Krishna Basin Development: Interventions to Limit Downstream Environmental Degradation

Jean-Philippe Venot, Bharat R. Sharma and K.V.G.K. Rao

The Journal of Environment Development 2008; 17; 269

DOI: 10.1177/1070496508320532

The Journal of Environment & Development
Volume 17 Number 3
September 2008 269-291

10.1177/1070496508320532
http://jed.sagepub.com
hosted at
http://online.sagepub.com

Krishna Basin Development

Interventions to Limit Downstream Environmental Degradation

Jean-Philippe Venot
International Water Management Institute, Hyderabad
Bharat R. Sharma
International Water Management Institute, New Delhi
K. V. G. K. Rao
Indwa Technologies Pvt. Ltd, Hyderabad

Since India gained Independence, the Krishna basin has seen an increasing mobilization of its water resources. Warnings of basin closure (minimal flow to the ocean) emerge during dry periods. Basin water development and local rural dynamics have led to a degradation of downstream ecosystems manifesting itself by salinizing soil and groundwater, increasing pollution, making mangroves disappear, and desiccating wetlands. Reversing this evolution requires the formal recognition of the environment as a water user in its own right and the implementation of an environmental water provision. This provision should be based on a two-tier allocation system with assured discharges in the irrigation canals of the delta and to the ocean. This will lead to further commitment of water resources, but this is needed to reconcile the social, economic, and environmental objectives of sustainable development. Other measures facilitating integrated natural resources management from the local to the basin level are needed too.

Keywords: *water resources development; rural development; integrated natural resources management; water allocation; environmental preservation; India*

Introduction

Water use for urban, industrial, and agricultural growth is approaching and in some cases even exceeding the availability of renewable water. Agroecosystem dynamics and excessive infrastructural development result in overcommitment of water. This particular approach to water resources management and development has led to significant degradation of various ecosystems (Pearce, Atkinson, & Mourato, 2006; Falkenmark,

Authors' Note: Please address correspondence to Jean-Philippe Venot, IWMI c/o ICRISAT, Patancheru 502 324, Andhra Pradesh, India; e-mail: j.venot@cgiar.org.

Finlayson, Chiuta, & Gordon, 2007), and many river basins in the world are facing an *environmental water scarcity* (Smakhtin, Revenga, & Doll, 2004). However, to date, most developing countries have paid little attention to this overcommitment and to its environmental consequences. Management tools to reverse or mitigate this evolution are rare.

The United States of America, South Africa, and Australia are countries where environmental water requirements have been mainstreamed in water resources policies and legislation. This mainstreaming led to the recognition of formal water allocation procedures as the most adapted tools to reconcile the social, environmental, and economic objectives of sustainable development and integrated water resources management. There is increasing evidence of the adverse impacts of water and land degradation on people's livelihoods (Emerton & Bos, 2005; Falkenmark et al., 2007; Millennium Ecosystem Assessment [MEA], 2005). Therefore, balancing environmental requirements and human consumptive uses is now widely regarded as a top priority, and the notion of environmental flows is establishing itself firmly. It is an attempt to find a compromise between productive uses and some protection threshold. But achieving this balance represents a considerable challenge in many of the world's river basins, especially in arid and semiarid areas of the developing world, as more vocal populations and associated water demands increase to sustain a broader economic development (National Commission for Integrated Water Resource Development Plan, 1999; United Nations Administrative Coordination Council/Inter-Secretariat Group on Water Resources, 1992; World Water Assessment Program, 2003).

However, most developing countries do not have well-defined procedures for effective water allocation, and water policies generally only list "allocation priorities." Although economically and socially or politically powerful users have comparatively well-developed methods for quantifying and justifying their water needs, the ecosystems continue to be the silent and weak water user. As such, environmental water requirements have not yet received the required attention in water policies and in the general discourse on water resource governance: They are generally ignored, as the water flowing to the sea is considered to be "lost or wasted" (see Government of Andhra Pradesh [GoAP], 2001a, and Smakhtin, Gamage, & Bharati, 2007, on the Indian case). The Indian National Water Policy of 2002 in particular provides guidelines for prioritizing water allocation to different competing sectors without mentioning how these priorities are to be translated on the ground. It provides precedence to drinking water over irrigation and hydropower. Industrial and navigation needs are given the last priority. Environmental concerns are mentioned and "ecology" is given fourth priority, but nothing is said on how this can be achieved (Ministry of Water Resources [MoWR], 2002).

This article is a case study on the Krishna River basin in South India. The basin has witnessed intense water development since India gained Independence, with little regard to the limits of available resources (Venot, Turral, Samad, & Molle, 2007); agroecosystems have dramatically evolved, resulting in downstream environmental degradation. The observed decline in the discharge to the ocean sends a strong signal: There is only little scope for further water supply development, and further taming the Krishna waters will exacerbate environmental degradation. Based on secondary data collection, field interviews with key informants and farmers, and a comprehensive review of the literature, this article investigates the linkages between rural development dynamics and the downstream environment in the Krishna basin to (a) understand when and how rural development and environmental preservation come or do not come into conflict, (b) investigate whether committed allocations for environmental flows could allow meeting the environmental and social objectives of sustainable development, and (c) identify other potential areas of intervention.

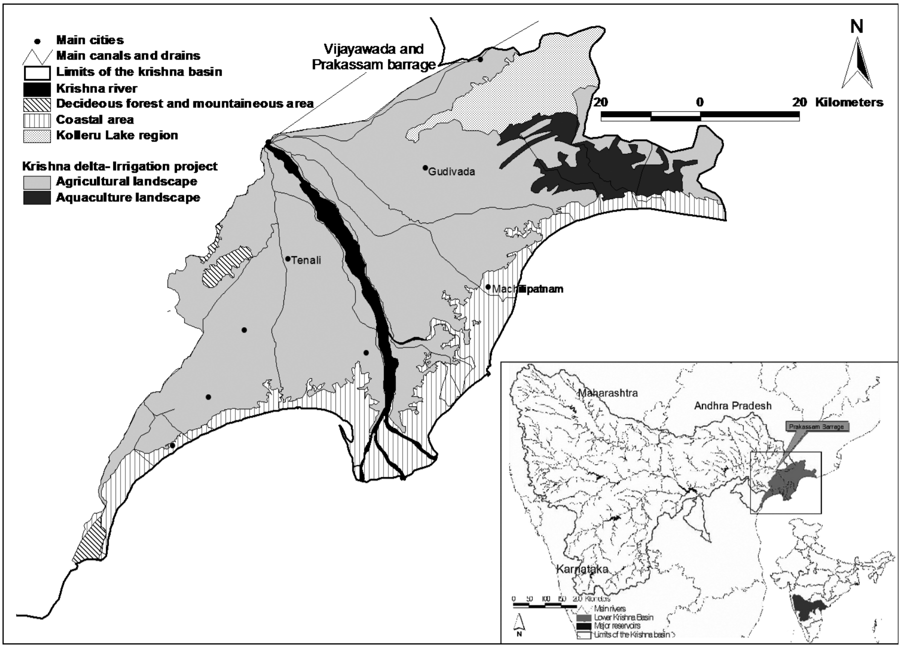
The first part of this article presents the main features of the lower Krishna basin. The second section presents a methodology for water allocation in the framework of environmental flows in a data-scarce context and applies this methodology to the Krishna basin. The third section provides a historical assessment of water availability and uses (water accounting) in the Krishna basin and depicts in further detail the rural dynamics and the institutional context of the lower Krishna basin as some of the main driving forces of downstream environmental degradation. The fourth section describes the linkages between agriculture, aquaculture, and the environment in the lower Krishna basin. A fifth section identifies possible interventions to mitigate current environmental degradation. Finally, a short paragraph concludes.

