectoral water use fractions, in particular reduced allocations for agriculture. However, this may be the subject of further analyses when the necessary data are available.

A selection of the results in Figure 3 is discussed and water volumes or percentages are given in two forms: 50 and 75% dependable flow. The business as usual scenario estimates that domestic and (agro)-industrial water use may rise to 20–25% of basin water availability. Out of this, 13–15% will be used by industries (including thermal power plants), 5–6% for domestic uses and 3% by the agro-industrial sector.

Water use for non-irrigation sectors was ~8% of the average basin-scale runoff in 2001 increasing to 9–10% in 2010, and 11–18% in 2020, reaching 14–28% of annual basin available water for average years. For low-water availability years (75% dependable flow), water use by non-irrigation sectors is estimated at 34% in 2030, roughly one-third of basin available water. This has profound implications for agriculture one year in four, given that all urban and industrial demands will inevitably assume priority and also offer minimal opportunities for conservation. Therefore, contingency plans will need to be made for increasingly variable water supply to agriculture, irrespective of the development of wastewater reuse.

Industrial water use is closely linked to the economy of a country; as GDP increases, so does industrial water consumption. Future industrial growth rates are assumed at 5% annually for all sectors except thermal power for the

Table IX. Annual production and water consumption with agro-industrial processing of the main crops in the Krishna Basin for 1998

Crop type	Cropped area in 1998 (km^2)	Production in 1998 (P_i) (t yr^{-1})	Per unit water use (ϖ_i) (m^3 t^{-1})	Water use (j_{FP}) (MCM yr^{-1})
Sugarcane	4 842	46 104 500	0.6 (0.3–1.0)[a]	28 (14–46)
Cotton	10 134	1 202 100	300 (270–780)[b]	361 (325–731)
Rice milling	22 361	5 995 900	0.05 (0.002–0.050)[b,c]	0.30 (0.12–0.30)
Total				~400

[a] HR Wallingford (2003).
[b] Centre for Science and Environment (2004).
[c] Water that is only used for polishing.

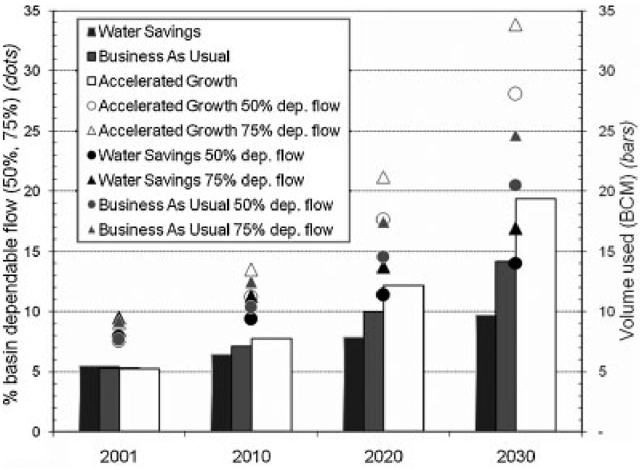

Figure 3. Water use volumes and percentages of 50% and 75% dependable flow in three scenarios for the Krishna Basin, for period 2001–2030

BAU and water savings scenario and 7% for the accelerated development scenario, based on data from the Government of India (2007). Industrial water use for the highest water-consuming sectors (excluding thermal) is estimated to increase from 0.4 to 0.9 BCM in 2010, 1.4 BCM in 2020, reaching 2.6 BCM in 2030 in the scenario of accelerated development (5% growth). Water use by thermal power plants increases from 2.7 to 9.5 BCM in the same period with a growth rate of 7%. Therefore, the key driver of industrial water demand will in fact be power generation, unless different cooling technologies are adopted. Cooling towers, for example, use significantly less water than flow-through systems currently in use in India (Vassolo and Döll, 2005). Since most of this water is returned to surface water bodies, the main impact of this demand will be on the need to maintain constant flows to the power plants and on water temperature.

Domestic water use is projected to increase from 1.6 BCM in 2001 to 2.0 in 2010, 2.6 in 2020 and 3.4 BCM in 2030, potentially taking respectively 2.2, 3.0, 3.8 and 4.9% of the basin water volume that is available in average years. Drinking water demand is therefore still modest in comparison to that needed in energy production. Agro-industrial water use remains relatively low but may reach almost 2 BCM in 2030, taking around 3% of basin available water by then.

