Modeling water supply and demand scenarios: the Godavari–Krishna inter-basin transfer, India

L. Bharati*, V. U. Smakhtin and B. K. Anand

International Water Management Institute, P.O. Box 2075, Colombo, Sri Lanka. Fax: +94-11-2786854

*Corresponding author. E-mail: L.bharati@cgiar.org

Abstract

The Government of India’s National River-Linking Plan (NRLP) aims to alleviate emerging water scarcity problems by transferring water from well endowed to more deficient areas. This study evaluated the plausible future scenarios of water availability and use under conditions of various cropping patterns, and with the explicit inclusion (for the first time) of environmental water requirements for one of the links of the NRLP: from the Godavari River at Polavaram to the Krishna River at Vijayawada—the ‘Polavaram Project’. The scenarios were evaluated using the WEAP (Water Evaluation and Planning) model. The study generates information for use in managing emerging trade-offs. The importance of explicit accounting for monthly variability in description of water supply and demand, in the monsoon-driven climate conditions of the region, is advocated. Such detailed scenario simulations and inclusion of previously unaccounted for factors/uses can help to create awareness of potential future problems, inform water management practices and suggest management alternatives. Results show that the proposed water storage and transfer will reduce water deficit within the project command area and significantly reduce dry slow river flow into the Lower Godavari Delta.

Keywords: India; Inter-basin water transfer; Irrigation; Water demand

1. Introduction

The National River-Linking Project (NRLP) was designed to alleviate emerging water scarcity problems in India. Transfers of ‘surplus’ water from primarily Himalayan rivers to more ‘deficient’ peninsular rivers is expected to reduce imbalances in water availability in the country. The Himalayan and peninsular components intend to transfer 33 and 141 km$^3$ of water, respectively, through the combined network of 30 links with a total length of 14,900 km (GOI, 1999a). The proposed plan, if fully completed, will be the largest ever infrastructure project in the world, with an estimated cost in 1999 of US$120 billion dollars. The additional benefits of the NRLP could include flood control, drought mitigation, increased irrigation, additional food-grain production and electricity generation.


© IWA Publishing 2009
This paper assesses whether the planned water transfer would satisfy the growing water demands in the Polavaram link command area and also analyzes its impacts outside of the command area. The link is planned to transfer water from the water surplus Godavari River (at Polavaram) to the water deficit Krishna River (at Vijayawada) (GOI, 1999b). The main reason for selecting this particular link is because the Polavaram Project is to be implemented in the near future, irrespective of other NRLP water transfers. The approach described in the paper, however, can be applied to other planned water transfers as well.

2. Description of the Polavaram project

2.1. Godavari–Krishna transfers

The Godavari River (Figure 1) is the second largest river in India, with a catchment area of 312,812 km² and a long-term average annual surface flow of 110 km³, of which 76 km³ is estimated as utilizable (Amarasinghe et al., 2005). Cultivable area in the basin is about 18.9 million ha. The already existing Arthur Cotton Barrage, located downstream of the future Polavaram Reservoir site, provides irrigation water to 170,000 ha in the lower Godavari Basin. As in other parts of India, the use of groundwater to meet irrigation water demands is also a common practice.
The Krishna River Basin is the fourth largest in India with a total catchment area of 258,948 km² and a long-term average annual surface flow of 78 km³, of which 58.0 km³ is considered to be utilizable (Amarasinghe et al., 2005). The cultivable area in the basin is about 20.3 million ha. Three large irrigation projects are operational in the basin. The Krishna Delta Project near Vijayawada, which is to directly benefit from the Polavaram water transfer, was constructed in 1852 (Figure 1) and designed to irrigate 530,000 ha of land. The Krishna Delta plays a vital role in the rice economy of the nation and, in addition to the major dam, a large number of informal irrigation sources such as groundwater tube wells, tanks and minor reservoirs are spread throughout the area. Due to the massive surface irrigation development and the rapid expansion of groundwater irrigation, the annual river flow at the outlet of the Krishna has decreased to some 36% of its pre-development level, and some studies have reported the “closure” of the basin (e.g. Biggs et al., 2007).