Human and Physical Setting of the Lower Krishna Basin

The Krishna River originates in the Western Ghats of Maharashtra, drains the dry areas of the Deccan Plateau, and forms a delta before discharging into the Bay of Bengal. The Krishna basin drains an area of 258,948 km^2 and covers parts of three South Indian states: Andhra Pradesh, Karnataka, and Maharashtra. Its climate is predominantly semiarid (with an average annual rainfall of 840 mm and potential evapotranspiration exceeding rainfall in all but 3 months during the peak of the monsoon; Biggs et al., 2007). Seasonal and interannual rainfall variability is one of the main characteristic of the climate of the Krishna basin (Biggs et al., 2007): River flows are highly variable and this makes forecasting and management a challenge. This article focuses on the impacts that rural development dynamics witnessed in the Krishna basin during the last 50 years have had on the lower Krishna basin, located in Andhra Pradesh (Figure 1), which bears the brunt of any intervention further upstream. The lower Krishna basin, with an average annual rainfall of 650 to 1,150 mm, representing three main agroecosystems has an area of 8,746 km^2 (Figure 1).

- The Krishna delta, where a large irrigation project irrigates 540,000 ha thanks to gravity canals drawing water from a barrage on the Krishna River at Vijayawada. The delta accommodates about 4 million inhabitants depending mainly on agriculture and aquaculture.

Figure 1
The Lower Krishna Basin in South India



- The Kolleru Lake, which is a freshwater inland lake designated as a wetland of international importance under the Ramsar convention. It is located between the Krishna and Godavari River deltas. Limits shown in Figure 1 are indicative: They do not correspond to the boundaries of the Ramsar site itself but correspond to a larger low-lying region designated as the Kolleru Lake region in this article. Aquaculture ponds are widespread in this region, where half a million people live.
- The coastal zone, where mangroves and natural vegetation have been progressively cut and replaced by aquaculture ponds.

Water Allocation in the Framework of Environmental Flows

Defining Environmental Water Provision in a Data-Scarce Context

The lack of an understanding and of a commitment to the notion of environmental flows in the developing world arises from two main questions: (a) how to define environmental water needs and (b) how to quantify them? Because many river basins of the world, notably in arid and semiarid areas, are closing (Murray-Darling, Colorado, Indus, and Jordan River basins; a generally accepted definition of a closed river basin is one where all available water is committed [Molden, 1997], resulting in little or no discharge to the ocean during years with average precipitation) the question of environmental flows is of crucial importance. Preserving ecosystems through formal mechanisms of water allocation, which recognize the environment as a water user in its own right, is needed; however, defining acceptable, if not optimal, environmental flows is a critical issue. Estimates of environmental flows will determine to what extent a river basin is closed and how new water resources can be developed. In closed or closing river basins, water resources cannot be further extended without impinging on actual uses: Understanding the environmental dynamics at stake and the interconnectedness between the environment and rural development is crucial in order to match environmental concerns with the social and economic objectives of sustainable development.

Environmental water requirements of a river basin can be defined, as a first approximation, as an ecologically acceptable flow regime. It is designed to maintain or upgrade a river in a desired, agreed, or predetermined status referred to as an *environmental management class* ranging from the natural (pristine) environment to a critically modified ecosystem. A detailed discussion of these notions can be found in Smakhtin and Anputhas (2006) and Tharme (2003).

Defining an annual volume of water to be set aside for the environment (bulk allocation), according to arbitrarily predefined preservation objectives, might be a futile exercise: It does not have any sound ecological meaning. Yet such a desktop assessment method constitutes the first step toward the recognition of the environment as a water user in its own right (Smakhtin et al., 2004). It is a basinwide reconnaissance assessment that has several advantages: It is rapid, generic, and non–resource intensive (Tharme, 2003). As a result, this low-resolution estimate of environmental flows based on a single arbitrary hydrological index (the discharge to the ocean) is considered to be most appropriate at the planning level of water resources development and could be used as a preliminary flow target. This is particularly adapted to developing countries where the water governance structure is weak and hydrological and ecological data scarce.

Assessing Environmental Water Requirements in the Krishna Basin

Allocating water to meet different environmental objectives. Based on the work by Smakhtin and Anputhas (2006), Table 1 presents what would be the possible environmental annual water requirements of the Krishna basin, measured at the head of the Krishna delta in Vijayawada (Figure 1), according to different objectives of downstream ecosystem preservation.

In arid and semiarid regions affected by the monsoon, the seasonality and interannual variability of water flows are crucial for the functioning of water-dependent

Table 1
Annual Environmental Water Requirements (EWR) for the Krishna Basin (Flow Measured at Vijayawada for Different "Protection Thresholds")

Environmental Status	Natural Ecosystem	Slightly Modified	Moderately Modified	Largely Modified	Seriously Modified	Critically Modified
EWR (% historical MAR)[a]	62.5	35.7	18.3	8.4	3.5	1.5
EWR (km^3/year)	48.5	27.7	14.2	6.5	2.7	1.2

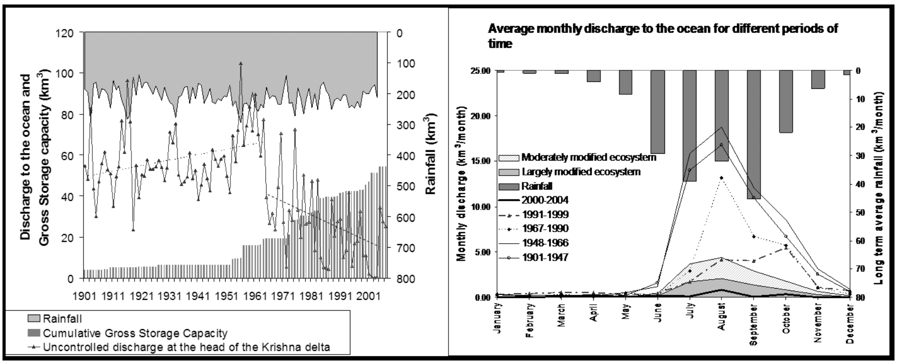
Source: Adapted from Smakhtin and Anputhas (2006).
a. The historical mean annual runoff (MAR) has been evaluated at 77.6 km^3/year (Central Water Commission, 2002).

ecosystems. It is generally recognized that environmental flows should be defined against this backdrop of natural variability of flow regime (Dyson, Bergkamp, & Scanlon, 2003). Based on the tenets of the natural flow paradigm (Poff et al., 1997), Figure 2 shows recommended monthly flow regimes to preserve the Krishna basin in a "moderately to largely modified" environmental status. These monthly flow regimes are obtained by scaling down the natural flow regime (approximated to the regime observed between 1901 and 1947 when only little impoundment and land use changes had affected the functioning of the Krishna basin drainage network) by 81.7% (for a moderately modified system) and 91.6% (for a largely modified status) to match the thresholds presented in Table 1. These two environmental statuses have been chosen as they are the two lowest acceptable environmental statuses as per the Department of Water Affairs and Forestry (1999) guidelines in South Africa.

Water availability and environmental status of the Krishna basin. Figure 2 provides the first striking indication of river-basin closure and environmental degradation: a decreasing discharge to the ocean and an altered flow regime. Before 1960, river discharge into the ocean averaged 57 billion cubic meters a year (km^3/year) and the threshold of 48.5 km^3/year, defining a *natural ecosystem* (Table 1), was reached with 76% reliability. Since 1965, the river discharge has steadily decreased at an average of 0.8 km^3/year, falling to 10.8 km^3 in 2000 (which is less than 19% of its pre-1960 value) whereas it was almost nil in 2004 (0.4 km^3). Only a little usable outflow, during the monsoonal period (July to October), reaches the ocean.