Impact assessment of urban water use

Cities larger than 100 000 inhabitants account for half of urban water use, and the two million+ cities together (Hyderabad and Pune) account for a quarter of urban water demand (Table II). The major part of the demand in these large cities is met from surface water. In contrast, rural water is most often diverted from groundwater through pumps in the villages or water is taken from irrigation canals (McKenzie and Ray, 2004). The National Water Development Agency (NWDA) estimated that by the year 2025, 50% of the rural domestic water requirement in all sub-basins of the Krishna Basin will be met by groundwater, while all urban water will be met completely by surface water. While there is some groundwater use in urban areas like Hyderabad, the percentage is relatively low (11%) due to the nature of the hard rock aquifers that underlie most of the Krishna Basin. There is evidence that this source is already over-exploited for agricultural use and that water tables have declined by 2.5 m at a rate of 0.18 m yr^{-1} between 1989 and 2004 (Massuel *et al.,* 2007). Like the distribution of villages in the basin, rural water withdrawal points are diffuse. These diffuse withdrawals and relatively low per capita water use rates are likely to have a marginal impact on the water availability to other sectors. Tension between sectors using a shared resource is most likely to emerge first over surface water that is shared between irrigation and urban agglomerations.

Key figures on urban and industrial water use are given below for four cities in the Krishna Basin, including an assessment of current and future impact on water availability and water competition.

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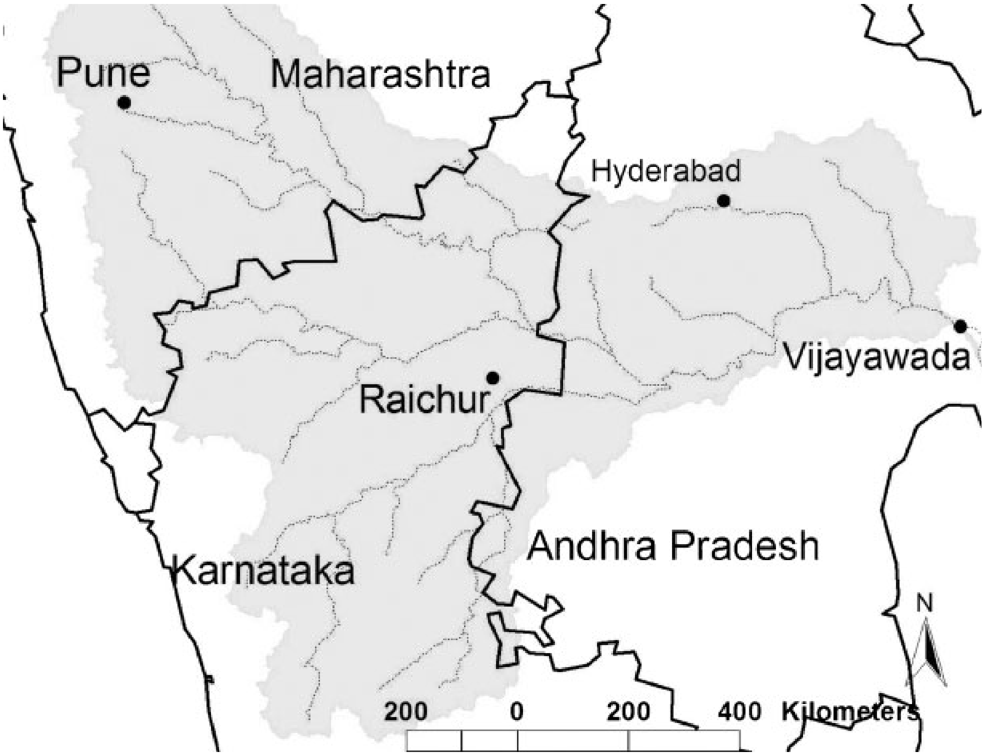

Figure 4. Location of the four cities in the Krishna Basin that were used in the assessment

Upper Bhima sub-basin and Pune agglomeration. In the Krishna Basin, the Upper Bhima Basin is the only sub-basin so far for which a vision has been reported for development up to 2025 (Upper Bhima Water Partnership, 2002). The main urban and industrial centre of the sub-basin and the second largest in the Krishna Basin is Pune (Figure 4). The Pune urban agglomeration consists of the municipalities Pune and Pimpri Chinchwad north of the river Mula. The present urban population exceeds 3 million, while Pimpri Chinchwad adds another 1.3 million people (Pune Municipal Corporation, 2004). Located near the high rainfall Western Ghats and near many reservoirs, it is currently supplied with fresh water from four dams: Khadakwasla, Panshet, Varasgaon and Temghar. The balance of the water from these reservoirs is used for irrigation down- and upstream of Pune city.

