RESEARCH REPORT

120

# Hydrological and Environmental Issues of Interbasin Water Transfers in India:

## A Case of the Krishna River Basin

Vladimir Smakhtin, Nilantha Gamage and Luna Bharati

International Water Management Institute

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*Vladimir Smakhtin, Nilantha Gamage and Luna Bharati*

**International Water Management Institute**
P O Box 2075, Colombo, Sri Lanka

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*The authors*: Vladimir Smakhtin is a Principal Scientist in Hydrology and Water Resources; Nilantha Gamage is a Research Officer in Remote Sensing and GIS; and Luna Bharati is a Researcher in Hydrology and Water Resoureces, all at the International Water Management Institute (IWMI), Colombo, Sri Lanka.

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*Cover photograph:* The collage on the front cover of this report was created by Mr. Sumith Fernando, Layout and Graphics Specialist, IWMI, using two original photographs. The photograph on the left shows the left bank main canal of the Nagarjunar Sagar Project on the Krishna River in Andhra Pradesh State of India (photo credit: Mr. Jean-Philippe Venot, IWMI, Hyderabad, India). The photograph on the right shows the Tungabhadra Reservoir on the Krishna River in Karnataka State of India (photo credit: Mr. Daan van Rooijen, IWMI, Ghana)

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# Contents

# Summary

This report examines aspects of hydrological and environmental feasibility of interbasin water transfers in India and forms part of the larger research project which deals with multiple aspects of the National River Linking Project. The study uses the water transfer links in and out of the Krishna River Basin as examples. It reviews the hydrological and environmental sections of existing national feasibility reports, analyzes the methodology used for the assessment of surface water availability for each transfer and illustrates the potential environmental impacts of the transfers in the deltas of the Godavari and Krishna rivers. It is shown that the planning process, as presented, has not considered the variability of flow within a year, which is high in monsoon-driven Indian rivers. As a result, much more water may be perceived to be originally available at a site of transfer. The use of alternative techniques, such as a low-flow spell analysis and a storage-yield analysis, to reevaluate the availability of the surface water at proposed transfer sites is advocated. It is shown that water transfer planning is based on the maximum projections for future irrigation adopted by each state which falls within each river basin. This boosts irrigation requirements and serves as the driver for future water resources development. It is emphasized that environmental water demand needs to be calculated (using the desktop technique developed earlier) and explicitly included at the planning stage—similar to the demands of other sectors. This “contingency” demand would reserve some water for environmental use in the future, while more detailed national approaches for environmental flow assessment are being developed. Environmental impacts of reduced water and sediment inflows to the Godavari and Krishna deltas are examined in the context of the most downstream link from the Godavari (Polavaram) to the Krishna (Vijayawada). It is shown that the Krishna Delta has retreated noticeably during the last 25 years. Environmental flows need to be provided to at least delay this “shrinkage” which threatens agricultural production and mangrove ecosystems.

# *Hydrological and Environmental Issues of Interbasin Water Transfers in India: A Case of the Krishna River Basin*

*Vladimir Smakhtin, Nilantha Gamage and Luna Bharati*

## Introduction

The National River Linking Project (NRLP) was proposed as *the solution* to water-related problems in India. It envisages transferring water of the Ganga, Brahmaputra and Meghna rivers through the Mahanadi and Godavari river basins, all normally referred to as “water surplus” basins, to the “water-deficient” basins in the south and west (e.g., http://www.riverlinks.nic.in/). The NRLP is a contentious issue in Indian society and the media and amongst academics. Many scholars argue that the needs assessment of NRLP is inadequate. Others are of the view that the assessment of water surplus/deficits in Indian river basins, conducted as part of the NRLP proposal, has ignored environmental issues. Yet, others think that definitions of surplus and deficient basins need to be made more explicit and that alternative water management options, those that are less costly, easier to implement and more environmentally acceptable, have not been considered.

Extensive work has been done in India on various aspects of water transfers related to the NRLP. However, the project as a whole has not reached implementation which, to a certain degree, mirrors the fate of some other large-scale water transfer projects in the world. At the same time, some individual NRLP links are about to be constructed. Perhaps, one of the major reasons for the slow development of the project is the lack of clarity and transparency in technical design, justification of transfers and decision making on the one hand, and the enormity of both the challenge and the scale of the transfer on the other. In an ideal world, any water transfer project may be justified if it satisfies the following broadly defined criteria (Interbasin Water Transfer 1999):

1. The area of delivery must face a substantial deficit in meeting present or projected future water demands after considering alternative water supply sources and all reasonable measures for reducing water demand.
2. The future development of the area of origin must not be substantially constrained by water scarcity; however, consideration to transfer that constrains future development of an area of origin may be appropriate if the area of delivery compensates the area of origin for productivity losses.
3. A comprehensive environmental impact assessment must indicate a reasonable degree of certainty that it will not substantially degrade environmental quality within the area of origin or area of delivery; however, transfer may be justified where compensation to offset environmental injury is provided.
4. A comprehensive assessment of sociocultural impacts must indicate a reasonable degree of certainty that it will not cause substantial sociocultural disruption in the area of origin or area of water delivery; however, transfer may be justified where compensation to offset potential sociocultural losses is provided.
5. The net benefits from transfer must be shared equitably between the donor area and the receiving area.

The International Water Management Institute is conducting a research project, which aims to highlight, discuss and – where possible – resolve some of the controversial issues pertaining to the NRLP thus stimulating the debate on India's water future. This report is one of the multiple outputs of this research project. The primary focus of the report concerns the hydrological feasibility and environmental impacts of NRLP, which are reflected by criteria 1, 2 and 3 above. It is not the objective of the report to analyze all NRLP links from all possible angles of technical and environmental feasibility. The authors rather aim to a) identify and examine those technical and environmental aspects which may have been underappreciated in previous discussions on NRLP and need to receive further attention, and b) illustrate their importance on one or several (but very few) links. More specifically, first this report briefly describes the proposed links in and out of the Krishna River from/to adjacent river basins (Figure 1). Krishna is a major river basin, spanning three states in peninsular India.[1] This is followed by the discussion, using some links as examples, on how water transfer planning may be affected by the resolution of the hydrological data. The report further focuses on the environmental aspects of one of these links: Godavari (Polavaram)-Krishna (Vijayawada); Figure 2. This link is the most downstream one in the Godavari-Krishna system and one which is currently being constructed. A companion report by Bharati et al. (n.d.) discusses the multiple aspects of water management of the Polavaram- Vijayawada link and examines the impacts of water management options and scenarios using an Integrated **W**ater Resources **E**valuation **A**nd **P**lanning (WEAP) model.

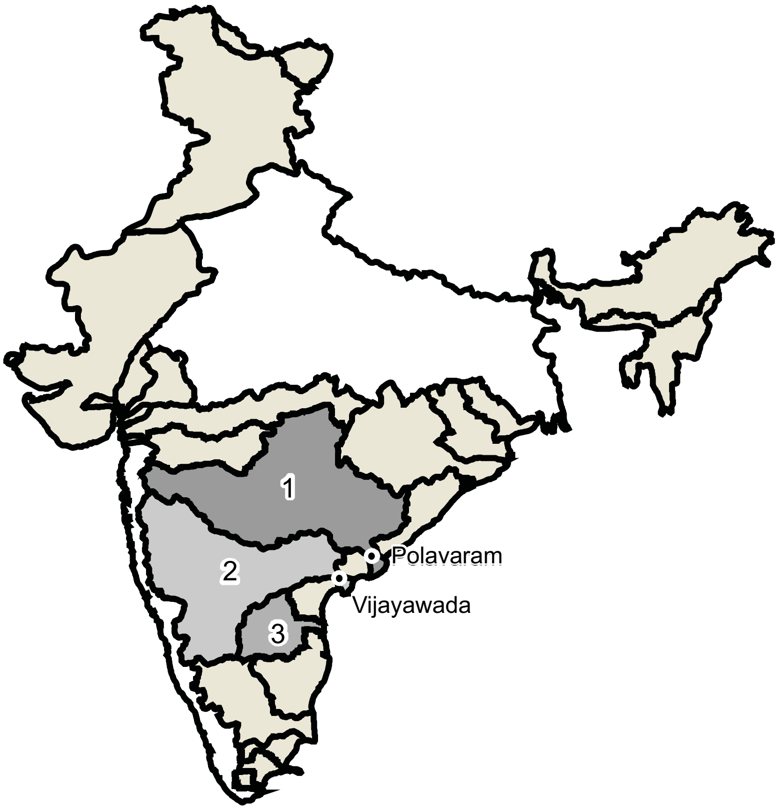

FIGURE 1. A schematic map of India, showing the boundaries of the major River Basins/drainage regions of the country. 1, 2 and 3 are Godavari, Krishna and Pennar Basins, respectively.

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[1] The Krishna River Basin is one of five "benchmark basins" in which IWMI conducts research, where the intention is to integrate various strands of biophysical, socioeconomic and institutional research around the world.

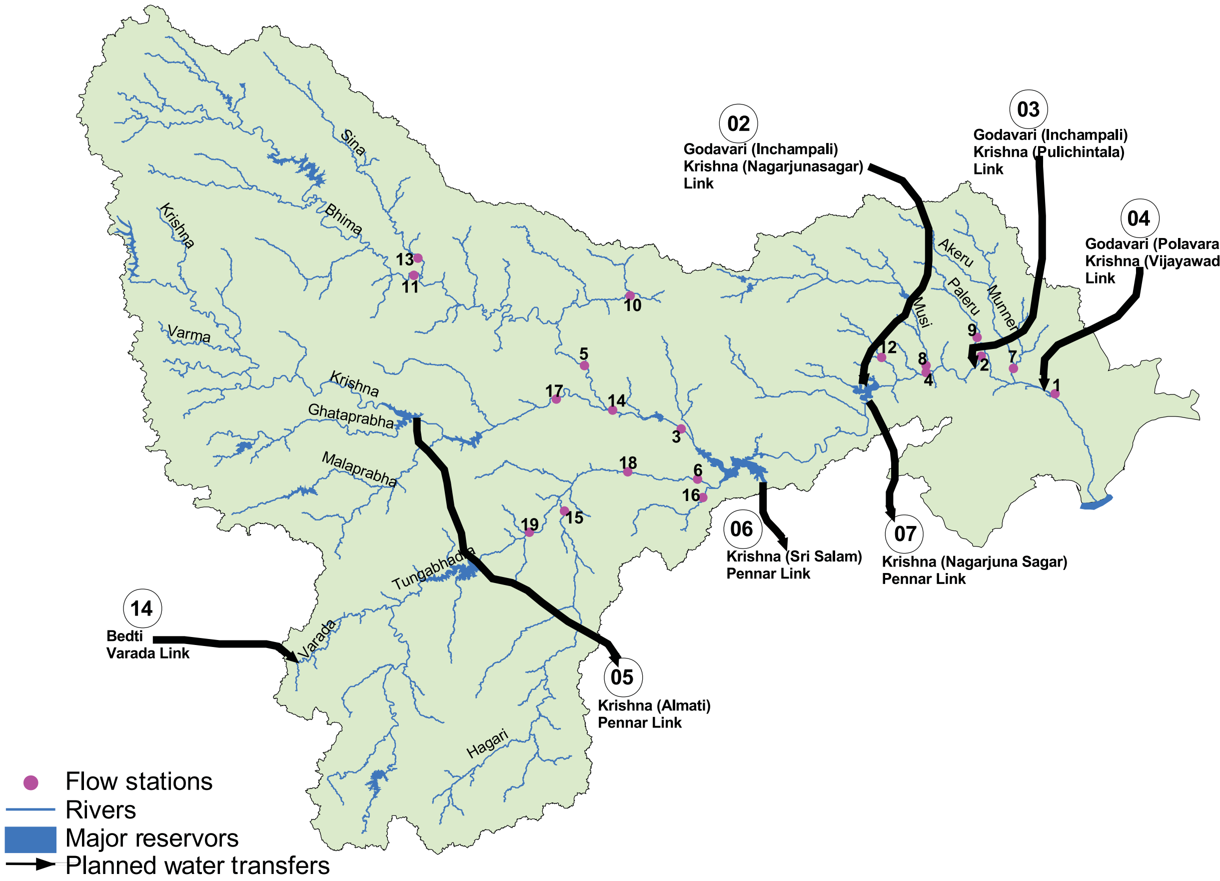

FIGURE 2. A schematic diagram of the Krishna River Basin, showing all proposed interbasin water transfers in and out of the basin (black lines with numbers) together with flow measuring points (stations) for which some observed flow data were available for the study. Link numbers are circled and correspond to the overall NRLP numbering system. Station numbering is for identification purposes only. Due to the low quality, short records or inappropriate locations relative to the link points, only a few of the shown stations are usable. These include records at station 3 (Krishna at Agraharam) and part of the record at station 1 (Krishna at Vijayawada).