In standard condition, the average discharge to the ocean observed between 1988 and 2000 (between the last two major droughts) was 21.2 km^3/year, but the threshold of 14.2 km^3/year defining a moderately modified ecosystem was only reached with 60% reliability. Similarly, monthly flow regimes (right panel of Figure 2) show that the Krishna basin is a moderately to largely modified ecosystem and that taming the Krishna waters leads to a 2-month delay in the peak outflows. This change

Figure 2
Evolution of the Krishna Discharge to the Ocean, Measured at the Head of the Delta, and Monthly Flow Regimes for Different Objectives of Environmental Preservation



Sources: Left panel, Biggs et al. (2007); right panel, Andhra Pradesh State Water Data Centre figures.

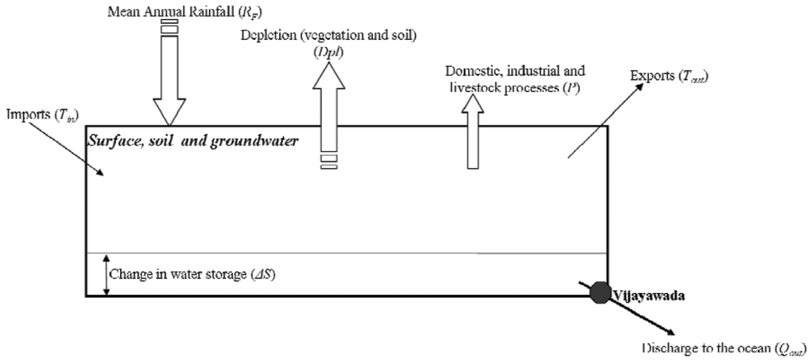
was also observed and analyzed by Smakhtin and Anputhas (2006), who suggest it may have affected the lower Krishna basin biosystems: Altered flow regimes are indeed one of the main threats to environmental sustainability (Bunn & Arthington, 2002).

The Drivers of Environmental Degradation in the Lower Krishna Basin

Shifting Landscape and Waterscape in the Krishna Basin

History of water development in the Krishna basin. The Krishna basin has seen an increasing development of its water resources and a dramatic expansion of irrigation since the 1850s. This phenomenon hastened after India gained Independence in 1947, and the total storage capacity (in large reservoirs) has multiplied eightfold since the 1950s to reach about 54.5 km^3 in 2002 (Figure 2; Biggs et al., 2007). Although their extent is not well quantified, small-scale irrigation projects commit significant volumes of water as well. Existing infrastructure regulates more than the 75% dependable annual flow. This may not generate significant cuts in water supply in most years, but it may lead to significant shortage in the lower reaches of the basin during dry years as upstream water supplies are not adjusted to reflect deficits in water availability. Along

Figure 3
Water Flows and Uses in the Krishna Basin



with this infrastructural development, surface water–irrigated areas have more than doubled since the 1950s: They covered 2.9 million hectares (Mha) in 1996-2002. At the same time, groundwater-irrigated areas extended owing to the boom of groundwater abstraction thanks to private pumps, shallow tube wells, and subsidized energy. Groundwater-irrigated areas have more than doubled during the last 50 years: They supplied about 1.9 Mha in 1996-2002. The total irrigated area in the Krishna basin covered 4.8 Mha in 1996-2002.

Basinwide water accounting: A methodology for quantification. The water accounting presented graphically in Figure 3 draws on the categories of water balance proposed by Molden (1997). It estimates water depletion, defined as the use or removal of water from a river basin that renders it unavailable for further use, over different periods of 10 years: This article focuses on long-term trends revealed by average balances.

The basin water balance respects the principle of conservation of mass, where total input equals total outflows and change in storage. This is represented by equation (1):

$$R_F + T_{in} = Dpl + P + T_{out} + Q_{out} + \Delta S \tag{1}$$

where

R_F is the mean annual rainfall measured from the data set of the Climatic Research Unit, University of East Anglia (2007).

T_{in} are water transfers entering the Krishna basin (noted imports in Figure 3). The amount of water transferred from other river basins is estimated from government statistics and data from water supply projects. In what follows, R_F and T_{in} are pooled together and designated as the net inflow in the Krishna basin.

Dpl is the depletion from any kind of land cover, and is estimated, as a first approximation, as the evapotranspiration (ET) of a given land cover. Evapotranspiration in irrigated fields and evaporation from reservoirs are derived from climate data and a Penman–Monteith equation (Allen, Pereira, Raes, & Smith, 1998); evapotranspiration by rain-fed agriculture and rain-fed vegetation is estimated after Biggs (in press) and Bouwer, Biggs, and Aerts (2007). Land cover is estimated on the basis of land-use statistics at the district level (GoAP, 2006; Government of Karnataka [GoKT], 2006; Government of Maharashtra [GoMH], 2005; and available online, with a subscription, at www.indiaagristat.com).

P denotes human and livestock consumptive uses or processes. Domestic and industrial uses are computed according to van Rooijen et al. (2008), assuming a water use efficiency of 70% in each sector. Livestock processes are computed according to Peden, Tadesse, and Misra (2007) and livestock statistics according to GoAP (2005), GoKT (2006), GoMH (2005), and www.indiaagristat.com.

T_{out} are water transfers out of the Krishna basin (noted exports in Figure 3). The amount of water transferred to other river basins is estimated from government statistics and data from water supply projects.

Q_{out} is the discharge to the ocean, measured at the head of the delta by the Irrigation Department of Andhra Pradesh. Pre-1980 values are from Biggs et al. (2007), whereas post-1980 values have been collected by the authors from the irrigation department offices of Vijayawada and Hyderabad.

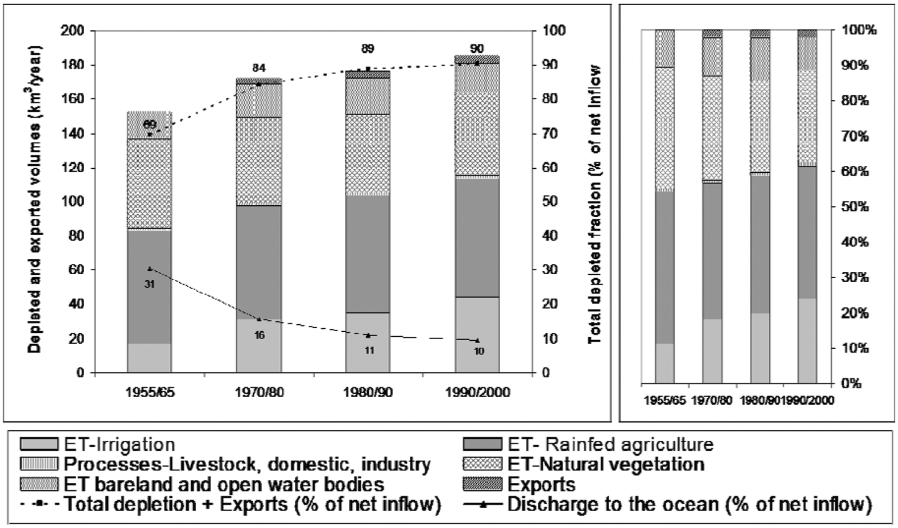
ΔS is the net change in water storage, including both groundwater and surface water storage and is calculated as the closing term of the water balance, for example, the difference between net inflows and outflows (evaporation from vegetation + human consumptive uses + exports + discharge to the ocean).