Groundwater is not widely used for urban water supply in Pune. Despite the vicinity of many reservoirs giving Pune a more favourable location compared to drier areas further from large reservoirs (like Hyderabad), competition for water is incipient. The annual requirement of Pune in 2001 was 325 MCM with a gross per capita availability of 294 lpcd (Pune Municipal Corporation, 2004). Water leakage in the piped supply system (26.5%) results in net water availability of around 216 lpcd, and includes industrial use. Water allocated to industries is assumed to be comparable with Hyderabad, around 17%. This reduces per capita domestic water use in Pune to 180 lpcd. Projected water demand of Pune by 2021 is 700 MCM, which would mean more than a doubling of current water requirement in 20 years (Maharashtra Krishna Valley Development Corporation, 2002).

An industrial area situated north of Pune uses a substantial amount of water from the Pavana reservoir, estimated to be over 200 MCM yr^{-1} (V. M. Ranade, Chairman Upper Bhima Water Partnership, personal communication, 17 May 2005), and it is expected that all existing reservoirs that supply some urban water will be used completely for that purpose within the next 25 years. This will inevitably affect water supply to the irrigated area downstream of Pune as no new sources are available. Already, farmers are using water from the Mula and Mutha rivers that contain mostly wastewater discharged from the urban area of Pune (V. M. Ranade, Chairman Upper Bhima Water Partnership, personal communication, 17 May 2005). Increases in urban needs will eventually result in the full use

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Table X. Expected change in Pune urban population, water requirement and percentage of current live storage capacity of the four reservoirs required

Year	Population Pune city (millions)	Historic water withdrawals / projected requirement[a]		% of current live storage capacity of 4 reservoirs (685 MCM)
		MCM	lpcd	
1961	0.5	22	124	3.2
1971	1.2	49	112	7.2
1981	1.8	100	152	14.6
1991	2.2	197	251	28.8
2001	3.0	325	294	47.5
2011	4.4	481	300	70.2
2021	6.5	708	298	103.4

[a] This may include water allocated to industries.
Source: Maharashtra Krishna Valley Development Corporation (2002).

of the four existing reservoirs for industrial and domestic purposes in Pune if no new water sources are allocated (Tables X and XI). Although urban water supply to Pune is secure, the additional water requirements will leave irrigated agricultural areas downstream of Pune with less water. As in the Hyderabad case, expansion of the current wastewater-irrigated area could compensate to some extent for expected losses. However, there will be a change in who has access to that water. Even if there are no long-term macroeconomic impacts, there will be losers who will need to be compensated or otherwise looked after.

Musi sub-basin and Hyderabad agglomeration. Hyderabad is the largest urban agglomeration in the basin, with a population of over 6 million people, making it the fifth largest city of India (Figure 1). Water use in 2004 was around 0.35 BCM yr^{-1} (Van Rooijen *et al*., 2005). Until 1960, water was supplied from two nearby reservoirs, Himayat and Osman Sagar, that were primarily developed to satisfy domestic and industrial water requirements in Hyderabad. Since then, augmentation of water supply began from the Manjira (1960) and Singur reservoirs (1990) and then from the Nagarjuna Sagar reservoir (2004). The majority of Hyderabad's water supply ($>$80%) comes from these external sources. Ambitious plans are in the pipeline to pump water from the Godavari River. At present, urban water supply is interrupted on average for a few hours per day. Per capita net water supply (excluding 30% distribution losses) is estimated at 80 lpcd. Van Rooijen *et al*. (2005) concluded that the impact of urban water use on irrigated agriculture will remain relatively low; Hyderabad will take 5–10% of average reservoir releases from Nagarjuna Sagar reservoir by 2030. Also, storm water runoff generates a similar volume to that of domestic wastewater, providing additional water to the wastewater-irrigated corridor downstream. Wastewater irrigation compensates for more than half of the traditional irrigated area lost, which is an opportunity that also needs to be considered. However, with a trend of reducing and lagged inflows to Nagarjunar Sagar as further upstream

Table XI. Storage capacities of the reservoirs that supply Pune with water

Reservoir	Varasgaon	Panshet	Khadakwasla	Temghar	Total
Distance to Pune city (km)	43	43	19	50	
River dammed	Mose	Ambi	Mutha	Mutha	
Storage capacity (MCM)					
Gross	374	303	85	108	869
Live	275	255	57	99	685
Dead	99	48	31	8	187

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development continues, the impact of urban water transfer in low flow years will be significant – as much as 30–40% of supplies available with a current return period of once every 10 years.