## Water Transfers in and out of the Krishna River Basin: A Review

In order to assess the degree to which criteria 1, 2 and 3 above are satisfied in planning of individual links in and out of the Krishna, the relevant chapters of the technical feasibility reports (Hydrology, Environment) produced by the National Water Development Authority (NWDA) of India have been reviewed. Most of the reports are available on the NWDA site in HTML format (http://nwda.gov.in/indexab.asp?langid=1). A brief summary of each link with the authors' comments is given below, starting from the most "upstream" link on Figure 2.

### Bedti-Varada Link (Link 14)

This is the only incoming link in the upstream part of the Krishna Basin for which no feasibility report is available at present. Salient features are listed on the NWDA web site, and some very limited anecdotal information is available (Dams, Rivers and People 2004). This proposal envisages the diversion of 242 million cubic meters (MCM) of "surplus" water of the Bedti Basin (in Western Ghats–flowing west into the Arabian Sea; not shown in Figure 2) to the water-"deficient"

Tungabhadra subbasin in Krishna (Figure 2). The water will be used to irrigate some 60,200 hectares (ha) of land and for hydropower generation. Two new dams in the Bedti Basin will be constructed with a combined total (live) storage of 98 (85.5) MCM. The larger reservoir will be connected by a link canal to a tributary of the Varada River.

So far, no environmental studies have been conducted around this link. The small tributaries involved in this project, however, may be very sensitive to flow changes. Also, located in the tropical humid forests (75% of the area) and declared by the International Union for the Conservation of Nature and Natural Resources (IUCN) as a biodiversity hot spot, the basins to be affected host 1,741 species of flowering plants and 420 species of birds and other wildlife. These numbers exceed those in the whole Kerala State, where the Bedti Basin is located. The flow will be discharged into the Varada without a receiving reservoir, which may increase channel erosion in localized parts of the river. Altered flow patterns may cause riparian zone degradation and create habitats for invasive species. The proposed project is expected to generate 3.6 megawatts (MW) of power but it may take over 61 MW to lift the water to the Varada.

## Krishna (Alamatti) – Pennar Link (Link 05)

This is one of the several links effecting water transfers from the Krishna Basin to the Pennar Basin (Figures 1 and 2). The link starts from the existing Alamatti Reservoir on the Krishna River (upstream catchment area 33,375 square kilometers [km$^2$]). This link is seen as a partial exchange for the Godavari water brought into the Krishna (links 02, 03 and 04 in Figure 2). However, since all the inward links from the Godavari bring water to downstream parts of the Krishna, and since the inflow from the Bedti link (if constructed) is minor, this link effectively transfers the existing "surplus" water from the upstream reaches of the otherwise "deficient" Krishna Basin into another "deficient" basin, the Pennar. The purpose of the link is to satisfy en route irrigation needs. A volume of 1,980 MCM of water will be transferred through a 587-km canal with an outfall into a tributary of the Pennar. A new (balancing) reservoir with a total (live) storage of 83 (73) MCM is to be constructed at the receiving end of the Pennar Basin at the Kalvapalli village, with an upstream catchment area of 5,616 km$^2$. The need for this new reservoir may need to be better justified as there is another dam (the upper Pennar) which commands the catchment area of 5,245 km$^2$ – just upstream of the proposed new one.

All water transfers in NRLP are planned from "surplus" basins or parts thereof to "deficit" basins. The basin is declared "surplus" if the balance of water "naturally" available (assured) in a river, 75% and 50% of the time on the one hand and the total demand for the next 25-50 years upstream of the point of a transfer on the other, is positive. If this balance is negative, the basin is perceived as a "deficit" one (the details of the methods used to establish whether a basin is surplus or deficit are described and discussed later in this report). At Alamatti, the "surplus" water at 75% and 50% assurance ("dependability" – in Indian terminology) is estimated to be 5,611 and 8,247 MCM, respectively, while the corresponding values for the receiving point of the Pennar at Somasila are -3,820 and -3,590 MCM, respectively. Such a large difference between surpluses and deficits of the donating and receiving basins is the major justification for the transfer.

The major feature of this link is the long canal, and a lot of attention is paid to the justification of its design and cost. It will pass through reserved forests and a bear sanctuary, where 17 wildlife species are reported including four endangered ones. Losses of, and disturbances to, habitat due to the lined canal, representing an obstacle to wildlife migration routes, are programmed into the project. It is suggested that wildlife "will migrate to surrounding forests," and thus impacts will be minimal. Possible measures to mitigate the disturbance to the sanctuary include realigning it, including the establishment of a "minimum protected area." The Kalvapalli Reservoir is anticipated to provide a waterfront for wildlife. The equivalent of about US$35,000 (in 2006 dollar terms) is allocated in the project for the improvement of the environment.

Water pollution in the Kalvapalli Reservoir is anticipated through silting and sedimentation, nutrient leaching and agricultural runoff containing fertilizers and pesticides while common mitigation measures, such as contour bunding, are planned. A beneficial aspect of the project is an anticipated increase in fish production. The link canal is seen as a facilitator of cross-migration of fish species which will increase fish population overall, although no justification for this, or evidence from other similar cases, is provided. Most ecological issues considered in this feasibility report are related to the link canal rather than to the donor or the receiving rivers per se. It is possible to suggest that no "ecological" releases from the Alamatti Dam are made or planned because there is no mention of such releases.

## Krishna (Srisailam) – Pennar Link (Link 06)

This is one of the several links effecting water transfers from the Krishna Basin to the Pennar Basin. The link starts from the *existing* Srisailam Reservoir on the Krishna River (with an upstream catchment area of 211,657 km$^2$) at its confluence with the Tungabhadra River (Figure 2). This link, similar to the Alamatti-Pennar link upstream, effectively transfers the existing "surplus" water from the otherwise "deficient" Krishna Basin into another "deficient" basin, the Pennar. This may result in less water downstream of the Srisailam Dam, and the reach between Srisailam and Nagarjuna Sagar dams will become even more water-deficient. The 75% and 50% assured annual flows at Srisailam are estimated to be 57,398 and 66,428 MCM, respectively, although the final surplus at 75% assurance at the site after all demands are satisfied is 6,017 MCM.

A volume of 2,310 MCM of water will be diverted through the existing Srisailam right main canal, which will operate 6 months a year from July to December (monsoonal and post-monsoonal seasons). The water will be discharged into the Nippulavagu, a natural stream, and will reach the Pennar River through the Galeru and Kunderu tributaries. No new infrastructure is required and no en route irrigation is planned: the transfer targets exclusively the destinations of Pennar and Cauvery basins (it has to be noted however that older transfers of this nature have resulted in the development of irrigation along the canal and capture of that water). As with other links, no provisions exist for environmental releases downstream of the Srisailam Dam. Some common impacts of water diversions (e.g., sedimentation of reservoirs, changes in hydrological regime due to flow regulation, waterlogging and salinity caused by irrigation and drainage) are discussed in general terms.

The major point made with regard to this link is that since there is no new storage and water is to be transferred through partially concrete-lined natural streams, there are no new submergence areas, waterlogging, or adverse impacts on flora and fauna. It is suggested that the conveyance streams can easily carry additional 163 cubic meters per second (m$^3$/s) of water (the amount of water transfer for 6 months in a year) in addition to their own "natural" discharges. It remains unclear how these streams will react to extra water during 6 months, what the riparian conditions are or how embankments will affect fish spawning.

## Krishna (Nagarjuna Sagar) – Pennar Link (Link 07)

This is a major transfer of 12,146 MCM of water from, and to, existing reservoirs: Nagarjuna Sagar Dam on the Krishna (upstream area of 220,705 km$^2$) and Somasila Dam on the Pennar. The 75% and 50% assured "natural" annual flows are 58,423 and 67,346 MCM, respectively. The purpose is to improve irrigation en route (where irrigation facilities are not adequate) and then to transfer water further to the south, where water shortages are said to be severer (a deficit of 3,820 MCM is envisaged at 75% assurance in the Pennar River with all irrigation plans in place). A new 393-km lined link canal and an existing right-bank canal from Nagarjuna Sagar will run in parallel over 202 km, because the latter can carry only 3,979 m$^3$/s annually while the proposed transfer is for three times more water. Such massive transfers may be possible only due to the chain of transfers from further north. The restructuring of the existing right-bank canal is not possible and therefore the construction of a new one is seen as a necessary option. Because no new storage is associated with this link, the feasibility report envisages no environmental impacts, and no costs are anticipated for mitigation of such impacts. This link is effectively part of the much longer water transfer line from the north to the south. Additional water transfer to the Nagarjuna Sagar Reservoir is planned through the Inchampalli-Nagarjuna Sagar link (see below).

## Godavari (Inchampalli) – Krishna (Nagarjuna Sagar) Link (Link 02)

This link involves the transfer of 16,426 MCM of water and the construction of a new major storage reservoir on the Godavari at Inchampalli. The upstream catchment area at this point is 269,000 km$^2$ and the gross (live) storage of the future dam is 10,374 (4,285) MCM. A low ratio of a live storage to gross is noteworthy. The water yields of the Godavari at Inchampalli at 75 and 50% assurance are estimated to be 66,193 and 76,185 MCM, respectively. The proposed irrigation plans are huge and, in all states involved, they exceed the sum of existing and ongoing irrigation projects. These plans are effectively the justification of the transfer. The irrigation requirement projected for the year 2025 on the basis of the states' irrigation plans is 40,723 MCM and the balance of all demands (irrigation plus others) at 75 and 50% assurance is 20,327 and 29,987 MCM, respectively. The Krishna River at Nagarjuna Sagar is estimated to have a deficit of 1,525 MCM at 75% assurance, which is another justification for the transfer. This water transfer is justified by a large irrigation development, which in itself will probably take many years to complete, and its feasibility will depend on the cost of water provided.