Figure 4 quantifies the main changes of the Krishna basin agroecosystems. It illustrates that the main trend is a strong increase of irrigation depletion that has more than doubled from 17.1 km^3/year during 1955-1965 to 44.3 km^3/year during 1990-2000. This implied a 19% rise in the total depletion during the period 1955-2000. The total depletion amounted to 181 km^3 during 1990-2000, that is, 88% of the net inflow to the Krishna basin. Consequently, the discharge to the ocean dramatically decreased and amounted only to 10% of the net inflow during 1990-2000 (2% of the net inflow was exported to other basins). This led to dramatic environmental changes in the lower Krishna basin (see next section). According to Smakhtin and Anputhas (2006), preserving the moderately to largely modified ecosystem of the Krishna basin would require an environmental flow allocation of about 6.5 to 14.2 km^3/year (Table 1). This will point to a rate of water resources commitment of 94% to 98%, showing that resources will be fully committed under average conditions. Yet this is needed to stop the increasing degradation of the environment that distresses livelihoods in the lower Krishna basin.

Rural Dynamics in the Lower Krishna Basin

The lower Krishna basin has a long history of irrigation: The first large-scale project was implemented in the early 1850s (Wallach, 1984). During 1954-1957, it was

Figure 4
Historical Water Account of the Krishna Basin (1955-2000, Nominal and Relative Value)



modernized and the actual project irrigates about 540,000 ha and is the "rice bowl" of Andhra Pradesh. Agricultural and rural dynamics of the lower Krishna basin are closely linked to the emergence of a large class of prosperous peasants or owner-cultivators who can be best termed "farmer-capitalists" (Upadhya, 1988). These agriculturalists largely benefited from the agricultural productivity boom of the Green Revolution (1965-1985) and from a strong state-driven institutional support to agricultural development until the mid-1980s (Landy, in press). They are both involved in agricultural production and surplus commercialization and, on the basis of their agricultural successes, they have progressively invested in other avenues (agro-industries, industries, manufacturing activities, real estates) and in education of their children. They dominate the social landscape of the lower Krishna basin but also have a broader political influence in Andhra Pradesh.

In the mid-1980s, and furthermore with the liberalization of the Indian economy in the early 1990s, the strong state-driven investments in rural development weakened: This pushed rural India into what is called an "agrarian distress" (Suri, 2006). Despite being less affected by this agrarian distress than rain-fed farmers in semiarid areas, the farmer-capitalists of the lower Krishna basin looked for other economic opportunities.

Aquaculture, strongly supported by the Government of Andhra Pradesh, was one of them and its development during the 1990s had significant impacts on the lower Krishna basin agroecosystems. Aquaculture developed mainly on unappropriated government lands (commons) for which land entitlements were delivered by *panchayats* (the local administrations). It came together with land speculation. Prospects of high revenues attracted poor farmers and fishermen who, being under both economic and political pressure, sold or leased out their land to rich local entrepreneurs and outsider investors. Although the land was officially entitled to them, small local farmers and fishermen became de facto laborers, hired on a daily or monthly basis by rich entrepreneurs (Rama Rao, Jairath, & Umesh, 2006). The emergence of social movements, backed up by the mobilization of the local elites who wanted to limit the in-migration of outsider investors who could have cornered the sector, pushed the government to legislate on shrimp farming in 1996 (Supreme Court of India, 1996). The legislation aims at controlling aquaculture development to limit environmental degradation but implementation remains a difficult task as it goes against the economic objectives of the Government of Andhra Pradesh to revive aquaculture (GoAP, 2001b). As generally documented in other cases (National Research Council, 2002), the change in the mode of access to land (from open access to governmental land, generally grazed to the benefit of the poorest, to a private access guaranteed by land entitlements for agriculture or aquaculture) is a main driver of the degradation of natural resources in the lower Krishna basin.

Institutional Context of the Lower Krishna Basin

In her study of the shrimp farming sector in India, Brugere (2006) clearly showed that conflicts over coastal resources and subsequent environmental degradation were predominantly the outcome of institutional failures, that is, the inability of institutions in place to deal with natural resources management issues. Mapping the Andhra Pradesh institutions involved in the use, control, and preservation of natural resources in regard to the lower Krishna basin is thus central to the understanding of the drivers of environmental degradation. It reveals a fragmented institutional framework familiar to water and natural resources managers in developing countries (GoAP, 2001b) with (a) several federal institutions (Ministry of Water Resources, of Environment and Forests, of Agriculture, and of Rural Development, the Marine Products Export Development Authority, etc.); (b) several state agencies (the Fisheries; Agriculture; Irrigation; Environment, Forests, Science and Technology Departments of the State of Andhra Pradesh; the Andhra Pradesh Pollution Control Board; the Shore Area Development Authority; the Aquaculture Authority, etc.); (c) several judiciary bodies (Supreme Court of India, High Court of Andhra Pradesh, Krishna Water Disputes Tribunal); (d) local institutions (panchayats, farmers, and fishermen associations); and (e) a multitude of regulations and legislations—the Wildlife Protection Act (1972), the Water Prevention and Control of Pollution Act (1974), the Environment Protection Act

(1986), the Coastal Regulation Zone Notification (1991), the Indian Fisheries Act (1997), the Coastal Aquaculture Authority Act (2005), etc.—for the most important one.

The lower Krishna basin is a vivid example of how local rural dynamics and identification of new economic opportunities (e.g., aquaculture) have led to the reconfiguration of the institutional context in which resource extraction takes place. The role and importance of local institutions have been diluted as the legal and institutional framework of natural resources management broadened in line with the increasing recognition of the importance of environmental preservation for sustainable development. This institutional formalization aimed at better preserving ecosystems but often led to further degradation of the environment. This does not mean that formalization is not needed: A strong institutional support is indeed essential to achieve governance systems supporting integrated resources management to ensure an environmentally sustainable development (Falkenmark et al., 2007; Gowing, Tuong, & Hoanh, 2006), but this reminds us of the need for further integration and coordination among different institutions that are generally pursuing overlapping but conflicting objectives in the long run. What is required is making the existing legal provisions context specific and their implementation effective. This could notably be done by making these regulations more easily available, building up enforcement mechanisms, training officials in the use and implementation of laws, improving the still low awareness of these policies among stakeholders, etc. (GoAP, 2001b). Finally, decision makers need to be convinced that protecting the environment can yield both environmental and social benefits (Bunn & Arthington, 2002).

Rural Development and Environment: Conflicting and Complementary Uses of Water

Wetlands, deltas, estuaries, and more generally coastal ecosystems are dramatically affected by any changes in water use and availability (Ramsar Convention Secretariat, 2006). The degradation of estuarine resources, owing to a variety of human activities within and outside the estuaries, has become a major environmental concern in India (Bhatta & Bhat, 1998). The Krishna basin is no exception: Warnings have emerged of environmental degradation in the lower basin because of long-term evolution and short-term changes of the Krishna basin agroecosystems and waterscape. Because of the inherent lack of suitable policies for regulating surface water and groundwater use in the Krishna Basin, environmental threats are likely, to be further sharpened and to dramatically affect the large population of the fragile ecosystem of the lower basin.

Surface Water and Groundwater Irrigation: Impacts on the Aquifers

The aquifer system of the lower Krishna basin. The lower Krishna basin has a multilayered aquifer system, and hydrological studies have shown that groundwater levels are shallow as a result of the influence of the canal network (GoAP, 2003). Seepage from unlined canals and return flows from irrigation are the main sources of recharge for the fresh shallow aquifer (0-30 m) used for agricultural and drinking purposes. The Krishna River is the main source of recharge for plains along the river channel (van Doorm, 2001). Deeper aquifers are generally brackish to saline and mainly recharged by slow seepage from upper levels and from the Krishna River itself during the monsoonal period.

Long-term trends: When agriculture development causes groundwater degradation. As observed in the entire Krishna basin, farmers in the lower basin have increasingly tapped the local aquifers for both agriculture and aquaculture. The Minor Irrigation Census of 2001 and district statistical handbooks indicate that 19,000 wells were used in the lower Krishna basin in 2001 (e.g., twice more than in 1987). If coastal and deltaic regions are subject to seasonally varying salinity and groundwater levels (Gowing et al., 2006), the long-term increase in groundwater abstraction observed in the lower Krishna basin has caused a lasting fall of the water table by 1 to 2 m during the last decade and to a progressive salinization of the aquifers (GoAP, 2003).