Lower Krishna sub-basin and Vijayawada city. Vijayawada is located in the delta of the Krishna River Basin on the bank of the river (Figure 4) and represents cities located in major irrigated command areas. Vijayawada had a population of nearly a million in 2001 (Government of India, 2001). Annual urban water supply is 58 MCM (in 2003) with net domestic water supply of 140 lpcd and an estimated one-quarter, or 14.5 MCM, going to industry. In addition, 800 MCM of water for thermal power generation is taken from and discharged back into the Krishna River. Annually, 48.1 MCM of the urban water is withdrawn from the nearby Krishna River (~75%) and 16.6 MCM originates from groundwater bore wells (~25%) (Centre for Economic Studies, 2002). Non-revenue water is about 60%, of which 20% is supplied for free through public taps and to various governmental agencies, and 40% is lost by way of leakages and theft (Vijayawada Municipal Corporation, 2006).

In the last four decades, Vijayawada's population growth was highest between 1981 and 1991, with a decadal population growth rate of 52%. Between 1991 and 2001, this rate fell to 22%. The annual growth rate between 2001 and 2021 is projected to be 3.3%, resulting in a population of 1.5 million in 2011 and 2.0 million in 2021 (Vijayawada Municipal Corporation, 2006). Vijayawada has traditionally been the main agricultural market centre of the Krishna Basin. It also acts as a centre of trading in consumer goods, textiles, cars, industrial products and more. The presence of a thermal power plant is said to have supported industrial development in and around the city. Water supply is currently sufficient, although withdrawals will have to increase to meet future water requirements. The Krishna delta, situated further downstream of the city, is known for its large irrigated area, the second largest after Nagarjuna Sagar canal command, having an average cropped area of over 3000 km^2 (Superintending Engineer Vijayawada, 2004). Due to weak monsoons and upstream development, total canal flow to the area was half of the long-term average in the years 2001 and 2002 (Table XII) (Venot *et al.,* forthcoming).

The urban demand is marginal compared to ''average year'' total canal flows to the Krishna delta; 53.9 out of 6295 MCM (0.9%) (Table XII). The relative volume of water that is used by urban Vijayawada is low even in ''dry years'' (2.0%), if assumed that urban water use remains constant in a dry year. If the estimated groundwater extraction would have to be replaced by Krishna River water, then the volume relative to irrigated agriculture in the Krishna Delta (KD) will still be minimal (1.1% for an average year and 2.7% for a dry year). It should be noted that, in this analysis, it is assumed that the total Krishna River discharge after the intake point of Vijayawada is being used for irrigation in the Krishna Delta, although a decreasing amount still flows to the sea and supports a much degraded coastal ecosystem (Venot *et al.,* forthcoming).

If there is a limit to available water in the Krishna River and if this is being shared by urban and agricultural use, then any additional water that would be pumped from the Krishna River would be at the cost of the volume of water diverted to the Krishna Delta irrigation scheme. However, the relative volume of water that is allocated to urban use is so small compared to the annual volume of water that is used for irrigation in the Krishna Delta, both for average

Table XII. Comparison of withdrawal for Vijayawada urban and thermal power use with agricultural water use in the Krishna Delta

	Water used in Krishna Delta (KD) [a]	Diversion from Krishna River for Vijayawada urban water use		Diversion from Krishna River for thermal power use	
	(MCM)	MCM	% of KD	MCM	%
Average year[b]	6 295	53.9	0.9	800	12.7
Dry year[c]	2 674	53.9	2.0	800	29.9

[a] This is the volume of water used for irrigation in the Krishna Delta derived from the summation of recorded canal flows of *kharif* and *rabi* seasons for left and right bank canals (Source: Superintendent Engineer's records, Vijayawada 2004).
[b] Average year is based on average of canal flows during 1980–2003.
[c] Dry year is based on average of canal flows during the dry years of 2001–02.

