Hydrological and Environmental Issues of Inter-basin Water Transfers in India: A Case Study of the Krishna River Basin

V. Smakhtin, N. Gamage and L. Bharati
International Water Management Institute, Colombo, Sri Lanka

Introduction

The National River Linking Project (NRLP) was proposed as 'the solution' to water-related problems in India. It envisages transferring the waters of the Ganga, Brahmaputra and Meghna rivers through Mahanadi and Godavari river basins—all normally referred to as , 'water surplus' basins—to the 'water deficient' basins in the south and the west (e.g., http://www.riverlinks.nic.in/). The NRLP is a contentious issue in Indian society, the media and among academics. Many scholars argue that the needs assessment of the 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. And there are others who 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 relating to the NRLP. However, the project as a whole has not reached implementation which, to a certain degree, mirrors the fate of certain other large-scale water transfer projects in the world. At the same time however, certain 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 in 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 (Inter-basin water transfer 1999):

1. The area of delivery to which the transfer of water is made must face a substantial deficit in meeting present or projected future water demands after consideration is given to alternative water supply sources and all reasonable measures for reducing water demand.

2. The future development of the area of origin, from which the transfer of water is made, must not be substantially constrained by water scarcity. However, such constraints may however be tolerable if the area of delivery compensates the area of origin for productivity losses accruing from the transfer.

3. A comprehensive environmental impact assessment must indicate to a reasonable degree of certainty that it will not substantially degrade the environmental quality within the area of origin or area of delivery. However, transfers may be justified where compensation to offset such environmental injury is provided.

4. A comprehensive assessment of socio-cultural impacts must indicate to a reasonable degree of certainty that it will not cause substantial socio-cultural disruption in the area of origin or area of water delivery. However, transfers may be justified where compensation to offset potential socio-cultural losses is provided.

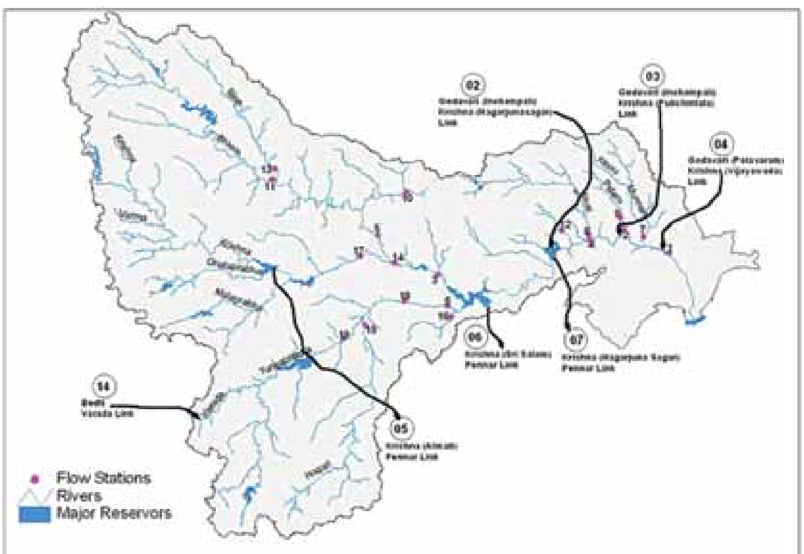
5. The net benefits from transfer must be shared equitably between the area of transfer origin and the area of water delivery.

The International Water Management Institute (IWMI) is conducting a research project, which aims to highlight, discuss and, where possible, resolve certain controversial issues pertaining to the NRLP, thus further stimulating the debate on India's water future. This paper is one of the multiple outputs of this research project. The primary focus of the paper concerns the hydrological feasibility and environmental impacts of the NRLP, which are reflected by criteria 1, 2 and 3. The objective of the paper is not to analyze all of the NRLP's links from all possible angles of technical and environmental feasibility, but rather the authors aim to: i) identify and examine those technical and environmental aspects which may still have been under-appreciated in previous discussions on the NRLP and need to receive further attention; and ii) illustrate their importance on one or several (but very few) of the NRLP's links. More specifically, this paper first 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 certain links as examples, on how water transfer planning may be affected by the resolution of the hydrological data. The paper 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 contemporaneous paper by Bharati et al. (2007) discusses the multiple aspects of water management of Polavaram—Vijayawada link and examines the impacts of water management options and scenarios using an integrated Water Resources Evaluation and Planning model (WEAP).