The salinization of the lower Krishna basin aquifers is due to two different processes. First, in the inland region where groundwater use is intensive, the shallow freshwater aquifer has been dramatically depleted and fossil saline water, trapped during the deltaic formation in deeper aquifers, has reached the upper horizons (GoAP, 2003). Some wells have turned saline and cannot be used for irrigation anymore. Second, in the coastal zone and in the tail-end region of the Krishna delta irrigation project, the decline in the water table led to seawater intrusion, which is likely to leave a permanent imprint on groundwater quality. GoAP (2007a) for example describes a landward intrusion of the saltwater–freshwater interface of the second aquifer (30-60 m deep) by 10 to 20 kilometers inland during the last two decades. Finally, highly loaded return flows from agriculture and aquaculture have also been identified as a main cause of pollution of surface water and groundwater in the delta. Agrochemical residues accumulate in the aquifers and nitrate pollution can be observed in some pockets of the delta (GoAP, 2001b). These are major concerns in a region where most of the population, notably in the coastal area, highly depend on fresh groundwater lenses tapped by hand pumps for domestic purposes and by electric motors for agricultural activities (GoAP, 2003). This makes clear that water needs of agriculture and aquaculture are conflicting with the objectives of environmental preservation.

Short-term changes: Impacts of low irrigation canal flows. The long-term trend of groundwater salinization has been further sharpened during the recent spell of drought as lower flows in irrigation canals (flows averaged 4.8 km^3/year during the period 2001-2004 compared to a long-term average of 6.15 km^3/year [1975-2000];

Venot, Sharma, & Rao, 2008) and in the Krishna River itself (see above) caused lower seepages, lower recharge of the upper aquifer, and further landward saline water intrusion. Lower and delayed canal flows compelled farmers to change their land use and cropping techniques (GoAP, 2003): They left some areas fallow and continued tapping groundwater to irrigate the remaining cropped areas while return flows concomitantly decreased. In spite of such adaptive strategies, paddy yields have been strongly affected by water scarcity and hence livelihoods (yields 70% below average were commonly reported in the tail-end regions of the Krishna delta irrigation project; Venot et al., 2008). Many freshwater ponds located in the south and east of the lower Krishna basin and historically supplied through the Krishna delta irrigation canals have also not been supplied all year long. This has negatively affected fish production in the region, and low water availability jeopardizes the sustainability of aquaculture (Venot et al., 2008). Finally, lower flows in the canals have led to domestic water shortage in the coastal zone, where brackish groundwater cannot be used for domestic purposes.

There is a clear need for measures of drought mitigation and regulation of on-farm practices to lessen the environmental consequences of a dry period. Maintaining a minimal flow in the irrigation canals of the Krishna delta could be a first step. It is needed to sustain the local agriculture but it could also indirectly participate in the preservation of the lower Krishna basin environment as it would also freshen the local aquifers through seepages. Interestingly, as early as 1976, the first Krishna Water Disputes Tribunal (in charge of apportioning water among the three states that share the Krishna water: Andhra Pradesh, Maharashtra, and Karnataka) mentioned the role of irrigation canal flows to limit salinization in the lower Krishna basin and designed its allocation accordingly (Government of India/Krishna Water Disputes Tribunal, 1976). This allocation could be a good basis for further refinement of the Krishna delta allotment given the backdrop of increased cropping intensity and groundwater abstraction.

Coastal Resources Use and Environmental Degradation

Relationships that communities nurture with their environment progressively evolve with the identification of new economic opportunities. Rural dynamics and a changing mode of access to natural resources in the lower Krishna basin had dramatic impacts on local ecosystems. The area of mangroves, for example, declined as (a) they have long been used for multiple purposes (see MEA, 2005, for different possible uses of mangroves) by a population of about 30,000 people increasingly attracted by a profitable brackish aquaculture sector; (b) more recently, their land status partially changed when exploitation licenses for agriculture and brackish aquaculture were delivered by the local authorities (before 1997); and (c) their management, long devolved to the local panchayats has been entrusted to governmental services such as the Departments of Forest and Fisheries.

Between the mid-1970s and the early 2000s, mangrove covers had decreased by about 2,200 ha in the lower Krishna basin. In 2001, mangroves covered about 8,000 ha, mostly in the mouth of the Krishna River (Venot et al., 2008). Mangrove areas are now protected and the creation of Coastal Regulation Zones, in 1991, is a first step toward integrated coastal management to notably regulate the exploitation of this fragile ecosystem. However, implementation difficulties remain and mangroves are still under the threat of several interconnected processes: (a) overgrazing, (b) overexploitation of timber products (GoAP, 2001b), (c) conversion to shrimp ponds (the Food and Agriculture Organization of the United Nations [2002] evaluated that 3% to 5% of all shrimp ponds in Andhra Pradesh had been dug in mangroves areas, this being about 1,200 ha in the lower Krishna basin), (d) alteration of tidal flows in and out of the mangroves and biota changes due to lower river flows and the formation of a sand bar in the mouth of the delta (Selvam, 2003), and (e) increasing pollution due to agriculture and aquaculture return flows, etc.

Land Degradation

Salinity problems are common features of coastal areas and deltaic environments (Gowing et al., 2006). But aquifer salinization and aquaculture development observed during the last decade and a relative lack of drainage are likely to have heightened the problem of soil salinization. The Andhra Pradesh Water Management Project (APWAM, 2005) evaluated that strongly saline and alkaline soils covered 25,000 ha and an extra 45,000 ha had lower but significant salinity levels. Decreasing irrigation canal flows and low rainfall further sharpen this problem: Adequate supplies are needed for flushing and leaching salt-affected soils in the tail-end areas of the canals but they are not available. This leads to further salinization.

Another source of land degradation is brackish aquaculture. First, soils are generally not adequately flushed and when done it is often with brackish groundwater: They become highly saline and improper to other kinds of reclamation (GoAP, 2001b). Second, contamination of bacteria, fungi, and viruses can lead to large-scale land degradation as observed during 1994-1996 (Brugere, 2006) even if shrimp farming remains mainly extensive. Third, saline percolation from ponds contaminates neighboring fields, which become unsuitable for paddy cultivation. Delineating different areas for aquaculture and agriculture could be a solution to some of these problems (Gowing et al., 2006).

Direct Impacts of Lower River Flows: Salinization and Erosion

There is evidence of increasing salinity in the river channels. The saline–freshwater interface in river water is progressively moving inland as a result of lower freshwater flows in the river (Saxena, Singh, Mondal, & Jain, 2003). This affects the small plains located along the river. Finally, Smakhtin et al. (2007) show that there is a tendency toward land losses to the sea as little water with lower sediment load (because of sedimentation in the many reservoirs built in the Krishna basin) reaches the ocean. Maintaining a given discharge to the ocean could allow limiting these losses that have remained restricted to small areas in the mouth of the Krishna River until now.

The Kolleru Lake: Acute Conflicts in an Endangered Wetland

The Kolleru Lake is a freshwater lake fed by several rivulets and is connected to the Krishna and Godavari irrigation systems through several canals and drains supplying water for drinking and agricultural purposes to the population of the lake area. The wetland has undergone dramatic changes during the last three decades. Land entitlements in the lake bed were granted to local farmers and fishermen as early as 1977-1978 and culture fisheries (fish and shrimp ponds) quickly replaced the traditional capture fisheries. As generally observed in the lower Krishna basin, the role of large local entrepreneurs has been tremendous in explaining the success of aquaculture development: They heavily invested in the sector by renting fishponds from local farmers and fishermen who were holding land entitlements (Rama Rao et al., 2006; in the late 1990s almost all ponds in the Kolleru region were leased out [GoAP, 2001b]).