From the environmental side, the major impacts are perceived to be related to the submergence area of the new reservoir, which leads to major resettlements. It is suggested however that aquatic life will develop in the new reservoir and that, for example, the loss of breeding grounds of crocodiles in the river due to submergence is negligible. The report indicates that the project will have an impact on the Singaram sanctuary and submerge 65 hectares of the Indravati National Park. It lists the known present fauna and birds in the area, which indicates no endangered species. No adverse impacts on aquatic life are identified, but no studies done to this effect are cited. Afforestation is proposed to compensate for the loss of forests to submergence.

## Godavari (Inchampalli) – Krishna (Pulichintala) Link (Link 03)

This link will divert 4,370 MCM from the Godavari into a new reservoir on the Krishna at Pulichintala, with a gross storage capacity of 1,296 MCM through a new, 312-km link canal. The yields at 75% and 50% assurance are estimated to be 66,193 and 76,185 MCM and surplus surface water balances after satisfaction of all projected requirements at Inchampalli are 20,327 and 29,987 MCM, respectively. Similar estimates are done for Muneru, Palleru and Musi tributaries of the Krishna.

The feasibility report explicitly suggests that all requirements of the Godavari downstream of Inchampalli can be met by the water available from the incremental catchment area located between Inchampalli and the Dowlaiswaram Barrage and with the surplus water transferred from Mahanadi. Therefore, no water is likely to be released from Inchampalli downstream and all water at Inchamapalli will be used for diversion to the Krishna. The feasibility report refers to simulations of the Inchampalli Reservoir at a monthly step over the period of 1951-1981 supplying both Pulichintala and Nagarjuna Sagar links (4,370 and 16,426 MCM). Simulations suggest that all requirements will be satisfied with a success rate of 76%. The environmental issues associated with this link are the same as those with the Inchampalli–Nagarjuna Sagar link, as they are for a common storage (Inchampalli).

## Godavari (Polavaram) – Krishna (Vijayawada) Link (Link 04)

This is the most downstream link in both the Godavari and the Krishna basins, and the one which is scheduled for construction. It is planned to divert 1,236 MCM of water from the new Polavaram Reservoir on the Godavari (with a live storage of 2,130 MCM) to the existing Prakasam Barrage on the Krishna through a new 174-km link canal. The transfer is designed to substitute releases for the Krishna Delta from the Nagarjuna Sagar Dam and to allow "saved" water to be used for other projects in the Krishna. The canal, operating throughout the year, will discharge into the Budameru, a river which flows into the Kolleru Lake (which is now effectively a large collection of aquaculture ponds), and from there the transfer will go through the Budameru diversion canal, discharging into the Krishna 8 km upstream of the Prakasam Barrage. There is already considerable infrastructure in the Lower Godavari below the proposed Polavaram Reservoir. Lift irrigation stations along the river provide irrigation in the Lower Godavari Delta. This may decrease the total area claimed to benefit from the Polavaram link. There is also no mention of how, and if, the existing canals will be integrated into the new canal system.

Approximately US$600,000 (0.2% of the project cost) is allocated a) to study the "environmental and ecological" aspects of the project by various organizations, and b) for protective measures as may be necessary. Since both donor and receiving points are nearly at the outlets of the Godavari and Krishna rivers, environmental impacts may only be felt in both deltas and en route the canals, where new irrigation, domestic and industrial requirements are targeted. Possible adverse impacts mentioned in the report include resettlement, submergence of forests, waterlogging and salinity in the command area. Planned mitigation measures include drainage systems in the command area to mitigate salinity, fish ladders through the Polavaram Dam to allow for movement of migratory fish, and studies of the nature of existing aquatic weeds in the submerged area and some others.

The National Council of Applied Economic Research (NCAER), New Delhi, India, was entrusted with the studies of socioeconomic and environmental implications of six interbasin water transfers including this one (Agricultural Finance Corporation Ltd. 2005). Their report indicates that the wild sanctuary in the proposed Polavaram Reservoir area will be marginally affected by the submergence, and the list of fauna in the area coming under submergence is given district by district. It is also suggested that wildlife conditions will actually improve due to the broad expanse of water in the new reservoir which is conducive to breeding of wildlife. The scientific basis for these conclusions is however unclear from the report. It is envisaged that endangered species (tiger, panther) will move to deeper forest areas away from the submerged areas.

It is indicated that after the Dowlaiswaram anicut has been constructed on the Godavari, fish migration (e.g., hilsa) from the sea to inland has become obstructed. It is stated that dams convert a river to a more placid lotic environment with reduced velocities, which impacts fish species and composition and size. However, no quantitative, link-specific conclusions are presented. Generic statements are also made about phytoplankton, seasonal flow pattern changes, etc. It is also admitted that the entire command area lies in the coastal belt with high rainfall, enhancing the risk of malaria, while a few general statements are made about vector breeding and a possible increase in waterborne diseases.

The Environmental Management Plan describes a variety of relevant measures including catchment area treatment through vegetative measures and structures (to reduce inflow of extra sediments into the reservoir), development of flora and fauna through compensatory afforestation, enhancing aquaculture through stocking of the new reservoir with exotic fish species, relocating some archeological structures and disaster management (concluding that there is no possibility of dam failure because probable maximum flood will be passed by the structure). The report however does not address deltas – relevant environmental issues such as reduced flow and sediment to deltas due to dam construction, resulting in stunted delta growth, seaside erosion or degradation of mangroves.

### General Observations

Overall, all NWDA feasibility reports are succinct summaries of the proposed interbasin water transfers. They have similar structures and levels of detail, and represent, effectively, the only source of publicly available technical information on the proposed transfers. As such, they are very valuable.

At the same time, they have similar shortcomings. The information presented remains limited and it is not possible to judge about the quality of the data used. Environmental aspects and impacts of the proposed projects are only generally described and are primarily related to the submergence area associated with new reservoirs and to resettlement of the population affected. It is clear that no provision is made for in-stream ecological releases from either existing or planned reservoirs. If a proposed link is to flood or otherwise affect existing wildlife sanctuaries, the latter are expected to be relocated/compensated, implying their relatively low importance. The general comments on environmental impacts make no reference to the link/site in question and cite no supporting studies. Technical aspects of some links need more clarity. For example, Bedti-Varada link does not seem to be justified from the hydropower angle (as it will produce far less energy than that used to get the water to it). Links starting from the Lower Godavari include the construction of a new Inchampalli Reservoir, which is designed to have a very low ratio of live to gross storage, making it a huge evaporation tank. The entire complex of interbasin water transfers is driven by significant irrigation expansion which extends to 2050. At the same time, it is not entirely clear where this new land for irrigation expansion is located because most of the proposed “new” irrigated land in the Krishna and Godavari basins is likely to be irrigated already (H. Turral, IWMI, pers. comm.). The approach can benefit more from a more integrated, basin-wide water resources planning. At present, water is planned to be transferred from the upper parts of the Krishna Basin, while at the same time other links will deliver water into the Krishna downstream. The reported low Benefit-Cost (B/C) ratio of some projects is also noteworthy. For example, Alamatti-Pennar and Polavaram-Vijayawada links have a B/C ratio of around 1.2 each, which makes the effectiveness of these links questionable. Finally, the methods by which water availability for the transfers was calculated require some comment and are discussed in the next section.

## How Much Water Is Actually Available for Transfers?

### A Summary of the “Official” Water Resources Planning Method

The methodology that the NWDA is using in planning water transfers is essentially the same for all links and is described in abbreviated form in every individual feasibility report. It is important to attempt to spell it out here because the NRLP has been criticized for not describing the basis on which the assessment of water availability and identification of surplus and deficient river basins have been made. This is a misconception because the issue is not so much that it is unclear, but rather whether it is entirely appropriate given the scale of transfers. The overall planning approach includes several sequential steps.

- The catchment upstream of the diversion point (donor) or receiving point (receiver) is split into several smaller subbasins to cater for spatial variability of rainfall and runoff over large areas.

The number of subbasins varies with links depending on the size of the catchment area upstream of the link point. For smaller links, like Bedti-Varada, such separation is not required and one subbasin may be used. Observed annual flows at one hydrological measuring station or many (e.g., in every subbasin) are calculated using original flow records. Observed records for different links vary in length. For example, a period of 100 years (1901–2000) is used for the Alamatti link whereas the corresponding period for the Srisailam link is 32 years.

- Since the observed flows are normally affected by various water abstractions, all these abstractions are calculated and "added back" to the observed flows. It is not entirely clear from the feasibility reports how this is done since types of abstractions differ, they have increased over time, especially during the last 20 years, and there is no inventory of the various abstractions in India (the latter is partially due to the competitive nature of interstate water management, where each state tends to leave its abstraction data undisclosed to its neighbors). Regardless of the methods used, procedural attempts take place to "naturalize" observed river flows, as these flows form the reference condition for assessing water availability for the transfer.
- Annual time series of weighted areal rainfall for each gauged basin is then calculated using the data from available/selected rainfall stations. A regression relationship between annual naturalized flows and annual areal rainfall is established.
- This regression analysis is then carried out for the entire *subbasin* (which is ungauged) using monsoonal rainfall time series as input. This allows monsoonal-period flows to be calculated for each year. The non-monsoonal portions of flow are then added to the monsoonal portion for each year thus building the annual time series of naturalized flows. It is not clear from the feasibility reports how the non-monsoonal portions are calculated, but the perception is obviously that these flows do not provide a significant contribution to the overall annual total flow volume.
- The calculated annual flow time series for individual subbasins upstream of the donor/receiver site are then summed up to produce the annual time series of naturalized flows at the link point. This time series is then presented in the form of a cumulative distribution (a type of a flow duration curve analysis), which shows the probability of exceedence of every annual flow in a record. This probability is termed "dependability" in Indian practice (an alternative term "assurance" is often used in other countries). This exercise allows flows occurring at the site to be visualized and interpreted all at once. The lower the flow the greater its "dependability" because other flows frequently exceed it. The higher the flow the lesser the dependability: floods are difficult to capture because they occur less frequently.
- The cumulative distribution function of annual flows at the donor/receiver site is used to estimate flows ("gross yields" in Indian terminology) with "dependabilities" of 50% and 75%. The selection of these assurances of supply is rather arbitrary but is not the most critical issue, since many different levels of assurance of water supply larger than 50% are conventionally (and similarly arbitrarily) used in water resources engineering practices worldwide (e.g., Smakhtin 2001)
- The annual flows at 50 and 75% assurance (further denoted as Q50 and Q75) are the major components of the water supply estimates. Other components include regeneration and known imports from other river basins. Regeneration (most likely an equivalent of "return flows"), is estimated as 10% of the net utilization from all present and future irrigation schemes and as 80% of the domestic and industrial uses to be met from surface water sources. The total water supply (WS) is calculated by summing up the assured flows with regeneration and imports

and deducting exports if any:

$$WS_{p\%} = Q_{p\%} + Imports + Regeneration - Exports \quad (1)$$

where, $_{p\%}$ denotes the assurance (50 or 75%). All calculations so far are performed at the *annual* time step. Most of the further decisions are based on the estimates performed at 75% assurance.