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and dry years, that impacts are expected to be minimal. But it should be noted that the use of monthly data series would probably give more insight into the importance of urban water use in more extreme water availability periods. The Vijayawada thermal power plant uses an estimated 800 MCM of water, equivalent to between 12.7 and 29.9% of total agricultural water used in the Krishna Delta in average and dry years respectively (Table VII).

Tungabhadra sub-basin – Raichur city. Raichur is the capital of Raichur district, located in Karnataka with a population of 206 000 in 2001 (see map, Figure 4), and is used here as an example of water supply to a mid-sized city. Annually, the city uses around 11 MCM (30 lpcd) of water that originates from three different sources. First and most important is the Krishna River (61%), at a distance of 20 km. Second is the Tungabhadra River (39%) from a distance of about 25 km and a relatively small volume is withdrawn from groundwater (0.4%). Urban industrial water use (excluding thermal use) is estimated at 0.37 MCM, which is 3.3% of the urban water supply (G. Mallikarjun, Assistant Executive Engineer, Raichur City Municipal Corporation, personal communication 21 June, 2005).

Raichur district has the biggest thermal power plant in the Krishna Basin, located 20 km north of Raichur. Its seven cooling towers serve a total annual generating capacity of nearly 1.5 million MWh that meets 40 and 31% of energy use in Karnataka state and the Krishna Basin respectively (Table VII). The thermal plant uses 920 MCM yr^{-1} (at 80 m^3 MWh^{-1}) from the Tungabadra River, mainly for cooling. It is assumed that only a small fraction of this volume is actually consumed. The Tungabhadra reservoir, primarily used in irrigation, is the source for the power stations, and its inflow reduced during 2002–04 from 8.8 to 3.3 BCM (Gaur *et al.,* in press). Water use by Raichur city (11 MCM) is marginal (0.3%) compared to 3.3 BCM; however, we estimate that water use for thermal power generation (920 MCM) accounted for almost 28% of Tungabhadra reservoir inflow in 2004. Actual water use by the thermal power plant may differ from our estimates, but our calculations suggest that its water use is significant and could affect reservoir operations, particularly in dry years.

Summary of city cases. Table XIII gives an overview of the findings of the city case studies. The impact of urban water withdrawal on the groundwater level has not been analysed. The biggest urban agglomerations, Hyderabad and Pune, withdraw significant volumes from all water sources that they rely on. The proximity of one river at Vijayawada and two rivers at Raichur seems to put them in a more favourable position. The table indicates a correlation between the volume of annual withdrawal and distance to source, number of sources and percentage of source in use. The number and distance of sources increase with the volume of water that is allocated to an urban agglomeration. This brings us to the conclusion that cities increasingly take water from new sources further away to satisfy rising demand. It seems to be a strategy followed by urban water supply authorities to secure supply in water-scarce periods and to quench an increasing urban thirst.

DISCUSSION

Basin-level water demand

The Krishna Basin study is based on several quantitative assumptions due to a lack of data. Those assumptions include a constant per capita water use in rural areas, a constant per capita water use in urban areas, a fixed threshold dividing rural and urban settlements, and a constant water consumption rate per unit of production for industry. While the consumption rates are based on data from individual case studies, they may in fact vary throughout the basin, with urban settlement size, and with time. Given the data limitations, the purpose of the study is to estimate the approximate magnitudes of urban and industrial water use, and to quantify the importance of several processes, including rapid urbanization and the large demand from thermal power production. Highlighting these processes suggests areas for future research that could more precisely determine water consumption patterns, particularly in small to mid-sized urban agglomerations and in thermal power production.

Impacts of this urban and industrial water use on agriculture can be anticipated for all growth scenarios in the future (up to 2030) and could be quite severe even in average years if it reaches 34%. There are likely to be a number of political and other factors that may rein in this expansion of non-agricultural water supply, but the implications

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Table XIII. Water supply characteristics of four major urban agglomerations in terms of water use in the Krishna Basin