[1]The Krishna Basin is one of five 'benchmark basins' in which IWMI conducts research from around the world, where the intention is to integrate various strands of bio-physical, socioeconomic and institutional research.

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.

Figure 2. A schematic diagram of the Krishna River basin, showing all proposed inter-basin 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 location relative to the link points, only a few of the shown stations are usable. These include record at station 3 (Krishna at Agraharam) and part of the record at station 1 (Krishna at Vijayavada).



Water Transfers In and Out of the Krishna Basin: A Review

In order to assess the degree to which the criteria 1, 2 and 3 above are satisfied in the planning of individual links in and out of Krishna, the relevant chapters of the technical feasibility reports (Hydrology, Environment), produced by the National Water Development Authority (NDWA) 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 on Figure 2, starting from the most 'upstream' link.

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. The salient features of the link are listed on the NDWA web site, together with very limited anecdotal information (Dams, Rivers and People 2004). This proposal envisages the diversion of 242 million cubic meters (MCM) of 'surplus' waters from 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 approximately 60,200 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 humid tropical forests (75 % of the area) and declared by the International Union for Conservation of Nature (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. This exceeds the biodiversity numbers from the whole of Kerala State, which is where the Bedti Basin is located. The flow will be discharged into the Varada without a receiving reservoir, which may increase channel erosion in the localized parts of the river. Altered flow patterns may also cause riparian zone degradation and create habitats for invasive species. The proposed project is expected to generate 3.6 MW of power, but it may take over 61 MW to lift the water to the Varada.

Krishna (Almatti)–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 Almatti Reservoir on the Krishna River (upstream catchment area 33,375 km2). This link is seen as a partial exchange for Godavari water brought into Krishna (links 2, 3 and 4 on Figure 2). However, since all the inward links from Godavari bring water to the downstream parts of Krishna, and since the inflow from Bedti link (if constructed) is minor, this link effectively transfers the existing 'surplus' water from the upstream reaches of an otherwise 'deficient' Krishna Basin into another 'deficient' basin in Pennar. The purpose of the link is to satisfy en-route irrigation needs. The 1980 MCM of water will be transferred through a 587 km long canal with an outfall into a tributary of Pennar. A new (balancing) reservoir with a total (live) storage of 83 (73) MCM is to be constructed at the recipient end in the Pennar Basin - at Kalvapalli village with an upstream catchment area of 5,616 km2. The need for this new reservoir may need to be better justified as there is another dam (upper Pennar) which commands the catchment area of 5,245 km^2 - just upstream of the proposed new one.

All water transfers in the NRLP are planned from ‘surplus’ basins or parts thereof to ‘deficit’ basins. The basin is declared ‘surplus’ if both the balance of water ‘naturally’ available (assured) in a river is 75 % and 50 % of the time positive and the total demand for the next 25-50 years upstream of the point of a transfer is also 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 paper). 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 figures for the recipient point of Pennar at Somasila are deficits of -3,820 and -3,590 MCM, respectively. Such a large difference between surpluses and deficits of the donor 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 the habitat due to the lined canal becoming an obstacle to wildlife migration routes, are programmed into the project. However, it is suggested that such affected wildlife ‘will migrate to surrounding forests’ instead, and thus the canal’s impact on wildlife will be minimal. Possible measures to mitigate the disturbance to the sanctuary include re-aligning it and establishing 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 is anticipated in the form of silting and sedimentation, nutrient leaching and agricultural runoff containing fertilizers and pesticides. As such, 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 in fish species, which will increase the overall fish population, 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 recipient rivers per se. It is possible to suggest that no ‘ecological’ releases from the Almatti 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 the latter’s confluence with the Tungabhadra River (Figure 2). Similarly to the Almatti – Pennar link upstream, this link effectively transfers the existing ‘surplus’ water from the otherwise ‘water deficient’ Krishna Basin into another ‘water deficient’ basin in Pennar. This may result in less water downstream of the Srisailam Dam and cause the reach between Srisailam and Nagarjuna Sagar dams to 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 is, after all demands are satisfied, at 6,017 MCM. 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 (monsoon and post-monsoon season). The water will be discharged into the Nippulavagu, a natural stream, and will reach Pennar through the Galeru and Kunderu tributaries. No new infrastructure is required and no en-route irrigation is planned, and the transfer targets exclusively as its destination, the 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. Certain common impacts of water diversions (e.g., sedimentation of reservoirs, changes in the 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 an additional 163 m3/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 the 6 months, and what the riparian conditions are or how embankments will affect fish spawning.