- Various demands are then estimated and projected for either the year 2025 or the year 2050, depending on the link. Agricultural water demands are estimated based on the state plans for irrigation development. Industrial requirement (assumed to be met entirely from surface water sources) is not known and is taken to be equal to domestic needs, which is based on population Figures. Hydropower requirement is taken to be equal to total evaporation from all hydropower projects. Environmental water demands are not accounted for. When “downstream” requirements are mentioned, they normally imply the requirements of downstream agriculture, industry or domestic needs, but not of aquatic ecology or recreation.
- The difference between the total available supply at 75% assurance (equation (1)) and the total projected demand at the same site (donor or receiver) becomes the basis for declaring the basin (or part thereof) as “surplus” or “deficit.” If the above difference is positive the basin is “surplus,” and if negative it is “deficit.”
- As a rule, each link includes at least one reservoir – either at the donor or at the receiver point or at both. The last step in the methodology is therefore a reservoir simulation modeling with current observed flows in place and with all future demands included. This step is performed with a *monthly time step*. Annual flow data for the available period are used as the basis for calculations. All gross annual current upstream water requirements are subtracted from the gross annual flow time series. This gives time series of annual actual inflows to a reservoir whether existing or new (e.g., to Alamatti, Inchampalli, etc.). These net annual inflows are distributed into *monthly* values using weights obtained from the actual monthly flow data at one of the nearby flow stations. The records used to calculate the weights may be short (e.g., 10 years in the case of the Srisailam). It appears from feasibility reports that average monthly weights are used for this, i.e., monthly flow distribution is assumed to be the same in dry and wet years. Monthly irrigation requirements are then calculated based on crop needs. Initial storage (initial condition for reservoir simulation) is often assumed to be the dead storage (this is typical for India, where it seems to be a common practice to assume full drawdown of the stored water every year and no provision for interannual storage). A reservoir simulation is carried out to identify whether the proposed transfer can be managed with the proposed storage and, if yes, then with what level of reliability - how many successful years out of all years simulated. A successful year is normally defined as a year in which 95% of all demands are met (which is quite a conservative [good] measure of success).

## The Issue of Data Resolution and Its Impact on Planning Estimates

It is clear from the above summary that flow data with an annual time step resolution were used as the basis to derive the estimates of dependable (assured) flows at link points. This approach requires comment. The existing literature on water resources systems suggests that although annual time step data may be used for preliminary (crude) planning of water supply systems, the preferred data type for this is monthly flow time series (e.g., McMahon and Adeloye 2005). The issue of data resolution is not a superfluous one: data resolution significantly affects the information content of hydrological time series. Figure 3 illustrates this point with the three most widely used flow data types – daily, monthly and yearly. The differences between daily and monthly flows in low-flow months are negligible due to minor variability of daily flows during low-flow months. However, the differences between the mean flow for the "year" and mean monthly flows in different months are pronounced: 8 months out of 12 have flows significantly lower than the yearly mean. Annual data resolution therefore does not capture "enough variability" in flows and can lead to overestimation of available water throughout the year.

Figure 4 further illustrates the impact of data resolution on the calculation of "highly dependable" flows. The Figure shows flow duration curves (FDCs) constructed, using annual and monthly flow time series for the same arbitrarily selected site on the Krishna River, for which some observed flow data were available. The flow exceeded in 75% of all years (75% dependable flow - in Indian terminology) is much higher than the flow exceeded in 75% of all months. NWDA feasibility reports use *annual* flow values at 75% dependability as a measure of surface water availability at the points of transfer (both donor and receiver). However, if more, monthly, information-"rich" data are used instead, the flow available at 75% dependability becomes an order of magnitude less than that determined using annual data resolution.

To obtain an FDC at Vijayawada, which is representative of more natural and less regulated conditions, the curve at Vijayawada (station 1 in Figure 2), established from the observed record of 1900–1965 (which retains more unregulated flows) has been scaled up by the ratio of mean annual flow for the above period to the "official" estimate of the mean annual flow at the Krishna outlet of 78 BCM (cited also in Smakhtin and Anputhas 2006).

To obtain an FDC at Srisailam, the "naturalized" duration curve at Vijayawada (Station 1 in Figure 2) has been multiplied by the factor of 0.84 – the ratio of catchment area at Srisailam (221,657 km$^2$) to the catchment area at Vijayawada (251,360 km$^2$). The data period used was 1900–1965 (despite the availability of more recent observations) to avoid the impacts of observed significant reduction of the Krishna flow in the last 50 years and ensure a more or less "unregulated" record.

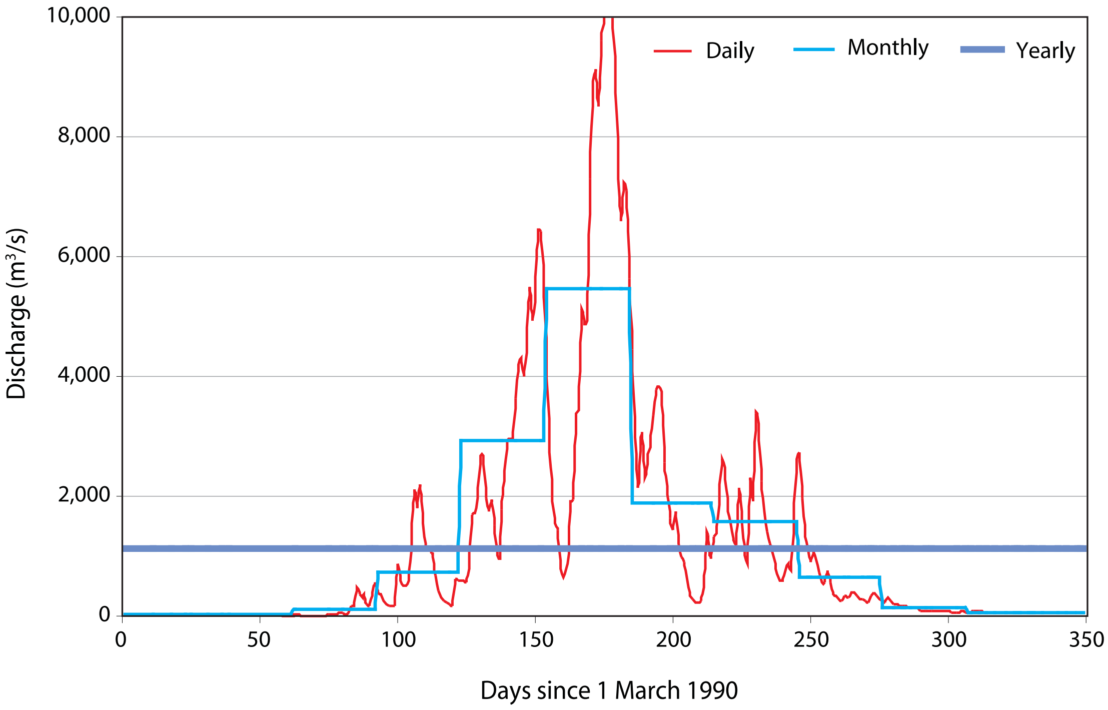

FIGURE 3. An illustration of different temporal data resolution: yearly, monthly and daily flows recorded in the Krishna River at Agraharam town during March 1990–February 1991.

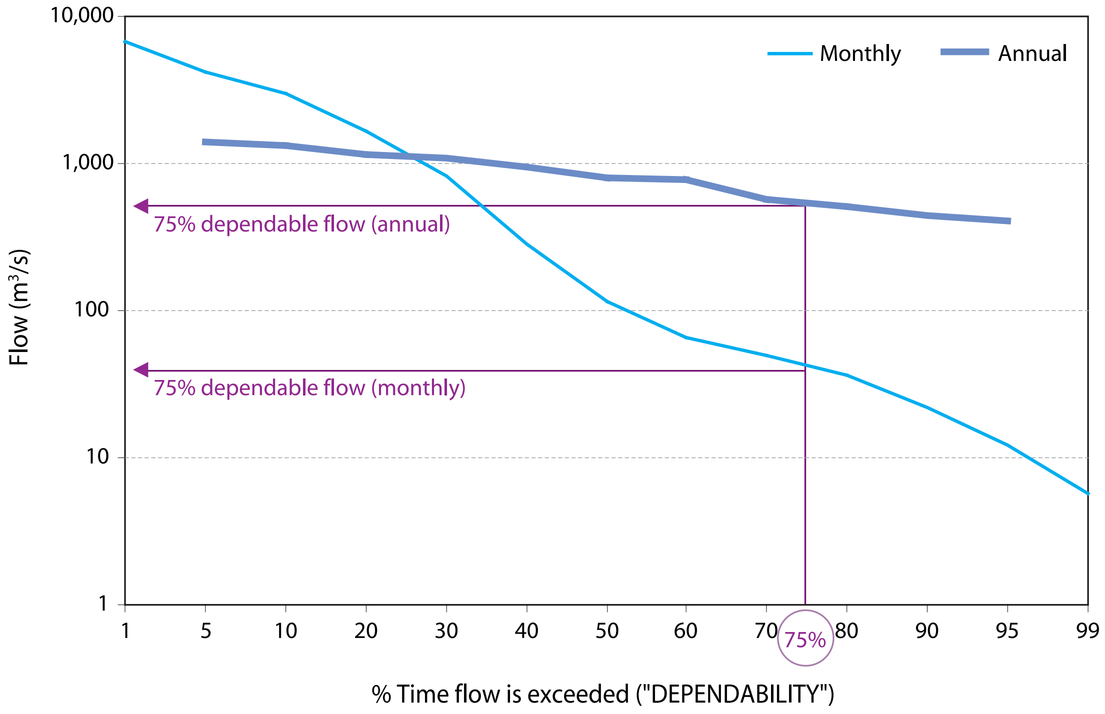

FIGURE 4. Flow duration curves for the Krishna River at Agraharam town based on 15 years of monthly flow data and constructed with annual and monthly aggregation levels.

The implications for the assessment of water available for transfer at link points are clearly very significant, if such assessment is made by simply reading off the 50 and/or 75% assured flows from “annual” or “monthly” FDCs. The very limited data available for this study did not allow reliable calculations to be carried out for all link points. Only a very few data sets, primarily from the Internet, were available. It is not possible to ascertain the accuracy of these data, but it is still possible to illustrate the abovementioned differences for some links. The link points for which dependable flows have been calculated are listed in Table 1. They are the only ones which can be effectively simulated with the limited data available.

To construct an FDC at Inchampalli, the duration curve at Polavaram (both in the Godavari Basin) has been multiplied by the factor of 0.874 – the ratio of the catchment area at Inchampalli (269,000 km$^2$) to the catchment area at Polavaram (307,880 km$^2$). Despite the availability of more recent observations the data period used was 1910–1960. This was to avoid many missing data at both ends of the record, particularly after 1960 and to ensure that less-impacted, more natural flow time series was used. This record gives a long-term mean annual flow estimate at Polavaram of approximately 105 billion cubic meters (BCM), which value is close to the “official natural” flow estimate of 110 BCM (cited also in Smakhtin and Anputhas 2006).