City and water sources	Population	Annual withdrawal for urban use		Distance to source	Reservoir capacity (or canal flow)	Design purpose of source	Percentage of source used
	(millions)	(MCM)	(%)	(km)	(MCM)		
HYDERABAD	6.0	380	100				
Nagarjuna Sagar Reservoir		123	32	120	11 560	Irrigation	1.1
Singur Reservoir		108	28	80	849	Irrigation/domestic	13
Manjira Reservoir		65	17	59	42	Irrigation	155[a]
Osman Sagar Reservoir		23	6	15	110	Domestic	100
Himayat Sagar Reservoir		19	5	9	84	Domestic	100
Groundwater		42	11	—	—	—	—
PUNE[a]	3.6	325	100				
Panshet, Varasgaon, Khadakwasla and Temghar Reservoir		325		30–43	651	Irrigation/domestic	50
Groundwater		Marginal	<5	—	—	—	—
VIJAYAWADA	0.8	72	100				
Krishna River		54	75	—	6 295[b]	Irrigation	1
Groundwater		18	25	—	—	—	—
RAICHUR	0.2	18	100				
Tungabhadra River		7	39	25	—	Irrigation	n.a.
Krishna River		11	61	20	6 295[b]	Irrigation	<1
Groundwater		0.4	<5	—	—	—	—

[a] Manjira reservoir receives additionally a water volume from Singur reservoir that exceeds Manjira's own capacity.

[b] Canal flow to Krishna Delta irrigation scheme.

are substantial. The more likely points of tension will be in low and very low water availability years and seasonally in unusually dry months at the start (or end of) the summer crop season, and in the second (out of monsoon) crop season (November–April).

Therefore, more distributed spatiotemporal modelling for the whole basin is needed, in a similar fashion to that done for Hyderabad (Van Rooijen *et al*., 2005), either using a dynamic programming approach, or through simple spreadsheet-based scenario analysis. A monthly time step analysis would be useful in highlighting the within-year water competition hot spots and could be used to generate some charts of frequency of occurrence of different levels of stress. Consultation work would be required with agricultural planners and the farming community to define stress and develop measures to prevent water scarcity and competition among sectors.

Urban water demand and urban centres. By 2021, the three states in the Krishna Basin are expected to be among the top five most urbanized in India, at levels of 50.5% for Maharasthra, 41.1% for Karnataka and 39.1% for Andhra Pradesh (Sivaramakrishnan *et al.,* 2005). This would suggest that the Krishna Basin will be among the most urbanized basins in India. Also, Mitra (2000) found for India that urbanization stimulates industrial growth and vice versa. The highest industrial growth rates are found in the more urbanized states. This would indicate increasing industrial activity and subsequent industrial water use. These trends are captured for the Krishna Basin using a range of growth rates for urban populations and industry.

In the Krishna Basin where available water is nearly fully utilized, local reallocation needs to be well planned to (1) generate maximum usable return flows (untreated and semi-treated wastewater) for agriculture and (2) to minimize contamination by industrial pollutants that would further limit the possibilities for wastewater reuse. There will also need to be good and fair compensation for farmers who lose all their irrigation supply in areas such as Pune. Other mechanisms of drought relief or compensation will be required for existing irrigators that suffer seasonal or annual shortages in low water availability years, as a result of high priority allocation to cities and industry. There remains much work to be done in valuing water in these competing uses and in establishing transparent mechanisms to manage transfer and assure equitable treatment of losers. Even identifying who are losers poses some challenges.

Power demands

The demand for power is expected to increase at least in tandem with the rates of population growth and economic growth. Of the total planned additional capacity in India of 41 110 MW from 2002 to 2007, the majority is thermal power of 25 417 MW (62%), compared to 14 393 MW of hydropower (35%) and 1300 MW (3%) of nuclear power (Government of India, 2007). The Ministry of Power's Eleventh Plan expects energy demands to increase by 9% yr^{-1} for 2007–11, which is comparable with GDP projections.

For the plan period 2007–11, an additional 15 585 MW of hydropower is required, which is 23% of the total planned power consumption. Nuclear power is described as an environmentally benign source of energy that will make an increasing contribution in the future. A moderate capacity addition of 3160 MW (5% of the total) is planned for 2007–11, while much more is expected in the Twelfth Plan. In the thermal power sector, a total of 50 124 MW (73% of the total) is planned in the Eleventh Plan period, of which 46 635 MW of coal based, 1375 MW lignite based and 2114 MW dependent on gas. The proportions of thermal and nuclear power will increase, as exploitable water resources for hydropower reach their limit.