Krishna (Nagarjunasagar)–Pennar Link (Link 07)

This is a major transfer of 12,146 MCM of water from and to existing reservoirs: the Nagarjunasagar Dam on the Krishna (upstream area of 220,705 km^2) and the 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 more severe (a deficit of -3,820 MCM is envisaged at 75 % assurance in Pennar with all irrigation plans in place). A new 393 km long lined link canal and an existing right-bank canal from Nagarjunasagar will run in parallel over 202 km, while the latter can only carry 3,979 m3/s annually the proposed link-canal is expected to transfer three times more water. Such massive transfers may only be possible 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 nor costs are for mitigation of those. This link is effectively part of the much longer water transfer line from the north to the south. Additional water transfer to Nagarjunasagar reservoir is planned through Inchampalli- Nagarjunasagar link (see below).

Godavari (Inchampalli)–Krishna (Nagarjunasagar) Link (Link 02)

This link involves the transfer of 16,426 MCM of water and a construction of a new major storage reservoir on Godavari at Inchampali. The upstream catchment area at this point is 269,000 km^2 and the gross (live) storage of the future dam is 10,374 (4285) MCM. A low ratio of a live storage to gross is noteworthy. The water yields of the Godavari at Inchampali 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 states' irrigation plans is 40,723 MCM and the balance of all demands (irrigation plus others) at 75 % and 50 % assurances is 20,327 and 29,987 MCM, respectively. The Krishna River at Nagarjunasagar 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 the feasibility of which would 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 paper indicates that the project will have an impact on the Singaram Sanctuary and submerge 65 ha of the Indravati National Park. It lists the known present fauna and birds in the area, which however does not include any endangered species. Although no adverse impacts on aquatic life are identified, the paper was not able to cite any studies which have been carried out in this regard. Afforestation is proposed to compensate the loss of forests to submergence.

Godavari (Inchampali)–Krishna (Pulichintala) Link (Link 03)

This link will divert 4,370 MCM of water 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 - long link canal. The water yields at 75 % and 50 % assurances are estimated to be 66,193 and 76,185 MCM respectively and the surplus surface water balances after satisfaction of all projected requirements at Inchampali are at +20,327 and +29,987 MCM, respectively. Similar estimates are done for the Muneru, Paleru and Musi tributaries of the Krishna.

The feasibility report explicitly suggests that all requirements in the Godavari, downstream of Inchampali, can be met by the water available from the incremental catchment area located between the Inchampali and Dawlaishwaram barrages and with the surplus water transferred from the Mahanadi. Therefore, no water is likely to be released from the Inchampali downstream and all water at Inchamapali will instead be diverted to the Krishna. The feasibility report refers to simulations of the Inchampali reservoir at a monthly step, over the period of 1951-1981, supplying both the Pulichintala and Nagarjunasagar links (4,370 and 16,426 MCM respectively). 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 Inchampali - Nagarjunasagar link, as they are for a common storage (Inchampali).