To obtain an FDC at Alamatti, the duration curve at Agraharam (station 3 in Figure 2 – the nearest to Alamatti with usable data) has been multiplied by a factor of 0.25 – the ratio of catchment area at Alamatti (33,375 km$^2$) to the catchment area at Agraharam (132,920 km$^2$). The data period used was 1983–2000 – the only period for which data at Agraharam were available. Since neither systematic data on water abstractions upstream of Agraharam nor “natural” flow estimates at Agraharam from alternative sources were available no corrections to the original flow data at Agraharam were possible. This may lead to underestimation of means and dependable flows. Observed data at Agraharam

TABLE 1. Estimates of surface water availability (MCM) at 50% and 75% dependability from annual (NWDA) and monthly (IWMI) data resolution for selected link points in and out of Krishna.

| Donor/Receiver point | Dependability 50% | | Dependability 75% | |
|---|---|---|---|---|
| | Annual data | Monthly annualized | Annual data | Monthly annualized |
| Krishna - Alamatti | 24,041 | 958 | 21,405 | 326 |
| Krishna - Srisailam | 66,428 | 8,626 | 57,398 | 1,684 |
| Godavari - Inchampalli | 76,185 | 10,546 | 66,193 | 4,497 |
| Godavari - Polavaram | 96,549 | 12,155 | 80,170 | 5,132 |
| Krishna - Vijayawada | Not available | 11,808 | Not available | 1,964 |

are historical data and are affected by upstream developments. The mean flow volume calculated at Agraharam from these data is 19,270 MCM which is very small compared to the 50% or 75% flows in Table 1 taken from NWDA. It is clear that such mean flow is not accurate and the error is transferred to the estimates of dependable flows at Alamatti.

Also, flows do not always have a linear relationship with the basin area. However, the above simplifications are unlikely to lead to major inaccuracies compared to the differences in estimates from annual and monthly time step data, for example. It has to be noted that should more reliable data be available the estimates in this study can be revised to ensure better compatibility with the data used in the feasibility reports.

Table 1 is presented for illustrative purposes – to show the remarkable differences between the two estimates in every case. It is noteworthy that, for example, the official estimate of the “natural” flow at the outlet (Polavaram) is around 110 BCM (a corresponding estimate obtained from the data as described above is 105 BCM, which is rather close). However, the 75% dependable flow at Polavaram is estimated to be 80.17 BCM (80,170 MCM in Table 1), which value is around 73% of the total long-term mean flow. While this estimate makes sense in the context of the annual time step used, it is virtually impossible to assume that such an enormous amount of water may be a reasonable estimate of water available 75% of the time, given the high variability of flow within a year in the Godavari, with a large number of low-flow months (the case similar to that shown in Figure 3).

## The Use of Spell Analysis for the Reassessment of Surface Water Availability

The two different data resolutions (annual and monthly) used to assess water availability effectively represent two different ways of thinking about the level of possible flow regulation. Annual flow data ignore within-year flow variability and, therefore, indirectly suggest that the river may be almost completely regulated for water supply. The use of monthly data (to assess water availability) implies that almost no future increase in abstraction is possible. Both approaches represent extreme cases. The “annual” one unjustifiably pushes up water availability estimates while the “monthly” one significantly reduces them. These approaches and their results are entirely acceptable. They may rather be thought of as representing the top and the bottom limits of assured water availability at a site.

It is perhaps more appropriate to use some form of water resources storage-yield analysis to establish maximum possible draft (reservoir yield) at the donor point of each transfer. This analysis is used to establish either what reservoir yield is possible, if a given/planned storage is constructed, or what reservoir storage is necessary with the required yield. In the context of estimating water availability (including water availability for transfers), a reservoir (or a system of reservoirs) could be some feasible maximum storage which will be used to make the water actually “available.” Assessment of surface water availability then becomes equivalent to the assessment of the yield (draft) of the reservoir with the above maximum feasible storage. The approach still needs to be based on monthly data to capture the seasonal flow variability.

Storage-yield analysis is a discipline of civil engineering and its description is beyond the scope of this study but it can be found in text books (e.g., McMahon and Adeloye 2005). In this study, we use the approach of spells (runs), which may be seen as a component of storage-yield analysis. A spell (run) is a hydrological event when river flow *continuously* stays below (above) a certain threshold flow. Each spell is characterized by the duration and excess or deficit flow volume. Deficit flow volume is a characteristic of a low-flow spell. Depending on a type of flow regime and a threshold there may be one low-flow spell or several in one year. Two examples of transfer sites from Table 1 are used below to illustrate the alternative assessment of water availability: Krishna (Srisailam) and Godavari-Polavaram. Other points were not, or could not be, considered due to lack of some data, unreliable data or closeness to other points.

In the case of the Srisailam site, the NWDA estimate of the annual yield which will be available for the transfer is 57,398 MCM or a constant flow volume of 4,783 MCM per month throughout the year. Placed in the context of the spell analysis, it becomes the flow threshold, which needs to be satisfied. Analysis of the monthly flow data at Srisailam (generated as explained earlier) suggests that every year, there is a significant continuous flow deficit below this threshold (Figure 5). The deficits range from the minimum of 27,500 to the maximum of 40,100 MCM. The latter, maximum deficit may serve as a crude indication of the storage required to maintain the NWDA estimate of the water yield at the Srisailam site.

Even given that the above estimate is rather crude, it is unlikely that without significant storage increase, water at the above high threshold can be made available. Also, while this storage is not impossible to construct in principle as it is only approximately 60% of the long-term mean annual flow at the site, and dams with larger percentages of that are known, it is hardly practical because:

- The cumulative dam storage upstream of Srisailam at present is already 17.1 BCM. More storage will not only be detrimental to the upstream basin but also inefficient in an already heavily regulated system.
- The dead storage of such a dam (or a combination of dams) in a flat basin like the Krishna is likely to be a large proportion of the total storage.
- No major additional storage construction is actually planned.

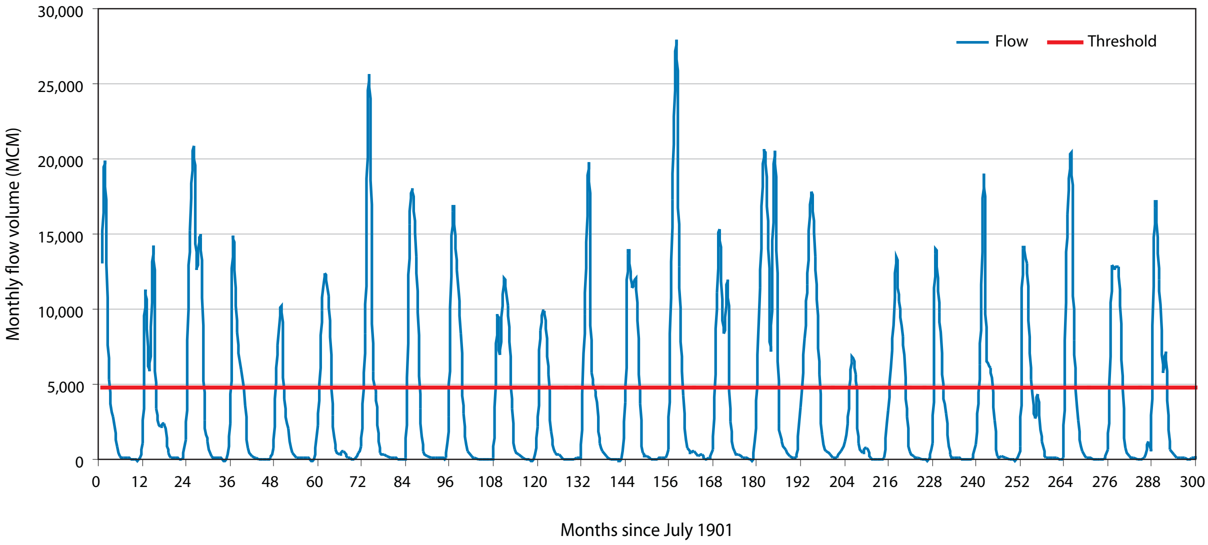

FIGURE 5. An extract from the monthly flow time series at the Srisailam site on the Krishna.

A cumulative storage of 20 BCM (which is slightly higher than the already existing storage upstream of Srisailam) has been used here as an arbitrary but feasible value in order to estimate how much water can be realistically made available. To achieve this, several runs with different flow thresholds have been carried out until the maximum deficit in the Srisailam time series has dropped to 20 BCM. The corresponding threshold flow is 2,700 MCM per month or 32,400 MCM on the annual scale.

A similar exercise has been carried out using the monthly flow time series at Polavaram. The total cumulative storage in the entire Godavari Basin (existing and planned as part of the NRLP) of 18.8 BCM has been increased to 20 BCM to allow for some limited additional, but feasible, storage growth in the future. The corresponding threshold flow in the Godavari at Polavaram has been estimated as 3,000 MCM per month or 36,000 MCM on the annual scale.

Tables 2 and 3 include the above two alternative estimates of surface water availability, which are still significantly lower than the corresponding NWDA estimates (obtained using annual time step data). These estimates have been used with the data on various demands presented by the NWDA in order to determine the impacts of reduced surface water availability on the overall basin water balance. The various demands have not been revised and are taken in all cases as is from the relevant NWDA reports. The environmental flow requirements have however been estimated and added to the Tables (these estimates have been made using the method developed by Smakhtin and Anputhas [2006] for the least acceptable environmental management class D with minimum possible environmental water demand). It has to be noted that this management class is, effectively, the “last resort,” the one in which there is a large loss of natural habitat, biota and basic ecosystem functioning. This is a situation that responsible governments would be expected to avoid.

As the above Tables illustrate, after significant reductions in surface water availability, which is the starting point in planning for interbasin water transfers, the overall water balance of each basin has changed dramatically from being essentially “water surplus” to being seriously “water deficit.” It is important to note that this change would occur regardless of

TABLE 2. Surface water balance (MCM) at the Srisailam Dam site, the Krishna (211,657 km$^2$).

| | NWDA | | IWMI |
|---|---|---|---|
| Surface water availability | | 57,398 | 32,400 |
| Surface water import (+) | | - | |
| Surface water export (-) | | 7,848 | 7,848 |
| Regeneration (+) | | | |
| Domestic use | 2,624 | | |
| Industrial use | 3,748 | | |
| Irrigation use | 2,773 | | |
| Subtotal | 9,145 | 9,145 | 9,145 |
| Overall availability | | 58,695 | 33,697 |
| Surface water requirement for (-) | | | |
| Irrigation use | 43,559 | | 43,559 |
| Domestic use | 3,278 | | 3,278 |
| Industrial use | 4,687 | | 4,687 |
| Hydropower | 1,154 | | 1,154 |
| Environmental use | n/a | | 5,300 |
| Subtotal | 52,678 | (-) 52,678 | (-) 57,978 |
| Surface water balance | | (+) 6,017 | (-) 24,281 |

TABLE 3. Surface water balance (MCM) at the Polavaram Dam site, the Godavari (307,880 km$^2$).

| | NWDA | | IWMI |
|---|---|---|---|
| Surface water availability | | 80,170 | 36,000 |
| Surface water import (+) | | 3,888 | 3,888 |
| Surface water export (-) | | 13,318 | 13,318 |
| Regeneration (+) | | | |
| Domestic use | 1,512 | | |
| Industrial use | 2,402 | | |
| Irrigation use | 3,138 | | |
| Subtotal | 7,052 | 7,052 | 7,052 |
| Overall availability | | 77,792 | 33,622 |
| Surface water requirement for (-) | | | |
| Irrigation use | 47,541 | | 47,541 |
| Domestic use | 1,890 | | 1,890 |
| Industrial use | 3,002 | | 3,002 |
| Hydropower (evaporation losses) | 6,380 | | 6,380 |
| Consumptive use from Polavaram | 3,808 | | 3,808 |
| Environmental use | n/a | | 8,200 |
| Subtotal | 62,621 | (-) 62,621 | (-) 70,821 |
| Surface water balance | | (+) 15,171 | (-) 37,199 |

whether environmental flow requirements are included as the component of the demand or not. It is acknowledged that the estimates suggested here may not be very accurate due to severe data limitations in the first place. However, the change cannot be attributed to data inaccuracies or limitations but, clearly, to the approach used for assessment of surface water availability. It is envisaged that if the original data used by NWDA were available, it would result in a similar change. The points made here attempt to attract attention to the need for increased accuracy in the overall planning process and to the need to revise the estimates of water availability and water balance using more advanced planning tools, more transparent processes as well as accepting environmental water requirements as a legitimate demand.