Several water transfers have been proposed from the Godavari to the Krishna (Smakhtin et al., 2007). Some of these links are planned as parts of much longer transfers from the Himalayas to the Peninsula. The most ‘downstream’ link—Polavaram to Vijayawada (Figure 1)—can, however, be seen as a ‘local’ project, because the main aim of this link is to transfer what is perceived as ‘surplus’ water from a more water endowed Godavari to an already water-deficient and over-utilized Krishna Delta. Furthermore, the project is expected to reduce informal irrigation and the use of groundwater in the Krishna Basin.

### 2.2. The Polavaram project

Figure 1 shows the proposed project including the site of the Polavaram Reservoir and the command area of the link canal. The project includes two canals, i.e. on the right and left bank of the Godavari River. The Polavaram—Vijayawada link command area is located on the right bank, with the link canal starting from the proposed Polavaram Reservoir. The climate in the command area of the Polavaram project varies from hot, semi-arid to sub-humid, tropical. The monsoon season (known as Kharif in India) extends from June to October, and the post-monsoon season (known as Rabi) extends from November to March, with a usual annual dry spell from April to May. Average annual rainfall is 1,000 mm, with over 80% falling during the Kharif season due to the southwest monsoon. The temperature varies from 44°C in May to 22°C in December. The overall population density in the command area is 543 persons per km² with 60% of the population dependent on agriculture (GoAP, 2003a, b, c, d).

The total cultivable area of the Polavaram link canal is 139,740 ha. Of this area, 71% (99,755 ha) is irrigated by bore wells, tanks and open head channels taking off from the river, and 29% (39,985 ha) is non-irrigated (GOI, 1999b). However, a more recent survey in the Polavaram area (Bhaduri et al., 2007), suggested that almost 95% of cultivated area in the link command area is already under irrigation at present. Therefore, the assumption that a significant new irrigated area will develop due to the implementation of the proposed link canal may not materialize, as the existing Arthur Cotton Barrage in the Godavari, the Prakasham Barrage in the Krishna and lift irrigation from the main river channel supply surface water to the deltas. Most of the ‘new’ area that, according to the feasibility study from 1999, is to be brought under irrigation is already being irrigated with groundwater, water from tanks or canals. Bhaduri et al. (2007) indicate that 84% of the command area is currently irrigated with groundwater, and 9% with water from canals. Hence the main role that the project might play is to reduce groundwater depletion and facilitate intensification of crop production.
The Polavaram Project would allow paddy, sugarcane, chillies and pulses to be planted, considering soil suitability, the agro-climatic conditions and local practices (GOI, 1999b). Furthermore, irrigated crop intensity is expected to reach 150%. The current existing cropping pattern in the area is dominated by paddy, sugarcane and tobacco during both the Kharif and Rabi seasons (Bhaduri et al., 2007). Increased upstream development, especially through the construction of reservoirs and irrigation systems in the Krishna basin, has resulted in declining downstream flows, which has affected cropping patterns in the Krishna Delta. When enough water is available, however, two rice crops are grown per year in the Krishna Delta, while in dry years, one rice crop and one less water-intensive crop during the Rabi season is practiced (Biradar, 2007). In the Godavari Delta, two paddy crops are grown. However, in both the Godawari and Krishna deltas, supplemental groundwater use is common practice.

The Project Plan suggests that the main left canal will transfer 3,663 million cubic meters (MCM) of water to meet future irrigation and industrial requirements. The link canal on the right bank will divert 5,325 MCM for irrigation, domestic supply and industry. The planned Polavaram reservoir will have a utilizable storage of 2,130 MCM (GOI, 1999b) and will submerge around 63,000 ha of land, which at present hosts 250 villages with a total population of 145,000 (GOI, 1999b, 2001; GoAP, 2006).