Time frames for agricultural adaptation and industrial water use stagnation

Insight into the pattern of basin industrial water use is relevant for basin resources management in general and to a range of other disciplines. The environmental Kuznets curve describes how emissions of pollutants first increase, then decrease during the course of economic development. Jia *et al*. (2006) showed that the Kuznets curve can also be applied to industrial water use in a country, based on empirical data from a range of countries that have passed their peak in industrial water use. After industrial water use increases in a development phase, it will eventually decrease with rising per capita income and further changes in economic structure. A relevant question for the

Krishna Basin is how much additional water will be needed in the industrial sector before reaching such a turning point. A correlation has been found between the industrial water use, the share of secondary industry in total GDP, and per capita GDP. Peak industrial water use has been reached by OECD countries when the GDP per capita reached between 10 000 and 25 000 USD (1995 constant prices). Wilson and Purushothaman (2003) project United States dollar (USD) per capita GDP for India to exceed 10 000 USD between 2040 and 2045, hence the estimated turning point for industrial water use lies beyond our time frame.

For different scenarios of growth in non-agricultural water use, we can look at the implications for agriculture in a number of different ways. There will be small average and sporadically severe reductions in cropped area as well seasonal effects on net cropped area through reduced cropping intensity and the ability to eventually harvest the sown area. The security of supply (or supply reliability) for irrigation will decrease significantly if the non-agricultural uses require 100% satisfaction in any year, and this is almost certain to be the case. To compensate and maintain or raise levels of crop production, improvements in crop water productivity will be required and may be achieved:

- on the same area of land, through reducing crop evapotranspiration (ET) using deficit irrigation strategies, or changes in crop type;
- on a reduced area of land, with same amount of ET but higher production per mm ET.

CONCLUSIONS

The relative share of non-irrigation uses in the annual available water volume in the Krishna Basin is relatively low due to the size of the reservoirs feeding the irrigation sector (for example the Nagarjuna Sagar and Tungabhadra). However, with the current rates of Indian economic development, the Krishna Basin is likely to change from being a predominantly agricultural one to an industrial and urbanized landscape.

The largest urban centres in the basin like Pune and Hyderabad, and the mid-sized cities Raichur (for thermal power) and Vijayawada (for industries), are likely to determine the development of industries in the Krishna Basin. The highest rate of growth in industrial production can be expected in the expanding areas or periurban fringes of these cities. In contrast, the rapid expansion of the service and IT sectors in Hyderabad will not directly increase industrial water use, as these industries do not need large volumes of water for their activities.

Domestic water use was 1.6 BCM annually in 2001, taking only 2% of total available surface water supplies, while rural areas are predominately supplied by groundwater. Nevertheless, the rural areas in the basin account for the largest share of domestic water use (40%), followed by the two cities that have more than 2 million inhabitants (Hyderabad and Pune, 25%), smaller cities (25%) and towns (9%). Overall population growth, urbanization and development (such as upgrading of water supply at city and household levels) are the most important factors in future increases in domestic and industrial water use.

The impact of increased domestic water use on irrigated agriculture will be greatest in large cities, which rely on surface water reservoirs. Urban water demand is concentrated in a relatively small area and can easily exhaust local water sources (Van Rooijen *et al.,* 2005), though in the Krishna Basin urban areas also withdraw water from distant sources (up to 120 km).

The main driver of increased non-agricultural diversion will be thermal power generation, which currently uses 2.3 BCM of a total of 2.7 BCM used in all industrial activities in 2001. It can be expected that water demand for thermal energy generation will rise at least at the same rate as population growth. It is highly likely that priority in the future will be given to this sector at the cost of the farm sector, though in many cases the water is used for cooling and much of it is returned directly to the water source. The arrangement of sources and outlets for process water in thermal plants, and the effect of thermal water demand on reservoir operations, will be key determinants in its ultimate impact on irrigated agriculture. The thermal power sector in India is not efficient in terms of water consumption ($80\,\mathrm{m}^3\,\mathrm{MWh}^{-1}$) when compared to global averages ($<10\ \mathrm{m}^3\ \mathrm{MWh}^{-1}$). This means that there is considerable potential for water conservation, which is reflected in changes in water use efficiency for each scenario. This variable could be refined with better projections of industrial development.

Agro-industries in the Krishna Basin currently use relatively little water ($0.4\ \mathrm{BCM\ yr}^{-1}$), which is only 1% of total average basin availability and is expected to increase to a maximum of 7% of average basin water available in

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2020. This reflects the generally low rate of food and agricultural processing in India in general, and water use from this industry might be expected to expand with the development of the food processing industry.