## Environmental Impacts of Reservoir Construction on the Godavari and Krishna Deltas

Interbasin water transfers are associated with the construction of new storage reservoirs. A lot has been said and written about submergence and resettlement (upstream) and impacts of changing flow pattern on fish (downstream) – all associated with reservoirs. At the same time, all in-stream storages anywhere in the basin have impacts on river outlets. Given the number of reservoirs already constructed in both basins (the Krishna and Godavari) as well as the planned massive storage construction associated with NRLP, it is only natural to highlight the issues of upstream development impacts on deltas and estuaries. These issues have not been considered in the NWDA reports. They also have a general tendency to be ignored in water resources planning worldwide. At the same time, depending on the river and the magnitude of upstream construction such impacts may be significant.

## Coastal Erosion: The Godavari Delta

Malini and Rao (2004) examined the recent changes in the Godavari River Delta, called the “rice bowl of Andhra Pradesh,” using remote sensing images. They discovered that the delta has regressed landward with a total net land loss of 1,836 hectares over the period of 1976–2000 (at a rate of 73.4 ha/year). It was suggested that reduced inflow of sediments, associated with upstream reservoir construction, is the main cause of reduced vertical accretion at the delta. At the same time, coastal subsidence, probably promoted by neo-tectonic activity and consequent relative sea-level rise has continued leading to shoreline retreat. Figure 6 illustrates the dynamics of flow and sediment load at the outlet of the Godavari (at Polavaram) and reservoir storage growth in the entire Godavari Basin since the beginning of the 1970s. The flow time series has been taken from Internet sources, the sediment load data have been read off similar graphs published by Malini and Rao (2004) and the storage data are from the ICOLD dam register. The flow time series has missing data during 1980–1990 and neither flow nor sediment data have been available after 1998. Cumulative dam storage (including large and medium dams) increased significantly in the early 1970s and has remained relatively constant for the last 30 years. However, it will increase abruptly again after the construction of the Polavaram Barrage and the major Inchampalli Dam (the growth of the total storage in the basin after the dam construction is shown in Figure 6 for an arbitrarily assumed Inchampalli Dam completion date of 2010).

While trends in the Godavari River flow cannot be ascertained from the available disrupted flow time series, the decreasing trend in annual sediment loads is clear from the sediment data (Figure 7, also shown by Malini and Rao [2004]). The mean annual sediment load has decreased from 100 million tons in 1978 (effectively an ending point in noticeable reservoir growth in the basin, Figure 6) to 46 million tons by the end of the 1990s. The current cumulative reservoir storage in the Godavari Basin remains relatively low (6.3 BCM, i.e., approximately 6% of the mean annual flow at the outlet). The storage growth is not the only one of significance as much water is also diverted from barrages, i.e., structures without any storage. A relatively small storage in the basin and a still noticeable decreasing trend in sediment load imply that the basin sediment regime is very sensitive to reservoir growth, if the latter remains to be seen as the main source of the problem. More sediment inflow reduction may therefore be expected after the construction of the Polavaram and Inchampalli storages, which will increase the ratio of storage to 19% of the natural flow in the basin.

## Coastal Erosion: The Krishna Delta

In this study, an attempt has been made to examine whether similar trends exist in the Krishna Basin, concerning the proportion of storage: annual flow is much larger than in the Godavari. The observations on sediment loads at the outlet of the Krishna at Vijayawada over the last 30–40 years have however not been provided by the Central Water Commission (CWC) during the course of the study. The only available data were for the period 1991–2000 (CWC 2006), which is rather short for any meaningful conclusions on trends. The comparison of the two short time series of sediment loads, at Agraharam (upstream of major reservoirs, Figure 2) and at Vijayawada (downstream of all major dams), has revealed a significant decrease in sediments downstream of the reservoir system (Figure 8). The differences are particularly noticeable in high-flow years (1994, 1999), when more sediment has reached Agraharam from the relatively unregulated upstream basin but all sediments were likely being trapped by the existing reservoir system (Srisailam, Nagarjuna

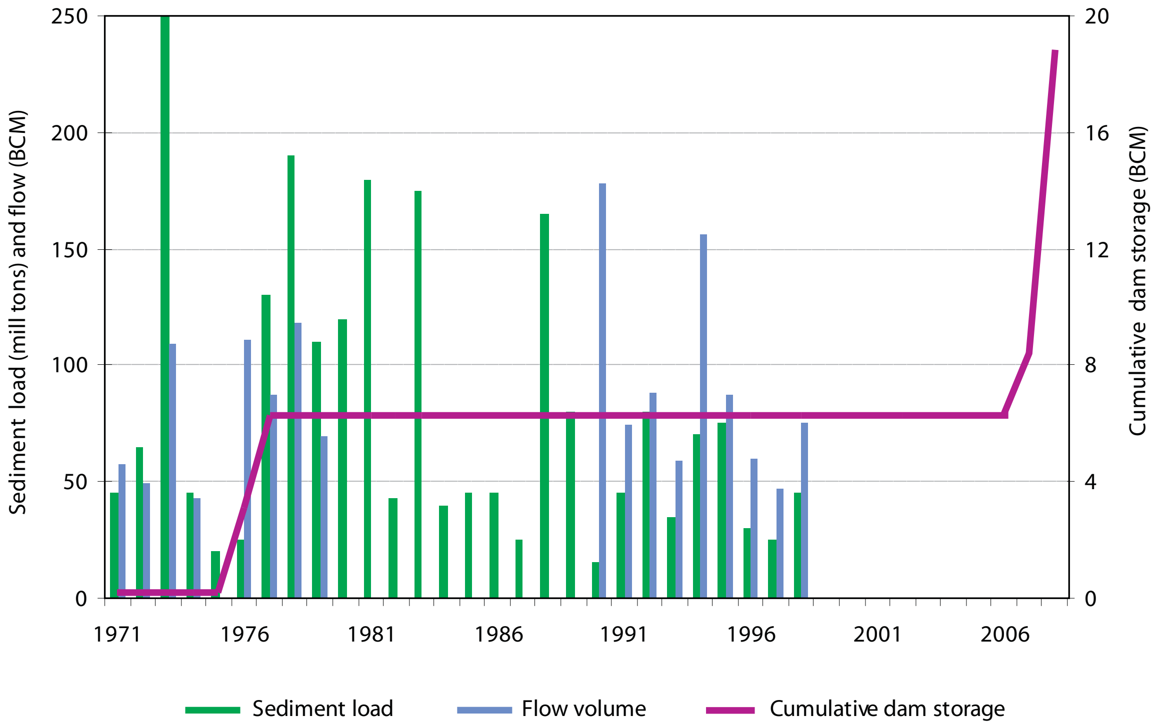

FIGURE 6. Time series of annual flows, sediment loads and cumulative storage in the Godavari Basin outlet at Polavaram.

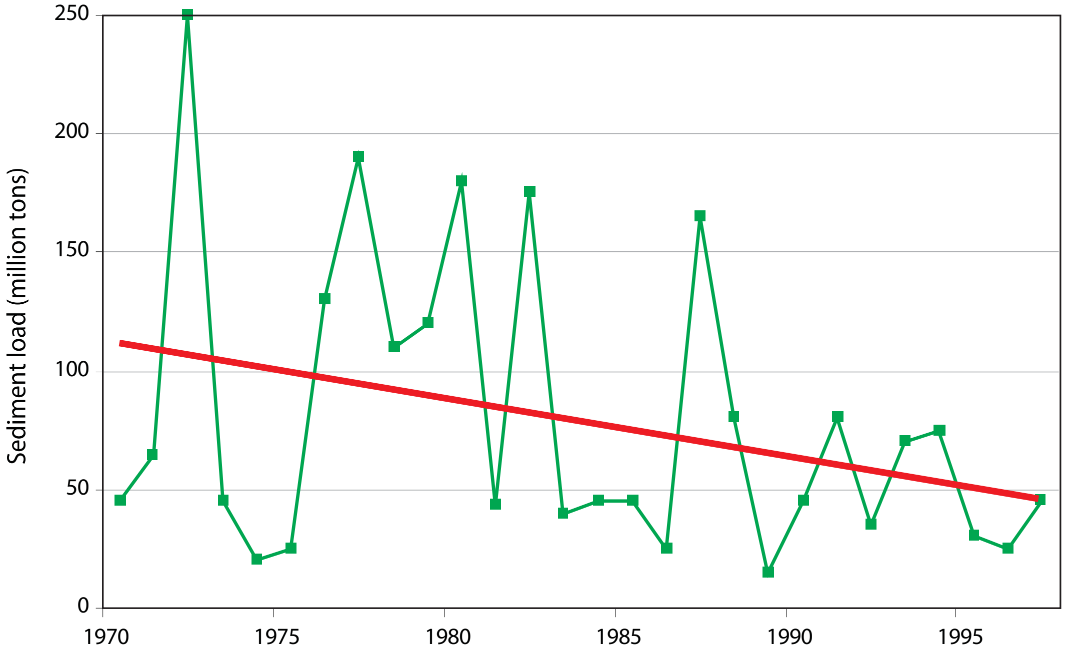

FIGURE 7. Time series of sediment load at Polavaram with a decreasing trend line.

Sagar) upstream of Vijayawada. The absence of sediment data prior to 1991 does not allow for further conclusions about sediment regime changes to be made. However, these changes are most likely very significant due to the marked reduction of river flow at the Krishna outlet (Figure 9) over the last 70 years. This reduction is due to various water diversions, groundwater development and increased cumulative reservoir storage in the basin, which has grown from almost zero in 1960 to 28.5 BCM at present. This present cumulative storage represents 36% and 132% of the natural and present-day Krishna mean annual flow, respectively.

To examine the potential impacts of reduced sediment inflow on the Krishna Delta, several remote sensing images of the area were analyzed. The images were obtained from Earth Science Data Interface (ESDI) at the Global Land Cover Facility (GLFC) on http://glcfapp.umiacs.umd.edu:8080/esdi/index.jsp and were selected from the period of 1977 to 2000 to form a "time series." The images included:

- Landsat 2 Multispectral Scanner (MSS) image dated 1 June 1977 with a spatial resolution of 57 meters (m).
- Landsat 5 Thematic Mapper (TM) image dated 10 November 1990 with a spatial resolution of 28.5 m.
- Landsat 7 Enhanced Thematic Mapper plus (ETM+) image dated 28 October 2000 with a spatial resolution of 28.5 m.