3. Methods

3.1. Overview of the WEAP 21 model

The Water Evaluation and Planning Model (WEAP), developed by the Stockholm Environment Institute (SEI), is designed to evaluate water resources development and management scenarios associated with changes in biophysical and socioeconomic conditions (Yates et al., 2005). In the WEAP model, water supply is defined by the amount of precipitation that falls on a catchment or a group of catchments. This supply is progressively depleted through natural processes, human withdrawals, or enhanced through accumulations/storages. Thus, the WEAP 21 model adopts a broad definition of water demand, where the catchment itself is the first point of depletion through evapotranspiration. The core of the model is a water balance equation that includes such components as catchment-scale rainfall-runoff processes, groundwater recharge, evaporative demands and surface and groundwater withdrawal and return flows. Water supplies and demands are linked to the stream network and water allocation components via the WEAP 21 interface, which keeps track of water allocations and accounts for groundwater and streamflow depletion and addition (Yates et al., 2005). The model optimizes water use in a catchment using an iterative Linear Programming algorithm which seeks to maximize the water delivered to demand sites, according to a set of user-defined priorities. Demand sites are assigned a priority that ranges between 1 and 99, where 1 is the highest priority and 99 is the lowest priority. When water is limited, the model progressively restricts water allocation to demand sites with the lowest priority. More details of the model are available in SEI (2001) and Yates et al. (2009).

3.2. Scenario formulation

In order to assess whether the planned water transfer would satisfy the growing water demands in the Polavaram link command area, and also analyze its hydrologic impacts outside of the command area, two main scenarios were simulated:
Scenario 1—Reference Scenario. Current water use under current supply and demand network. The water sources are groundwater and the river channel.

Scenario 2—With the Polavaram reservoir and Link canal. Water supply and demand after the construction of the Polavaram project. The water source is the Polavaram Reservoir and the link canal, ground water and the river channel.

As 95% of the cultivable area is already under irrigation (Bhaduri et al., 2007), it was assumed that substantial increases in irrigated area will not be possible. Therefore, in both scenarios, the agricultural land in the link command area was kept constant. Figure 1 illustrates, in a simplified way, the physiographic setting of the link canal, barrages and right and left bank command areas. In both the Krishna and Godavari Deltas, agriculture is still the major water user compared to domestic and industrial demands (Table 1) and increased agricultural production is the main goal of the Polavaram project. Therefore, the anticipated benefits of building the Polavaram Reservoir and the link canal system are mainly due to improved water supply leading to increases in cropping intensity and yields. The impacts of the Polavaram project were assessed by running the above two main scenarios under different crop rotation systems: i) paddy-paddy, ii) paddy-pulses (representing a low water intensity crop) and iii) sugarcane only. These cropping patterns reflect the regional practice of planting two paddy crops or sugarcane if farmers perceive no water scarcity, and a cropping pattern of paddy during the monsoon and a low water-intensive crop (e.g. pulses, tobacco) during the dry season under water scarce conditions. The domestic, industrial and livestock water demands were kept constant in all runs. Each crop rotation condition was run with and without the inclusion of environmental flow (EF) requirements. The results of the scenarios were compared and discussed in terms of unmet water demands.

3.3. Data and WEAP set up and simulations

The starting point of the analysis was the development of water demands in the study area: from agriculture, the domestic sector, industry and livestock. Each demand in the model is represented by a demand node. Monthly water demands from each node were assigned a priority level and linked to its available sources of water supply. Domestic water demand was given the first priority, followed by agriculture, industry and livestock—in that order.

In the model set up, the link canal command area was divided into sub-catchments based on a drainage map extracted from a digital elevation model (DEM). For the 6 sub-catchments that fell under the link command area (labeled R1–R6 in tables and figures presented here, though no links are shown in Figure 1), nodes corresponding to agricultural and domestic demand were created. However, as livestock and industrial water demands were very small, only one demand node representing livestock and one demand node representing industrial demand were created for the entire command area. Water demand data were available at mandal level (India’s third-level administrative subdivision after State and District). The mandal boundaries in the command area are shown in Figure 1. In the model, however, the sub-catchment represents the hydrological demand unit. Therefore, the mandals in the command area were assigned to the sub-catchments by merging them together using a Geographic Information System (GIS). The demand nodes that were closer to the sources of water supply were given higher priorities.
Table 1. Water demand for 2003 (MCM; not including loss and reuse) for domestic, industry, livestock and agricultural demand from the catchments within the link command area (R1–R6), Arthur Cotton command area and the left bank canal area.