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

This is the most downstream link in both the Godavari and Krishna basins, and the one which is scheduled for construction in the near future. It is planned to divert 1,236 MCM of water from the new Polavaram reservoir in the Godavari (with a live storage of 2,130 MCM) to the existing Prakasam barrage in the Krishna, through a new 174-km long link canal. The transfer is designed to substitute releases to the Krishna delta from the Nagarjunasagar 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 Koleru

Lake (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 expected to benefit from the Polavaram link. There is also no mention of how the existing canals will be integrated into the new canal system if and when it's operational.

Approximately US$600,000 (0.2 % of the project cost) is allocated: i) to study the 'environmental and ecological' aspects of the project by various organizations; and ii) 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 of the canals, where new irrigation, and domestic and industrial requirements are targeted. Possible adverse impacts mentioned in the paper include resettlement, submergence of forest, 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 to allow for movement of migratory fish, studies of the nature of existing aquatic weeds in the submerged area as well as other areas.

The National Council of Applied Economic Research (NCAER) of Delhi, India, was entrusted with the studies of socioeconomic and environmental implications of six inter-basin water transfers including this link (Agricultural Finance Corporation 2005). Their report indicates that the wildlife sanctuary in the proposed Polavaram reservoir area will be marginally affected by the submergence. In addition, the report indicates a list of fauna in the area coming under submergence, compiled on a district by district basis. 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 wildlife. The report however is unclear as to the scientific basis for these conclusions. It is further envisaged in the report that endangered species such as the tiger and the panther will move to deeper forest areas and avoid the submerging areas.

It is indicated that the construction of the Davlaishwaram anicut in the Godavari has obstructed fish migration from the sea to the inland (e.g., hilsa). It is stated that the dams convert a river into a more placid lotic environment with reduced velocities, which impacts the composition and size of fish species. However, the report fails to present any quantitative, link-specific conclusions in this regard. Generic statements are also made about phytoplankton, and changes in seasonal flow pattern etc. It is also admitted that the entire command area lies in the coastal belt where there is high rainfall, which enhances the risk of malaria. In addition, a few general statements are made about vector breeding and a possible increase in waterborne diseases.

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

General Observations

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

At the same time however, they all share similar shortcomings. The information presented remains limited and it is not possible to judge 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 the new reservoirs and the resettlement of the population affected. It is clear that no provision is made for the 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. In addition, the technical aspects of certain links need more clarity. For example, the Bedti-Varada link does not seem to be justified from the hydropower angle (as it will produce far less energy than the amount used to transfer the water). Links starting from lower Godavari include the construction of a new Inchampali 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 inter- basin water transfers is driven by significant irrigation expansion that extends into the year 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 however, benefit more from 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 certain projects is also noteworthy. For example, the Almatti - Pennar and Polawaram - Vijayavada links both have the B/C ratio of around 1.2, which makes the effectiveness of these links questionable. Finally, the methods by which water availability for the transfers were calculated require 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 out this method 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 the assessment 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 separated into several smaller subbasins to cater for the spatial variability of rainfall and runoff over large areas. The number of subbasins varies with the links – depending on the size of the catchment area upstream of the link point. For smaller links, like the Bedti -Varada, such separation is not required and one subbasin may be used. Observed annual flows at one or more hydrological measuring stations (e.g., in every subbasin) are calculated using original flow records. The observed records used different time lengths for different links. For example, a period of 100 years (1900-2000) is used for the Almatti link, while a period of 32 years (1951-1983) is used for the Srisailam link.

- 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 the types of abstractions differ, they have increased over time, especially in 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, accounting for these abstractions attempts to 'naturalize' observed river flows, because these flows form the reference condition for assessing water availability for the transfer.

- The annual time series of weighted areal rainfall for each gauged basin is then calculated using the data from available / selected rainfall stations, and a regressive 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 the monsoon rainfall time series as input. This allows the monsoon period flows to be calculated for each year. The non-monsoon portions of flow are then added to the monsoon portion for each year thus building the annual time series of naturalized flows. It is not clear from the feasibility reports how the non-monsoon portions are calculated, but the perception is obviously that these flows do not provide a significant contribution to the overall volume of annual total flow.