Aware of the dramatic environmental changes affecting the Kolleru Lake, the Government of Andhra Pradesh took very strong symbolic decisions to protect the region. In 1999, the wetland was declared a wildlife sanctuary under India’s Wild Life (Protection) Act of 1972. Furthermore, in November 2002, the Kolleru Lake was designated a wetland of international importance under the International Ramsar Convention (GoAP, 2007b). The protected area covers 308 km^2. Despite the official recognition of the remarkable character of the Kolleru Lake ecosystem, environmental degradation and lake encroachment continued in the early 2000s. In 2006, aquaculture ponds covered between 10,300 (Nageswara Rao, Krishna, & Malini, 2004) and 12,200 ha (Anonymous, 2007) of the protected area whereas agriculture covered an additional 5,000 to 6,000 ha. Other environmental problems include (a) increasing pollution due to aquaculture and agriculture effluents, (b) lack of drainage, (c) subsequent eutrophication of the lake, increasingly covered with waterweed, (d) decrease in and contamination of the fish population of the lake, and (v) increased siltation leading to floods (Anjaneyulu & Durga Prasad, 2003).

Protecting the lake ecosystem has long been presented as a government priority (GoAP, 2001b). However, removing illegal fishponds from the protected area has always been a highly sensitive question, opposed by a powerful lobby. Although the Andhra Pradesh High Court of Justice passed an order to remove illegal fish tanks in 2001 (“Kolleru Lake, a Sanctuary,” 2001), the measure has been delayed several times. Finally in February 2006, the Supreme Court of India passed an order to remove illegal encroachments in the lake (“Panel Wants Kolleru Lake Cleared,” 2006). This decision was strongly opposed by fishermen and farmers lobbies on the grounds that this move was threatening their livelihoods. Land entitlements have however been cancelled and it is estimated that about 19,500 ha of aquaculture ponds were demolished on June 15, 2006 (GoAP, 2007b). This required the involvement of police forces to maintain public safety ("Operation Kolleru Resumes," 2006). Some ponds still remain and the transfer of the Conservator of Forests in charge of the protection of the Ramsar site under political pressure highlights the political sensitivity of a measure affecting both large investors and landless farmers pushed into precarious situations. Other measures to rejuvenate the lake are being taken or contemplated and the specialized organization Wetlands International is entrusted with the writing of a multidisciplinary integrated management plan for the restoration of the Kolleru Lake (Narsimhulu, personal communication, May 7, 2007).

Possible Future Strategies and Mitigation Measures

Since India gained Independence, the Krishna basin has witnessed an increasing development of its water resources with little regard to the limits of availability and sustainability. This led to a decreasing discharge to the ocean pointing out to the progressive closure of the Krishna basin: altered flow regimes led to downstream environmental degradation. However, the high discharges to the ocean observed in 2005-2007 (29 km^3/year, owing to good monsoonal rains) highlight that the Krishna basin is in transition and that there is scope for limiting and reversing environmental damage for the benefit of local livelihoods. Mitigation measures could take several forms.

Implementing an Environmental Water Provision

Taking the South African case as a model (Tharme, 2003), this article calls for a formal allocation of water to be set aside for the purpose of environmental preservation. This 'environmental allocation' is necessary as the highest costs of environmental degradation are typically borne by people depending directly on ecosystem services for their livelihoods and who are generally among the poorest in developing countries (Emerton & Bos, 2005; Pearce et al., 2006). This environmental "reserve" needs to be embedded in a broader framework for long-term adaptive water- allocation mechanisms to meet growing and competing water demands.

The current Krishna Water Disputes Tribunal put in place by the Government of India and in charge of apportioning the Krishna water among the three riparian states of Andhra Pradesh, Karnataka, and Maharashtra is expected to reach a decision between 2008 and 2010 and it could be an appropriate platform to devise such environmental allocation. However, at present, the tribunal mainly involves decision makers and bureaucrats from the three states and needs to be made more responsive to local communities' demands through involving local users in the negotiatory process of water apportionment for both social and environmental benefits (refer to Iyer, 2003, and Janakarajan, 2007, for the prospects and problems related to involving farmers in the resolution of water-sharing conflicts).

The Tribunal award (based on Integrated Water Resources Management principles) should (a) be defined at the basin level, (b) be based on a comprehensive and transparent understanding of the basin hydrology, (c) estimates long-term reliable supplies in any part of the basin in light of actual and projected use, and (d) be informed on the ecological consequences of altered flow regimes. Once a given amount of water is protected for the sake of environmental preservation (this will also allow sustaining the livelihoods of the poorest), the remainder could be apportioned to human consumptive uses following the priorities set up in the National Water Policy of India (MoWR, 2002).

The environmental provision could be defined as a two-tier allocation. First, a given discharge in the irrigation canals of the Krishna delta to meet the agriculture and domestic demand of the local population and also the environmental requirements of groundwater recharge and salt leaching from the soil. The award of the first Krishna Water Disputes Tribunal (e.g., 5.1 km^3/year) could be used as a first basis for further refinement given the backdrop of increased cropping intensity and groundwater abstraction. This requires further study on the extent and spatial distribution of groundwater abstraction in the lower Krishna basin. Second, a fixed annual discharge to the ocean, maintained by the Irrigation Department of Andhra Pradesh (as proposed by the Government of Andhra Pradesh, 2001b) put under public scrutiny, to limit seawater intrusion in the river branches and preserve the functioning of downstream ecosystems. Smakhtin and Anputhas (2006) evaluate that this would require between 6.5 and 14.2 km^3/year. Water commitment would then become 94% to 98% of total water availability, showing that water resources are fully committed under average conditions and that further water resources development will be tantamount to sectoral and/or regional reappropriation of water. In times of drought, intensive agricultural water uses in upstream semiarid regions of the basin (paddy and sugarcane cultivation for example) are likely to be the first to be curtailed with necessary mitigation procedures (see below).

Supply Augmentation Project: Transferring Water

Supply augmentation projects to increase water availability in the lower Krishna basin through the transfer of water from the Godavari basin (Godavari–Krishna link at Pollavaram; National Water Development Agency, 2007) are a partial response and hold short-term promises to support agriculture, counterbalance the observed decline in the discharge of the Krishna River, and limit environmental degradation. They also illustrate the persistence of an engineering-based approach to water resources development and do not bring long-term solutions to the pending problems the region is facing. Finally, they raise social, political, economic, and ecological issues, often overlooked (Venot et al., 2007), and are based on the concept of "surplus water" that has been questioned by Smakhtin et al. (2007) in the case of the Godavari basin.

Technical and Institutional Responses

Local rural dynamics are some of the main causes of environmental degradation in the lower Krishna basin, and mitigation strategies include

- Technical interventions such as the reconfiguration of the soil surface and subsurface drainage systems (APWAM, 2005);
- Regulation of local practices: monitoring the use of fertilizers and pesticides through agricultural extension services, regulating groundwater access, and limiting the depth and number of wells in use through policies of electricity supply and pricing and policies of access to credit; and
- The delineation of zones with different development and environmental objectives: the Coastal Regulation Zone Notification of 1991 is a first step forward but its implementation is hindered by the current institutional setup of natural resources management.