<table>
<thead>
<tr>
<th>Demand site</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sept</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture-R1</td>
<td>23.7</td>
<td>25.0</td>
<td>34.3</td>
<td>48.3</td>
<td>53.8</td>
<td>37.5</td>
<td>66.3</td>
<td>71.8</td>
<td>72.6</td>
<td>77.7</td>
<td>67.8</td>
<td>38.5</td>
</tr>
<tr>
<td>Agriculture-R2</td>
<td>25.0</td>
<td>26.4</td>
<td>36.3</td>
<td>51.1</td>
<td>56.9</td>
<td>39.6</td>
<td>70.0</td>
<td>75.9</td>
<td>76.7</td>
<td>82.1</td>
<td>71.7</td>
<td>40.7</td>
</tr>
<tr>
<td>Agriculture-R3</td>
<td>16.7</td>
<td>17.7</td>
<td>24.3</td>
<td>34.2</td>
<td>38.1</td>
<td>26.5</td>
<td>46.9</td>
<td>50.8</td>
<td>51.4</td>
<td>55.0</td>
<td>48.0</td>
<td>27.2</td>
</tr>
<tr>
<td>Agriculture-R4</td>
<td>57.5</td>
<td>35.4</td>
<td>22.0</td>
<td>28.4</td>
<td>42.1</td>
<td>46.0</td>
<td>105.3</td>
<td>115.8</td>
<td>126.0</td>
<td>159.0</td>
<td>177.7</td>
<td>125.9</td>
</tr>
<tr>
<td>Agriculture-R5</td>
<td>27.1</td>
<td>28.6</td>
<td>39.3</td>
<td>55.4</td>
<td>61.6</td>
<td>42.9</td>
<td>75.9</td>
<td>82.3</td>
<td>83.2</td>
<td>89.0</td>
<td>77.7</td>
<td>44.1</td>
</tr>
<tr>
<td>Agriculture-R6</td>
<td>3.0</td>
<td>3.1</td>
<td>4.3</td>
<td>6.0</td>
<td>6.7</td>
<td>4.7</td>
<td>8.3</td>
<td>9.0</td>
<td>9.1</td>
<td>9.7</td>
<td>8.5</td>
<td>4.8</td>
</tr>
<tr>
<td>Domestic-R1</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Domestic-R2</td>
<td>0.5</td>
<td>0.6</td>
<td>0.6</td>
<td>0.5</td>
<td>0.6</td>
<td>0.5</td>
<td>0.6</td>
<td>0.6</td>
<td>0.5</td>
<td>0.6</td>
<td>0.5</td>
<td>0.6</td>
</tr>
<tr>
<td>Domestic-R3</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Domestic-R4</td>
<td>1.7</td>
<td>1.8</td>
<td>1.8</td>
<td>1.7</td>
<td>1.8</td>
<td>1.8</td>
<td>1.8</td>
<td>1.6</td>
<td>1.8</td>
<td>1.7</td>
<td>1.7</td>
<td>1.8</td>
</tr>
<tr>
<td>Domestic-R5</td>
<td>6.3</td>
<td>6.5</td>
<td>6.5</td>
<td>6.3</td>
<td>6.5</td>
<td>6.5</td>
<td>6.5</td>
<td>5.8</td>
<td>6.5</td>
<td>6.3</td>
<td>6.5</td>
<td>6.5</td>
</tr>
<tr>
<td>Domestic-R6</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Industry</td>
<td>8.1</td>
<td>8.4</td>
<td>8.4</td>
<td>8.1</td>
<td>8.4</td>
<td>8.4</td>
<td>8.4</td>
<td>7.6</td>
<td>8.4</td>
<td>8.1</td>
<td>8.4</td>
<td>8.4</td>
</tr>
<tr>
<td>Left bank canal</td>
<td>54.6</td>
<td>56.4</td>
<td>56.4</td>
<td>84.7</td>
<td>176.7</td>
<td>475.6</td>
<td>507.4</td>
<td>537.5</td>
<td>622.3</td>
<td>717.9</td>
<td>204.9</td>
<td>176.7</td>
</tr>
<tr>
<td>Livestock</td>
<td>2.0</td>
<td>2.1</td>
<td>2.1</td>
<td>2.0</td>
<td>2.1</td>
<td>2.0</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
<td>2.0</td>
<td>2.1</td>
</tr>
<tr>
<td>Prakasham Barrage Irrigation</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>51.4</td>
<td>205.6</td>
<td>719.5</td>
<td>770.9</td>
<td>822.2</td>
<td>976.4</td>
<td>1,130.6</td>
<td>257.0</td>
<td>205.6</td>
</tr>
<tr>
<td>Arthur Cotton Barrage</td>
<td>31.1</td>
<td>32.1</td>
<td>32.1</td>
<td>113.1</td>
<td>360.1</td>
<td>1,178.9</td>
<td>1,262.0</td>
<td>1,343.9</td>
<td>1,586.8</td>
<td>1,835.9</td>
<td>441.0</td>
<td>360.1</td>
</tr>
<tr>
<td>Total</td>
<td>258.7</td>
<td>245.3</td>
<td>269.7</td>
<td>492.6</td>
<td>1,022.1</td>
<td>2,591.0</td>
<td>2,933.6</td>
<td>3,130.0</td>
<td>3,623.0</td>
<td>4,177.6</td>
<td>1,374.3</td>
<td>1,044.1</td>
</tr>
</tbody>
</table>
The agricultural water demand for each sub-catchment was calculated using the FAO Crop Requirements Method option in the WEAP model (FAO, 1998). The domestic, livestock and industrial water demands were calculated using the statistical reports of the Indian Government (GoAP, 2003a, b, c, d). Water demands from outside the link command area (but still to be affected by the proposed water transfer) were also added to the model set up. These additional demands included:

- demands from mandals on the left bank command area of the Godavari River (Figure 1), based on the quantity of water to be transferred from the left bank canal (GOI, 1999b);
- irrigation demands from the Prakasham Barrage;
- irrigation demands from the Arthur Cotton Barrage.

The Arthur Cotton and Prakasham Barrage irrigation command areas lie in the Krishna and Godavari Deltas, downstream of the proposed Polavaram Reservoir and command area (Figure 1). These additional demand sites were not represented in the model as catchments, but as sites where a fixed quantity of water is abstracted from the sources of supply on a monthly basis. Each demand site was assigned a priority, which determined the water allocation order. In Scenario 1, the Arthur Cotton Barrage command area in the Godavari Delta was given a higher priority than the irrigation demands in the link command area catchments. In Scenario 2, however, the link command area demands were given a higher priority than the Lower Delta.

The sources of water supply that were built into the model were precipitation (for the catchments), surface water and groundwater. Precipitation supply was calculated based on monthly data from a climate station located in the Krishna Delta. Surface water flows in the Krishna and Godavari were obtained from river gauging stations upstream of the Polavaram project. Ground water in the model was represented by a node and water availability was calculated based on the storage capacity and natural recharge values which were based on GoAP (1995, 2006). The maximum withdrawal rates from groundwater were based on the storage capacity and groundwater recharge rates for the area.

The Polavaram Reservoir was simulated using the salient features published in the government feasibility report (GOI, 1999b), where the link canal is designed to transfer 5,325 MCM of water per annum. The gross storage capacity of the reservoir is to be 5,511 MCM and the live storage is 2,130 MCM. The annual evaporation loss from the reservoir has been estimated to be 989 MCM. The reservoir releases were based on seasonal variations in water demand i.e. more water is transferred during the dry season.