The Krishna Basin is still in a primary stage of classic industrial development. Current industrial water use is 5% of average basin availability, which is below average for a low-income country (8%). India is expected to sustain rapid economic development with a projected constant real GDP growth rate of 6% (Wilson and Purushothaman, 2003). India's likely path to becoming a middle- and high-income country entails increasing industrial water use that will reach a level typical for high-income countries: 59% (United Nations Educational Scientific and Cultural Organization – World Water Programme, 2006). The development of industries, food processing and population growth, especially in cities, will inevitably entail a growth of water demand in these sectors, which in turn will pull water out of irrigated agriculture. Competition and conflicts may arise in critical irrigation periods when water availability is low.

Comparison of the Krishna Basin with other basins

As a result of severe problems with water availability and water quality, China's Yellow River basin is increasingly the subject of research in relation to water resources management. Expected water shortage in the basin for the year 2010 is estimated at 3.1 BCM (4.3%) (Xi *et al.,* 1996 in Xu *et al.* 2002) and 2.08 BCM (4.1%) (Zhang *et al*., 1999 in Xu *et al.,* 2002). Xu *et al.* (2002) calculate that water shortage in the basin will be 2.29 BCM (4.5%) by 2010, based on estimations of water demands with the use of a dynamic model. Unless alternative sources are developed, shortages in 2020 and 2030 will be 6.24 (11.1%) and 6.62 BCM (11.2%) respectively. The marginal increase of shortage between 2020 and 2030 (only 0.1%) can be explained by an expected drop in water demand in the agricultural sector. The authors argue that inter-basin transfer to supply water to the Yellow River Basin is unavoidable, even when wastewater is recycled. Development of the ambitious south–north water transfer project is ongoing, aiming to transfer 40–50 BCM, of which 20 BCM would be allocated to cities and industries that are rapidly growing in the North China plain (Berkoff, 2003).

The Lerma–Chapala Basin in Mexico is experiencing increased use for all consumptive sectors, particularly the domestic and industrial sectors, resulting in a state of crisis in relatively dry years, in this rapidly urbanizing and closed basin (Scott *et al.,* 2005). Unlike the Krishna Basin, a recent change in water law, basin-level water resource planning, increased user participation in water management and nascent inter-sectoral water markets were institutional innovations developed in response to the emerging challenges. However, the lack of appropriate mechanisms to allocate scarce water resources to consumptive demands generates competition that may severely degrade the resource base, both in terms of quantity and quality. In 1999, a large-scale water transfer occurred to Lake Chapala when the city of Guadalajara obtained 240 MCM of upstream reservoir water without compensating farmers upstream for the loss of water originally intended for irrigation. Trends in the state of Guanajuato, the largest water user in all sectors in the Middle Lerma sub-basin, indicated that the number of urban users is rising at 4.1% annually, of which 4.0% represent domestic and commercial water users. More notable is a 9.2% annual increase in industrial use (Comisión Estatal de Agua y Saneamiento de Guanajuato, 1999 in Scott *et al*., 2005). Urban water use is almost exclusively met by groundwater, while most surface water is used for irrigation. After applying economic valuation techniques for water use by the different sectors, Scott *et al*. (2005) advocate water reallocation mechanisms that ensure financial compensation to irrigators in water-short basins. The real opportunity for compensation based on water markets lies in transfers of agricultural water to commercial and industrial use, where the estimated and actual values of water are significantly higher. Examples of compensation paid to farmers where water is transferred from agriculture to urban use can be found in cities like Seville (Spain) and Chennai (India) (see Molle and Berkoff, 2006).

Molle and Berkoff (2006) provide a wide range of examples in which urban areas out-compete the irrigation sector to satisfy increasing water needs, including Hyderabad. Their conclusion, that urban water use can have an impact on agriculture, is also the case at the larger scale of the Krishna Basin. Meinzen-Dick and Appasamy (2002) address the process of urbanization and the emerging competition for water. They discuss water values for different sectors and three options for meeting increasing demands: increasing supply through new sources, reallocation from other sectors and urban demand management. In the Krishna Basin, the first option is through water transfer from the Godavari Basin, where reallocation is visible without compensation and urban demand management has so far not been considered and is not generally likely in the medium term.

NOTE

[1] http://www.eia.doe.gov/emeu/international/electricitygeneration.html

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