Other generic interventions such as strengthening the institutional context, facilitating the coordination between departments, maintaining a database on wetlands, mangroves, and soil and water salinization, and promoting the role of the resource users in the decision-making process are commonly advocated (GoAP, 2001b; Gowing et al., 2006). To avoid that any of these "environmentally oriented" interventions distress local livelihoods, there is a need for providing attractive alternatives to the poorest communities: crop insurance schemes, attractive output markets for farmers tempted to diversify (notably toward fruits and vegetables production and livestock systems), subsidies to adopt microirrigation, and creation of adequate nonfarm livelihood opportunities (notably in the agro-processing sector). Finally, ecosystem services (including freshwater and brackish water aquaculture) provide an important means of livelihood to the vast resource-poor population but are presently poorly appreciated. One of the most promising ways of placing the preservation of ecosystems on the water agenda is through an economic valuation of the services sustained by ecosystems (Emerton & Bos, 2005; Pearce et al., 2006). This shall help in internalizing the objective of environmental preservation in the decision-making process of water allocation currently dominated by economic and political motives.

Conclusion

Rural development dynamics in the Krishna basin have led to rising overcommitment of available water resources: signs of basin closure are apparent during dry periods and altered flow regimes have led to environmental damage in the lower Krishna basin, which (a) bears the brunt of any intervention upstream and (b) witnessed dynamics of natural resources use whose short-term financial gains conflict with the objective of a sustainable development. Environmental degradation manifests itself by increasing soil and groundwater salinity, aquifers and surface water pollution, scarcity of freshwater resources, shrinkage of mangrove covers and desiccation of the Kolleru Lake. Recognizing the environment as a water user in its own right and implementing an *environmental reserve* are difficult but necessary measures for both environmental sustainability and the livelihoods of the vast poor population.

Given current data availability, present understanding of the hydrology and ecology of Indian river basins, and current commitment of decision makers toward the objective of environmental preservation, only average allocations administratively defined are possible. The Krishna Water Disputes Tribunal is expected to reach a decision between 2008 and 2010 and could be an appropriate platform to devise such environmental allocation if made more responsive to local communities' demands. These average allocations still leave problems of management during dry years. But once a basinwide planning or reconnaissance-level assessment is generally recognized as necessary and benefits from a strong commitment of the different users and managers, environmental provisions could evolve to a more complex set of environmental flow rules defined in a polycentric governance setup allowing participation of all for an integrated management of natural resources, notably water, at different levels from the local level (regulating practices), to the state level (with notably integrated coastal management), and finally the basin level (integrated basin management and water allocation procedures with the involvement of both the federal and the state governments) (for more precision on the rules, concepts and methodologies that could be considered see, Tharme, 2003). That water development in the Krishna Basin has happened with little regard to the formal allocation mechanisms defined in the mid-1970s also illustrates the need for a clear governance system with legally empowered actors who could act to stop any project contradicting the award of the Tribunal (Venot et al., 2007). Ecology being only the fourth priority in the National Water Policy of India, the latter is unlikely to be effective in its present form for the purpose of environmental preservation. What is needed now is a strong commitment of the decision makers toward the aim of environmental preservation (Falkenmark et al., 2007) and this will only be achieved if managers and decision makers are convinced that providing environmental flows can produce environmental as well as economic and social benefits. More research is needed to link altered flow regimes, environmental degradation, economic valuation of ecosystem services and social and economic marginalization.

References

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). *Crop evapo-transpiration: Guidelines for computing crop water requirements*. FAO Irrigation and Drainage Paper No. 56. Rome: Food and Agricultural Organization of the United Nations.

Andhra Pradesh Water Management Project. (2005). *Proceedings of the First Annual Workshop Held at RARS, Tirupati. March 1st-12th of 2005*. Hyderabad, India: Acharya N. G. Ranga Agricultural University.

Anjaneyulu, Y., & Durga Prasad, M. K. (2003). *Lake Kolleru—Environmental status (past and present).* Hyderabad, India: B. S. Publications.

Anonymous. (2007). Kolleru Lake Profile. Retrieved April 25, 2007, from http://westgodavari.org/DRDA%20WEBSITE/KOLLERU%20WEBSITE/KOLLERUPROFILE.htm

Bhatta, M., & Bhat, M. (1998). Impacts of aquaculture on the management of estuaries in India. *Environmental Conservation, 25*(2), 109-121.

Biggs, T. W. (in press). Simplified models of evapo-transpiration from rainfed crops in southern India. *Agricultural and Forest Meteorology*.

Biggs, T. W., Gaur, A., Scott, C. A., Thenkabail, P., Rao, P. G., Krishna, G. M., et al. (2007). *Closing of the Krishna Basin: Irrigation, streamflow depletion and macroscale hydrology* (IWMI Research Report 111). Colombo, Sri Lanka: International Water Management Institute.

Bouwer, L., Biggs, T. W., & Aerts, J. (2007). Estimates of spatial variation in evaporation using satellite-derived surface temperature and a water balance model. *Hydrological Processes, 22*(5), 670-682.

Brugere, C. (2006). Can integrated coastal management solve agriculture-fisheries-aquaculture conflicts at the land-water interface? A perspective from new institutional economics. In T. P. Tuong, C. T. Hoanh, J. W. Gowing, & B. Hardy (Eds.), *Environment and livelihoods in tropical coastal zones: Managing agriculture-fishery-aquaculture conflicts* (pp. 258-273). Oxford, UK: CABI.

Bunn, S. E., & Arthington, A. H. (2002). Basic principles and ecological consequences of altered flow regime for aquatic biodiversity. *Environmental Management, 30*(4), 492-507.

Central Water Commission. (2002). *Water and related statistics*. New Delhi, India: Central Water Commission, Water Planning and Projects Wing.

Climatic Research Unit, University of East Anglia. (2007). Monthly precipitation data. Retrieved May 11, 2007, from http://www.cru.uea.ac.uk/~mikeh/datasets/global/

Department of Water Affairs and Forestry. (1999). *Resource directed measures for protection of water resources. Vol. 3: River ecosystems*. Version 1.0. Pretoria, South Africa: Institute of Water Quality Studies, DWAF.

Dyson, M., Bergkamp, G., & Scanlon, J. (Eds.). (2003). *Flow. The essentials of environmental flows.* Gland, Switzerland: IUCN.

Emerton, L., & Bos, E. (2005). *Value: Counting ecosystems as an economic part of water infrastructure*. Gland, Switzerland: IUCN.

Falkenmark, M., Finlayson, M., Chiuta, T., & Gordon, L. (2007). Ecosystems, water and agriculture: Towards a shift in thinking. In D. Molden (Ed.), *Water for food, water for life: A comprehensive assessment of water management in agriculture*. London: Earthscan, and Colombo, Sri Lanka: International Water Management Institute.

Food and Agriculture Organization of the United Nations. (2002). FAO Aqua-book 2002. Retrieved April 25, 2007, from www.aquaculture.tn.nic.in/pdf/FAO%20Aqua41-79.pdf

Government of Andhra Pradesh. (2001a). *Andhra Pradesh Vision 2020. Vol. I: Sectoral overview of water and water management.* Hyderabad, India: Author.

Government of Andhra Pradesh. (2001b). *Andhra Pradesh water vision. Position paper No. 3: Strategic overview of the aquatic ecology.* Hyderabad, India: Author.

Government of Andhra Pradesh. (2003). *Freshwater-saline water interrelationhip in the multi-aquifer system of the Krishna Delta. R&D project. Abridged version.* Hyderabad, India: Groundwater Department, Government of Andhra Pradesh.

Government of Andhra Pradesh. (2006). *Statistical abstract of Andhra Pradesh, 1955-56 to 2004-2005.* Hyderabad, India: Ministry of Agriculture.

Government of Andhra Pradesh. (2007a). *Presentation on the nature of coastal alluvial aquifer in the Krishna Delta*. Paper presented at the International Water Management Institute Workshop on Groundwater Externalities, September 5th of 2006, Hyderabad, India.

Government of Andhra Pradesh. (2007b). *Notes on agriculture and related activities*. Retrieved April 24, 2007, from www.aponline.gov.in/Apportal/SocioSurvery0607/Chapters/5.%20Agriculture.doc.