The environmental flow requirements were estimated using the method described by Smakhtin & Anputhas (2006). The method takes into account the limitations of available hydrological and ecological information in India at present, but ensures that elements of natural flow variability are preserved in the estimated environmental flow time series, as required by contemporary hydro-ecological theory. The method is based on the use of a flow duration curve—a cumulative distribution function of monthly flow time series. The curve is calculated for several categories of aquatic ecosystem protection—from ‘largely natural’ to ‘severely modified’—and the required EF volume and elements of flow variability are set to progressively reduce with the decreasing level of ecosystem protection. The EF calculated for the lowest acceptable category D (‘largely modified’ rivers) were used in this analysis. In the model runs with the inclusion of environmental flow requirements, the highest priority was given to environmental demands. The runs with the inclusion of environmental
flow requirements were run with a crop rotation of paddy-paddy and paddy-pulses. Simulations were conducted over the period from June 1991 to May 2005.

4. Results and discussions

4.1. Scenario 1: reference scenario with current water supply and use

Under the current system of water use, the average annual un-met demand for a period from June 1991 to May 2004 in the command area of the link canal is 1,643 MCM for a paddy-paddy system. Figure 2 shows the cumulative monthly average unmet demands for agriculture, domestic use, industry and livestock uses under different simulation runs: paddy-paddy, all sugarcane, paddy-pulse, paddy-paddy with environmental flows and paddy-pulse with environmental flows. The unmet demands occur in all months except July and August (peak of the monsoon). Changing cropping pattern may decrease the unmet demands. For example, planting only one paddy crop during the rainy season and pulses (a low water intensity crop) during a Rabi season decreased water deficits by up to 48% (Figure 2). As expected, giving EF (even very small environmental flow requirements, corresponding to the least acceptable Environmental Management Class D) a high priority in the water allocation scheme, increased the unmet demands for other uses (agriculture, industry, and domestic). The un-met demands are the highest for the simulation that combines a paddy-paddy rotation with environmental flow requirements (Figure 2).

Annual demands from the Arthur Cotton Barrage are 8,199 MCM for irrigation and 378 MCM for domestic and industrial use (GOI, 1999b). Assuming these demands and a paddy-paddy cropping system,
the mean annual simulated unmet demand for the command area of the Arthur Cotton Barrage in the Godavari Delta is 818 MCM. This constitutes 10% of the mean total annual demands. The model also considered loss and reuse during transmission. Information on groundwater was not available for the areas outside of the Polavaram link command area. Therefore the demands in the model were linked to surface water supplies. Bhaduri et al. (2007) found that groundwater is used in this area. Consequently, the unmet surface water demands at present are probably being met by groundwater extraction. The water deficit in the Godavari Delta is in the Rabi and dry seasons (December to May; Figure 3). There is no deficit in the months from June to November. Therefore, the analysis shows that although there may be surplus water during the Kharif season, in other months there is a deficit in the Godavari Delta which is being met by ground water. In the area supplied by the Prakasham Barrage in the Krishna Delta, the annual total demand is 5,139 MCM (GOI, 1999b). The model calculated 27 MCM of annual average unmet demand after 2003. Similarly, a mean annual un-met demand of 2,057 MCM was calculated for the left bank command area in the Godavari. Similar to the Arthur Cotton Barrage command area, the water deficit in the left bank command area is only in the Rabi and dry seasons (December to May; Figure 3).

In order to check if estimated EF requirements are being met in the Krishna Delta, under present conditions, the EF for Class D were plotted against observed flow from the gauging station at Vijayawada (Figure 4). The Vijayawada gauge is downstream of the Prakasham Barrage (Figure 1). As shown in Figure 4, the situation in recent years has deteriorated as more water is being used upstream for various purposes. Annual analysis for the Godavari showed that during the 14 year modeling period, the EF requirements are not met during the dryer years (based on rainfall data). Figure 5 illustrates that the unmet EF requirements are highest in June, when water demand for agriculture is high. The unmet EF plot shown in Figure 5 is simulated with a paddy-paddy cropping pattern. Delays in the onset of the rainy season will affect water available for EF. Paddy sowing was assumed to start in June. Therefore, if the monsoon does not start in June, irrigation water demand will increase. The EF for class D are met from August to November.