Three basic layers were used to detect morphological changes in the delta: band 4 (near infrared [NIR]), band 2 (red) and band 1 (blue). These layers have characteristics that are suitable for coastal mapping, differentiation of vegetation from soil, reflectivity of vegetation vigor and delineation of water bodies. The first, "oldest" image was assumed to be the reference condition against which changes in the other two images were detected. The entire delta shoreline was examined to demarcate the zones of erosion and deposition using ERDAS 9.0 software. The areas of deposition and erosion between two consecutive dates (i.e., in 1990 and 2000) were identified and calculated using ArcGIS software. The areas around selected points (primarily the mouths of the main distributaries), where significant changes were expected to occur were closely examined, highlighting the zones of erosion and deposition at each. The image of the Krishna Delta showing selected areas where detailed assessment of erosion and deposition has been made is presented in Figure 10. Figures 11 and 12 display the sequence of images for years 1977, 1990 and 2000 for some of the selected areas circled in Figure 10. The black lines in each image represent the reference position of the land mass at the start of the period, in 1977. Figure 13 shows areas of predominant erosion and deposition during the period between 1977 and 2000 for the entire delta shoreline, while table 4 summarizes the calculated characteristics of these processes for the entire delta over the same period.

TABLE 4. Areal extent of erosion and deposition in the Krishna Delta over 23 years (1977–2000).

| Point no. | Erosion (ha) | Deposition (ha) | Net loss (ha) | Rate of loss/ gain (ha/yr) |
|---|---|---|---|---|
| 1 | 598 | 483 | 115 | 5.0 |
| 2 | 478 | 178 | 300 | 13.0 |
| 3 | 275 | 31 | 244 | 10.6 |
| 4 | 326 | 74 | 252 | 11.0 |
| 5 | 79 | 98 | -19 | -0.8 |
| 6 | 894 | 3 | 891 | 38.7 |
| Total (23 years) | 2,650 | 867 | 1,783 | 77.5 |

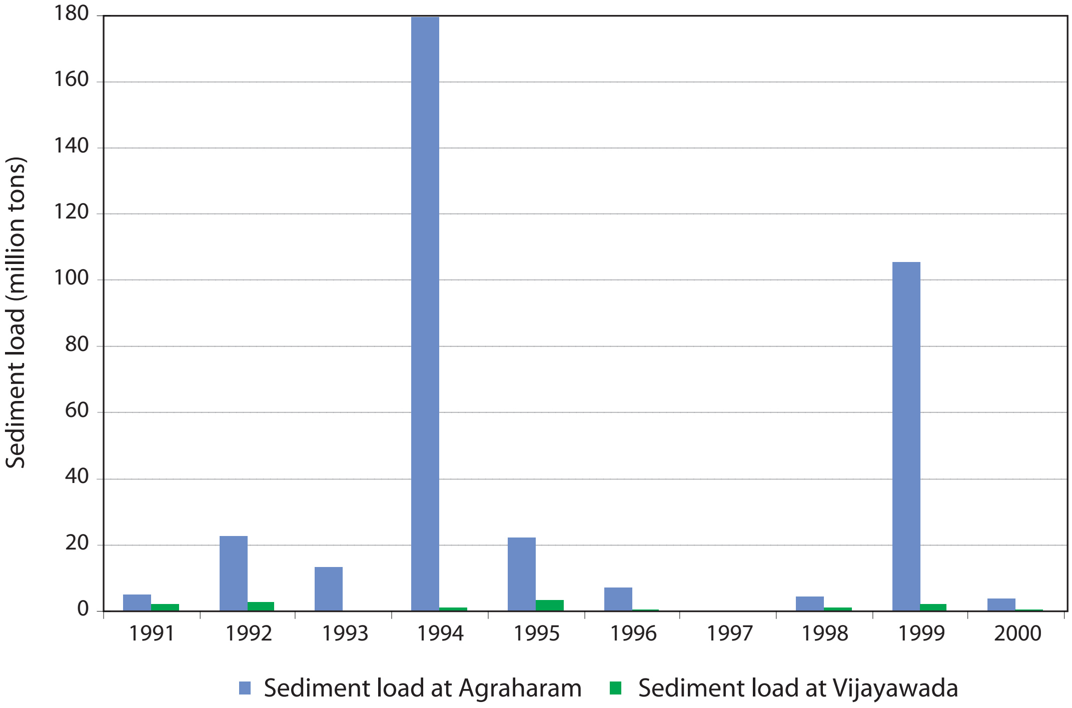

FIGURE 8. The time series of sediment loads in the Krishna at Agraharam and Vijayawada.

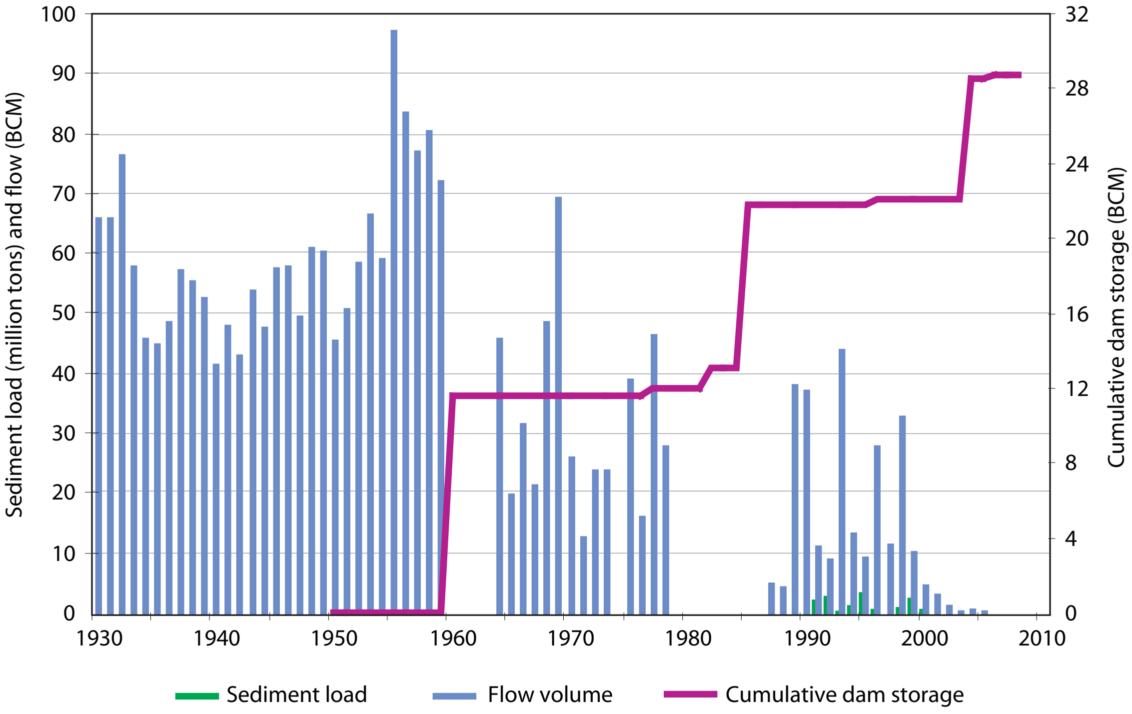

FIGURE 9. Time series of annual flows, sediment loads and cumulative storage in the Krishna Basin outlet at Vijayawada.

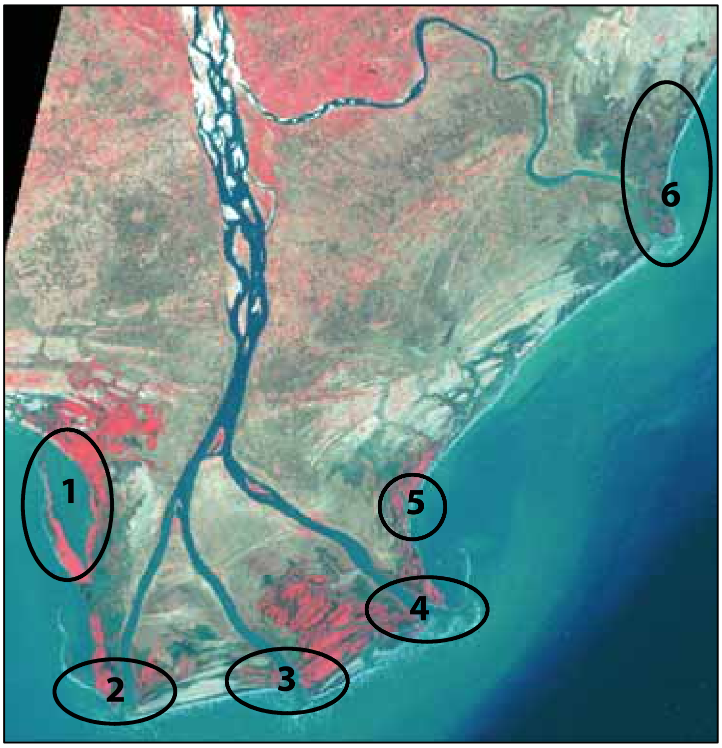

FIGURE 10. The image of the Krishna River Delta indicating the areas where a closer inspection of erosion and deposition was made.

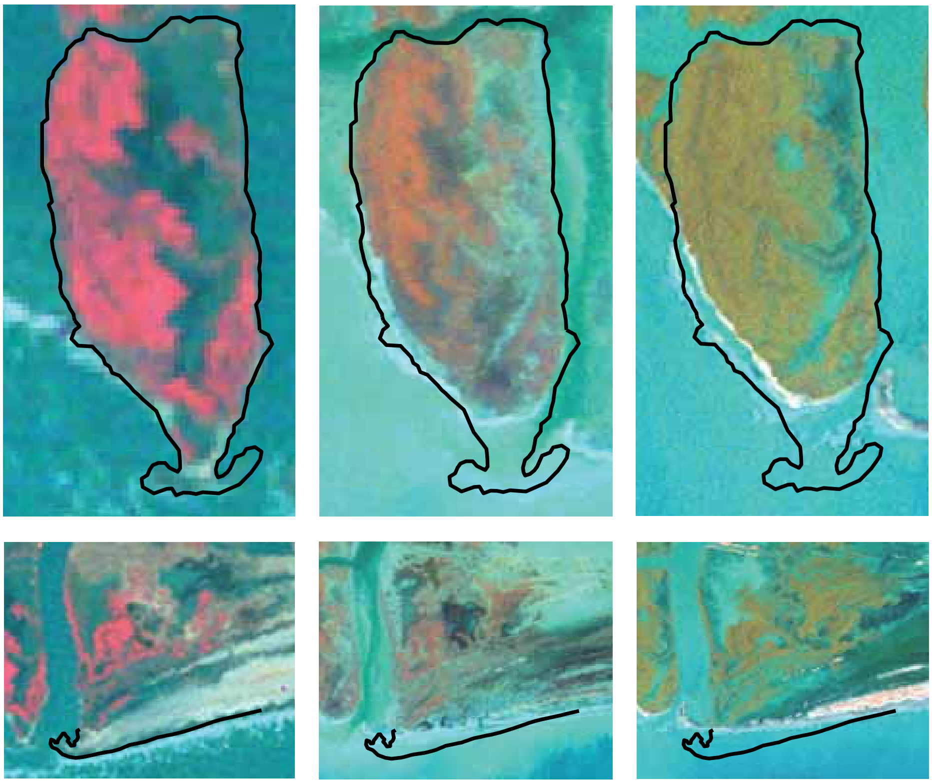

FIGURE 11. The changing morphology of the selected area 2 in 1977, 1990 and 2000. The top and bottom rows of images show the dynamics of the right and left banks of the distributary, respectively.