Government of India/Krishna Water Disputes Tribunal. (1976). *The further report of the Krishna Water Disputes Tribunal with the decision*. New Delhi: Government of India.

Government of Karnataka. (2006). *Statistical abstract of Karnataka 2000-2001*. Bangalore, India: Directorate of Economics and Statistics.

Government of Maharashtra. (2005). *Statistical abstract of Maharashtra State 1997-98 and 1998-99*. Mumbai, India: Directorate of Economic and Statistics.

Gowing, J. W., Tuong, T. P., & Hoanh, C. T. (2006). Land and water management in coastal zones: Dealing with agriculture-aquaculture-fishery conflicts. In T. P. Tuong, C. T. Hoanh, J. W. Gowing, & B. Hardy (Eds.), *Environment and livelihoods in tropical coastal zones: Managing agriculture-fishery-aquaculture conflicts* (pp. 1-16). Oxford, UK: CABI.

Iyer, R. (2003). Cauvery dispute: A dialogue between farmers. *Economic and Political Weekly, 38*(24), 2350-2352.

Janakarajan, S. (2007, August). *Rethinking on policy: Can stakeholders' dialogue contribute to conflict resolution, social learning and sustainable use of water*. Paper presented at the seminar Water, Politics and Development, August 12, 2007, World Water Week, Stockholm.

Kolleru Lake, a sanctuary: Court. (2001, July 31). *The Hindu*.

Landy, F. (in press). *Feeding India: The spatial parameters of food grain policies*. New-Delhi: Manohar.

Millennium Ecosystem Assessment. (2005). *Ecosystems and human well-being: Synthesis*. Washington, DC: Island Press.

Ministry of Water Resources. (2002). *National water policy*. New Delhi, India: Ministry of Water Resources, Government of India.

Molden, D. (1997). *Accounting for water use and productivity* (SWIM Paper 1). Colombo, Sri Lanka: International Water Management Institute.

Nageswara Rao, K., Krishna, M. G., & Malini, H. B. (2004). Kolleru lake is vanishing—A revelation through digital processing of IRS-1D LISS-III sensor data. *Current Science, 86*(9/10), 1312-1316.

National Commission for Integrated Water Resource Development Plan. (1999). *Integrated water resource development: A plan for action*. New Delhi, India: Ministry of Water Resources.

National Research Council. (2002). *The drama of the commons. Committee on the human dimension of global change*. E. Ostrom, T. Dietz, N. Dolsak, P. C. Stern, S. Stonich, & E. U. Weber (Eds.). Division of Behavioral and Social Change and Education. Washington, DC: National Academy Press.

National Water Development Agency. (2007). Retrieved March 5, 2008, from http://nwda.gov.in/index-main.asp?linkid=84&langid=1

Operation Kolleru resumes amid heavy security. (2006, April 21). *The Hindu*.

Panel wants Kolleru Lake cleared of encroachments. (2006, April 21). *The Hindu*, p. 1.

Pearce, D., Atkinson, G., & Mourato, S. (2006). *Cost-benefit analysis and the environment. Recent developments*. Paris: OECD.

Peden, D., Tadesse, G., & Misra, A. K. (2007). Water and livestock for human development. In D. Molden (Ed.), *Water for food, water for life: A comprehensive assessment of water management in agriculture* (pp. 485-514). London: Earthscan, and Colombo, Sri Lanka: International Water Management Institute.

Poff, N. L., Allan, J. D., Bain, M. B., Karr, J. R., Prestegaard, K. L., Richter, R. E., et al. (1997). The natural flow regime: A paradigm for river conservation and restoration. *BioScience, 47*(11), 769-784.

Rama Rao, J., Jairath, J., & Umesh, P. (2006). Pollution through Aquaculture: Kolleru Wildlife Sanctuary. *Economic and Political Weekly, 41*(7), 585-587.

Ramsar Convention Secretariat. (2006). *Ramsar handbooks for the wise use of wetlands. Vol. 10: Coastal management: Wetland issues in integrated coastal zone management* (3rd ed.). Gland, Switzerland: Ramsar Convention Secretariat.

Saxena, V. K., Singh, V. S., Mondal, N. C., & Jain, S. C. (2003). Use of chemical parameters to delineation fresh groundwater resources in Potharlanka Island, India. *Environmental Geology, 44*, 516-521.

Selvam, V. (2003). Environmental classification of mangrove wetlands of India. *Current Science, 84*, 757-765.

Smakhtin, V., & Anputhas, M. (2006). *An assessment of environmental flow requirements of Indian river basins* (Research report no. 107). Colombo, Sri Lanka: International Water Management Institute.

Smakhtin, V., Gamage, N., Bharati, L. (2007). *Hydrological and environmental issues of interbasin water transfers in India: A case of Krishna River basin* (Research report no. 120). Colombo, Sri Lanka: International Water Management Institute.

Smakhtin, V., Revenga, C., & Doll, P. (2004). *Taking into account environmental water requirements in global-scale water resources assessments* (Comprehensive Assessment research report No. 2). Colombo, Sri Lanka: Comprehensive Assessment Secretariat.

Supreme Court of India. (1996). Judgment on coastal shrimp aquaculture: S. Jaganath vs. Union of India. Judgment of Kuldip Singh and Sagir Ahmed on December 11, 1996.

Suri, K. C. (2006). Political economy of agrarian distress. *Economic and Political Weekly, 41*(16), 1523-1529.

Tharme, R. E. (2003). A global perspective on environmental flow assessment: Emerging trends in the development and application of environmental flow methodologies for rivers. *River Research and Applications, 19*, 397-441.

United Nations Administrative Coordination Council/Inter-Secretariat Group on Water Resources. (1992, January 26-31). *The Dublin statement and report of the conference*. Paper presented at the International Conference on Water and the Environment: Development Issues for the 21st Century, Dublin.

Upadhya, C. B. (1988). The farmer-capitalists of coastal Andhra Pradesh. *Economic and Political Weekly, 23*(27/28), 1376-1382, 1433-1442.

van Doorm, A. (2001). *Salt water intrusion in the Krishna Delta: R&D Project Krishna delta, Vijayawada, Andhra Pradesh*. Internship report, Vrije Universiteit, Amsterdam.

van Rooijen, D. J., Turral, H., and Biggs, T.W. (2008.) Urban and industrial water use in the Krishna basin. *Irrigation and Drainage*. Forthcoming.

Venot, J. P., Sharma, B. R., & Rao, K. V. G. K. (2008). *The lower Krishna basin trajectory: Relationships between basin development and downstream environmental degradation* (Research report no. 125). Colombo, Sri Lanka: International Water Management Institute.

Venot, J. P., Turral, H., Samad, M., & Molle, F. (2007). *Shifting waterscape: Explaining basin closure in the lower Krishna basin, South India* (Research report no. 121). Colombo, Sri Lanka: International Water Management Institute.

Wallach, B. (1984). Irrigation developments in the Krishna Basin since 1947. *Geographical Review, 74*(2), 127-144.

World Water Assessment Program. (2003). *Water for people – Water for Life, The United Nations World Water Development Report*. Paris: UNESCO.

Jean-Philippe Venot is a PhD scholar with the International Water Management Institute (IWMI) and the Laboratoire Gecko at the University of Paris X-Nanterre, France. He is currently in the IWMI-Hyderabad Office (India). His research involves issues of river basin management and the relationships between environment and societies.

Bharat R. Sharma is a senior researcher with the International Water Management Institute (IWMI). He is currently in the IWMI New Delhi office (India). His research involves issues of water management and planning in India

K. V. G. K. Rao is currently an independent consultant in Indwa Techologies Pvt. Ltd. and has been working as an agricultural scientist for several Indian institutions over several decades.