![Unmet water demand in the Godavari Delta](image-url)

Fig. 3. Scenario 1: monthly average (1991–2004) unmet demands based on water requirements from the Arthur Cotton Barrage and the Polavaram left bank command area.
4.2. Scenario 2: with the Polavaram reservoir and link canal

The simulations with the link canal and reservoir show that there are minimal unmet demands for agriculture, domestic, and livestock requirements within the link command area (Figure 6). Figure 7 shows monthly average unmet demand (for 1991–2004) from agriculture, domestic use, industry and livestock for the link command area under different cropping patterns as well as with EF requirements. The unmet demands occur during the period from January to June, and changing cropping pattern to paddy-pulses almost nullifies the unmet demands which exist under other crop rotations (Figure 7). This is definitely an improvement for the link command area compared with scenario 1 (Figure 2) where the unmet demands are one order of magnitude higher. Introducing EF for downstream Krishna and Godavari, especially coupled with a paddy-paddy cropping pattern, increases the unmet demands during the months from January to June (Figure 7). When comparing these values to Scenario 1 in Figure 2, one can conclude water deficits within the link command area have decreased. However, if EF requirements are included, then there is a deficit in the link command area under a paddy-paddy cropping system.

The mean annual unmet demands for the left bank command area and the Arthur Cotton Barrage command area were 799 MCM and 5,270 MCM, respectively. Compared to Scenario 1, the water deficit is smaller in the left bank command area, but higher in the Arthur Cotton Barrage command area, which is expected since water in the Godavari is being stored and diverted to the Polavaram command area. As with the current situation (Scenario 1), there is a water deficit in the Arthur Cotton command area only in the Rabi and summer seasons (December to May). The situation of un-met demands for the Prakasham Barrage irrigation area shows improvement as there was no water deficit, with the exception of 2003, which was a particularly dry year. This water deficit occurs again only in March and can be alleviated by growing pulses or another low water-intensive crop during the Rabi season. Therefore, analysis with the link canal (Scenario 2) showed that although the pressure on water resources within the left and right
bank command areas reduces, there will be an increased deficit in the Arthur Cotton Barrage command area. This deficit is, however, only during the Rabi and summer seasons.

4.3. Comparing scenario 1 and 2

In the two analyses (Scenarios 1 and 2), demands from the mandals in the link command area were also supplied with groundwater, but due to the lack of groundwater recharge data from the Arthur Cotton Barrage, Prakasham Barrage and the left bank command area, demands were linked to surface water

![Figure 5](https://iwa.silverchair.com/wp/article-pdf/11/S1/140/406763/140.pdf)

**Fig. 5.** Scenario 1: unmet environmental water demand under current conditions with a paddy-paddy cropping pattern. Environmental flows are given the highest priority and a paddy-paddy cropping pattern is simulated.

![Figure 6](https://iwa.silverchair.com/wp/article-pdf/11/S1/140/406763/140.pdf)

**Fig. 6.** Scenario 2: monthly average (1991–2005) unmet water demands under a paddy-paddy crop rotation. Unmet demands in the link command area are minimal compared to those in the Arthur Cotton Barrage area and left bank.
availability. In reality, however, some of this un-met demand is met by groundwater. It is possible that increased aquifer recharge due to irrigation in the Polavaram link command area will provide additional groundwater resources for the Lower Delta where the Arthur Cotton Barrage command area is located. However, more studies are necessary to make accurate predictions on the sustainability of groundwater use. A key objective of the Polavaram Project is to reduce groundwater use. Therefore, if there is an increase in the pumping of groundwater in the Lower Delta to maintain the existing agricultural production (due to less water delivered), this objective will not be met and the pressure on the natural aquifers will increase.