FIGURE 12. The changing morphology of the selected area 4 in 1977, 1990 and 2000. The top and bottom rows of images show the dynamics of the southern and northern parts of the area, respectively.

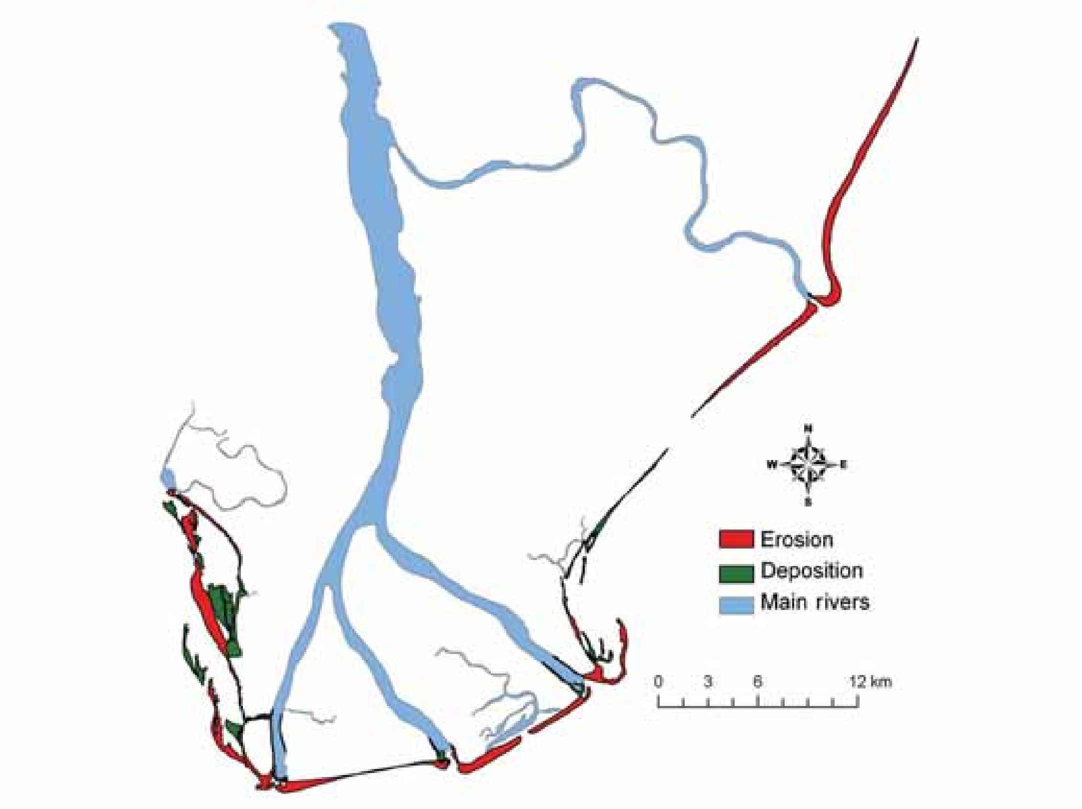

FIGURE 13. A contour of the Krishna Delta showing areas of erosion and deposition during the period between 1977 and 2000.

The results suggest that while areas of predominant erosion and deposition interchange, the overall tendency is towards the regression landward with losses of land to the sea, the situation similar to that in the Godavari Delta. The annual net loss rate of 77.4 hectares is almost the same as that in the Godavari Delta (73.4 ha/year; Malini and Rao 2004). One noticeable feature of the Krishna Delta is also its higher ratio of erosion to deposition (3.05 versus 1.6 in the Godavari) over the same period, which suggests that coastal erosion is more "effective" in the Krishna Delta than in the Godavari, despite the slightly smaller area (4,700 km$^2$ versus 5,100 km$^2$) and shorter shoreline of the former (134 km versus 160 km). Erosion is also a dominant process through most of the coastline, while deposition is limited to certain sections only (Figure 13).

## Possible Causes and Implications of Coastal Erosion

The regression of both deltas cannot be explained by the sea-level rise. Analysis of the available sea-level data in the region for the period 1970–1996 (measurements at Visakhapatnam and Chennai) and for the period 1990–2001 (calculations from daily tide gauge data at the Kakinada to the north of the Godavari Delta) did not reveal any significant rising or falling trends (Malini and Rao 2004). Therefore, coastal erosion in the Krishna and Godavari deltas can only be explained by the above-illustrated reduced sediment supply that, in turn, is due to upstream flow regulation. In addition, human activities in delta regions (e.g., conversion of cropland and mangrove swamp areas into aquaculture ponds) may also be responsible for sea transgression leading to coastal erosion and shoreline retreat of the deltas (e.g., Sarma et al. 2001).

Analysis of the longer sediment load data series for the downstream parts of the Krishna and the use of more recent and more resolute remote sensing images would result in more detailed quantification of delta erosion. However, even with the existing limited data, it is possible to suggest that upstream basin storage development leads to the said retreat of deltas. The Krishna River is already effectively a "closed basin" as only occasional high flows "spill" into the delta with almost zero sediment contribution to it (Figure 8). Therefore, the storage that is already constructed in the Krishna will have a long-lasting detrimental effect on the delta and its agricultural productivity (the situation in the Godavari Delta will also most likely deteriorate after the construction of the additional storages planned as part of the NRLP).

Detailed sedimentation modeling studies would be useful in *all* major deltas of India in order to develop a better understanding and quantification of the links between upstream water and sediment flow reduction, upstream storage growth and man-induced changes in deltas, on the one hand, with deltas' erosion and retreat, on the other. Such studies could allow the specification of necessary environmental flow releases to be made for the maintenance of delta sediment regimes.

Coastal erosion may be seen as a slow process. However, there are a few aspects which promote negative environmental impacts associated with it. One is the saltwater intrusion. Bobba (2002) conducted a numerical modeling study of the Godavari Delta and showed that saline intrusion may become a major factor of reduced agricultural productivity in that delta due to increased groundwater pumping and reduced freshwater inflow (the authors could not identify a similar published study for the Krishna Delta). Coastal erosion, caused by similar factors facilitates saltwater intrusion deeper in the delta adversely affecting the productivity of land. Additionally, although highly uncertain in quantitative terms, there is the potential sea-level rise in the next 50 years due to climate change, although the limited available observations have not detected it so far. This rise can lead to even more coastal erosion and deeper saltwater penetration, accelerating delta degradation. This research was not the scope of the current study and needs to be carried out as a separate and detailed project. While quantification of the above impacts will be developed, even limited environmental flow releases from existing reservoirs in the Krishna and Godavari will delay the adverse environmental processes in both deltas. New storage reservoirs need to be planned so as to allow sediments to reach deltas. Construction of the most downstream reservoirs, particularly as large as Inchampalli, will definitely not serve this purpose.

## Conclusions

- All NRLP transfers are justified based on the premise that a "natural" annual flow volume which has exceeded 75% of the time (e.g., 30 out of 40 years) is available for water utilization. This does not consider the variability *within a year*, which is extremely high in monsoon-driven Indian rivers. As a result, more water is perceived to be originally available at a site of transfer. Alternative techniques, based on a low-flow spell analysis and, more importantly, a storage-yield analysis, may be used to reevaluate the surface water availability at proposed transfer sites.
- All NRLP transfers are further justified based on the maximum plans for irrigation (for 2025 or 2050) adopted by each state within each river basin. This boosts irrigation requirements and serves as the driver for future water resources development. Maximum irrigation development is therefore effectively programmed into India's Water Future for the next half a century without alternatives or much discussion of its technical and economic feasibility.
- A few points on the Krishna (e.g., Alamatti, Srisailam) are classified as "surplus" and are to become "donors." At the same time, some links (e.g., Bedti-Varada) are expected to bring water into the Krishna, upstream of the "surplus points." Some "deficit" points in the Lower Krishna then rely on transfers from the Mahanadi through the Godavari, rather than on more naturally available water from the Upper Krishna. It does not appear entirely logical to isolate subbasins and describe them as "surplus," since they contribute differentially to downstream water availability. There may be a need for more integrated water resources planning whereby all future water transfers in and out of the same basin are considered and simulated together.
- The demands which are currently considered in feasibility reports include irrigation, hydropower, industry and domestic use. It is suggested that at least an environmental demand for environmental management class D is also explicitly included at the planning stage – even as a contingency item. This class is the least acceptable from an ecological point of view and requires a very limited environmental water allocation, in the range of 10–15% of the long-term annual flow. This would be a precautionary measure in the absence of other, more detailed, information at present. It is envisaged that even such a minimal allocation will make some transfer plans less feasible, as was illustrated in this report. The main point however is that environmental water demand should be explicitly considered in water resources planning, similar to the demands of agriculture, industry, hydropower and domestic needs.
- In this report, for the donor and receiver points on the Polavaram-Vijayawada link, the environmental flow requirements have been calculated using the planning technique of Smakhtin and Anputhas (2006). These demands, as scenarios for two environmental management classes, have been used in detailed water resources modeling of this link. The results of this modeling are described in a companion report (Bharati et al. n.d.).

- Locating reservoir sites (particularly as large as the planned Inchampalli Dam) in the most downstream, normally flat, areas of river basins is problematic from an engineering perspective. Such reservoirs have large surface water areas, which drastically increase evaporation and incur a large dead volume, which reduces the active storage and makes it inefficient. It also captures most of the sediment supply to downstream deltas, which are the “rice bowls” of India, due to the high land productivity. It has been demonstrated that the Godavari and Krishna deltas have been in retreat over the last 25 years, which is related, most likely, to reduced flow and sediment flow to deltas. Environmental flows need to be provided to at least partially arrest/delay this “shrinking of deltas” which threatens agricultural production and mangrove ecosystems, despite the fact that this shrinking is slow.
- It is not possible to properly reevaluate any plans without having the same starting conditions, i.e., the same hydrological data. Consequently, only cautious statements can be made at present regarding the quantitative side of planned water transfers. However, no relevant and detailed hydrological data have been made available to this project despite all continuous efforts to obtain them. This leads to two more points. First, if these data are available (the actual NWDA flow time series for each donor/receiver point considered), it is possible to revise the estimates presented in this report. Second, the continued policy of hydrological “data secrecy” is not conducive to good water resources planning and development in India and will not lead to socially and environmentally acceptable water projects. In fact, it is one of the major stumbling blocks on the way to scientific and engineering progress in water science in the country. India needs a centralized data storage and dissemination system. Such a system could be developed within a time frame of 2–3 years. However, policies of free data access could and should be reinforced before that. Without such reinforcement difficulties in resolving water controversies in India will remain.

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**Postal Address**
P O Box 2075
Colombo
Sri Lanka

**Location**
127, Sunil Mawatha
Pelawatta
Battaramulla
Sri Lanka

**Telephone**
+94-11-2880000

**Fax**
+94-11-2786854

**E-mail**
iwmi@cgiar.org

**Website**
http://www.iwmi.org

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