Salient features published in the government feasibility report (GOI, 1999b) were used to simulate the storage volumes of the proposed Polavaram reservoir. Published monthly net evaporation was also used to calculate evaporation losses from the reservoir. The reservoir was found to reach the inactive zone (3,381 MCM) during every dry season, which means that the water stored during each monsoon will be utilized during the dry season of that same year. The storage capacity of the reservoir does not provide storage and ensure water for inter-annual variations.

Analysis of the Godavari river flows in the delta showed that during the 13-year modeling period, the EF requirements were not met during June in 1993, 1997, 2000 and 2003. In the simulation, EF requirements were set under a paddy-paddy cropping pattern, where paddy sowing was set to start in June. Therefore, as water demands for agriculture are high during this month, if the monsoon rains (which usually start in June) are delayed then there will be un-met demands for agriculture as well as for EF requirements. In both scenarios, June has the highest un-met EF for the Godavari. The storage in the Polavaram reservoir, as mentioned above, is utilized within each year. Therefore, in this case, the reservoir does not also provide water to compensate for delays in the onset of the monsoon rains. The EF
requirement, which is more critical in the Krishna River, does not improve after the link and the subsequent water transfer, as most of the water that is transferred will be utilized for en route irrigation demands. In the Krishna, the highest unmet EF demands are also in June and July, at the start of the monsoon season.

5. Conclusions and implications

In this study, detailed monthly analysis was done to test the feasibility of the Polavaram Reservoir and water transfer scheme. The study suggests that water resources management in the region has to be done on a seasonal basis by taking monthly variability into consideration. The simulations show that the proposed Polavaram Reservoir and link canal will reduce the seasonal pressure on water resources for the proposed command area of the reservoir. However, this will result in increased water deficits during Rabi and summer months in the Lower Godavari Delta, which is being supplied water through the Arthur Cotton Barrage. Therefore, water deficits may simply be transferred from one area to another. The water deficits exist only in the dry months. Changing cropping patterns, for example by planting paddy during the monsoon season and a low water-intensive crop such as pulses in the dry season in the link command area, will decrease unmet demands for the Lower Godavari Delta. However, this will not be enough to continue the present water use patterns in the Arthur Cotton Barrage command area. A part of the problem is that the storage capacity of the proposed Polavaram Reservoir may not be sufficient to meet the planned irrigation requirements and other demands in the link command area, as well in the Arthur Cotton and left bank areas.

Similarly, the need to ensure EF should also be considered in the context of seasonal variability, as it is mostly in the dry months that water allocation problems become critical. In the Godavari, it will not be possible to meet EF requirements in June, just before the start of the monsoon, if the onset of the rainy season is delayed. Meeting EF requirements in the Krishna is a bigger problem than in the Godavari and the situation is not likely to improve even after the Polavaram project, as most of the water that is being transferred will be used for en route irrigation.

In this study, the analysis of the water transfer is done purely on hydrological terms, as the main justification for the NRLP is based on the transfer of ‘surplus’ water to ‘deficit’ basins. It is, however, also recommended to integrate an economic analysis into the assessment, whereby the benefits of the project’s incremental water supply can be compared against the losses (e.g. second season rice crop in the Godavari Delta). The planning of water transfer schemes should also look at the land and production loss, displacement costs and other impacts associated with water infrastructure development. While all possible attempts have been made by the authors to acquire the best input data available, it was not always possible and hence a number of assumptions had to be made. Information available on economic and social analysis look similarly fragmented (GOI, 1999b).

Inter-basin water transfers have been an integral part of water resources management all over the world. However, careful integrated planning and analysis is necessary to ensure that proposed high investment schemes are able to operate as planned and can deliver the expected long-term benefits.

Acknowledgements

This study is part of the research project on the assessment of the National River-Linking Project (NRLP). The project is funded by the CGIAR Challenge Program on Water and Food (CPWF).
The continuing efforts made by Dr A. Gaur and Jean-Philippe Venot (IWMI, India) to acquire data are gratefully acknowledged. The authors are grateful to Dr H. Turral and Dr Chandrashekhar Biradar (IWMI, Colombo) for their valuable comments on this paper.

References


Received 15 November 2007; accepted in revised form 17 July 2008