- The calculated annual flow time series for individual subbasins upstream of the Donor/ Receiver site is then summed up to produce the annual time series for the 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 is at the donor site, the more 'dependable' it is because flows in other years frequently exceed it. The higher the flow however, the less dependable it is. 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 although rather arbitrary is not the most critical issue, since many different levels of assurance of water supply larger than 50 % are conventionally (and similarly arbitrarily) used worldwide in the practice of water resources engineering (e.g., Smakhtin 2001).

- The annual flows at 50 % and 75 % assurances (further demoted 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 prepared at the *annual* time step. Most of the further decisions are based on the estimates derived from annual flows 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 state plans for irrigation development. The industrial requirement (assumed to be met entirely from surface water sources) is not known and is taken to be equal to the domestic water demand, which is based on population figures. The hydropower requirement is taken to be equal to the total evaporation from all hydropower projects. Environmental water demands are not however, accounted for in the estimates. When 'downstream' requirements are mentioned, they normally imply the requirements of downstream agriculture, industry or domestic needs, but not aquatic ecology or re-creation.

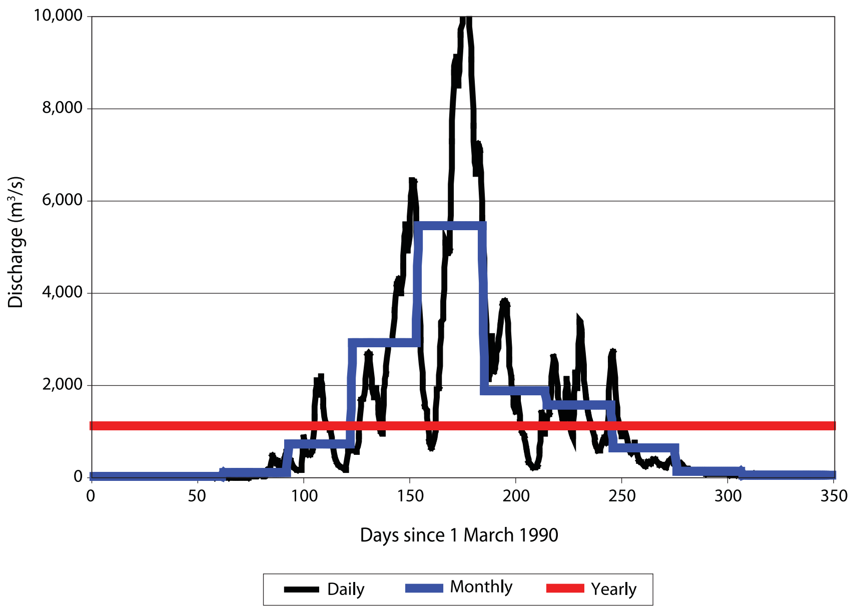
- The difference between the total available supply (equation 1) at 75 % assurance and the total projected demand at the same site (Donor or Receiver) becomes the basis of declaring the basin (or part thereof) as a 'surplus' or 'deficit'. If the above difference is positive- the basin is a 'surplus', if negative – it is a 'deficit'.

- As a rule, each link includes at least one reservoir – either at the Donor or at the Receiver point or at both points. The last step in the methodology is, therefore, a reservoir simulation modeled on the current day observed flows and including all future demands. 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 a time series of annual actual inflows to a reservoir whether existing or new (e.g., to Alamtti, 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 the feasibility reports that average monthly weights are used for this calculation—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 (which is typical for India, where it seems to be a common practice to assume full draw down of the stored water every year and no provision for inter-annual storage). A reservoir simulation is carried out to identify whether the proposed transfer can be managed with the estimated storage and, if yes, then with what level of reliability—how many of the simulated years will be deemed successful years. 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 annual time step resolution were used as the basis for the estimates of dependable (assured) flows at link points. This approach requires comment. The existing literature on water resources systems suggest that although annual time step data may be used for the preliminary (crude) planning of water supply systems, the preferred data type for this is the 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 the hydrological time series. Figure 3 illustrates this point with the three most widely

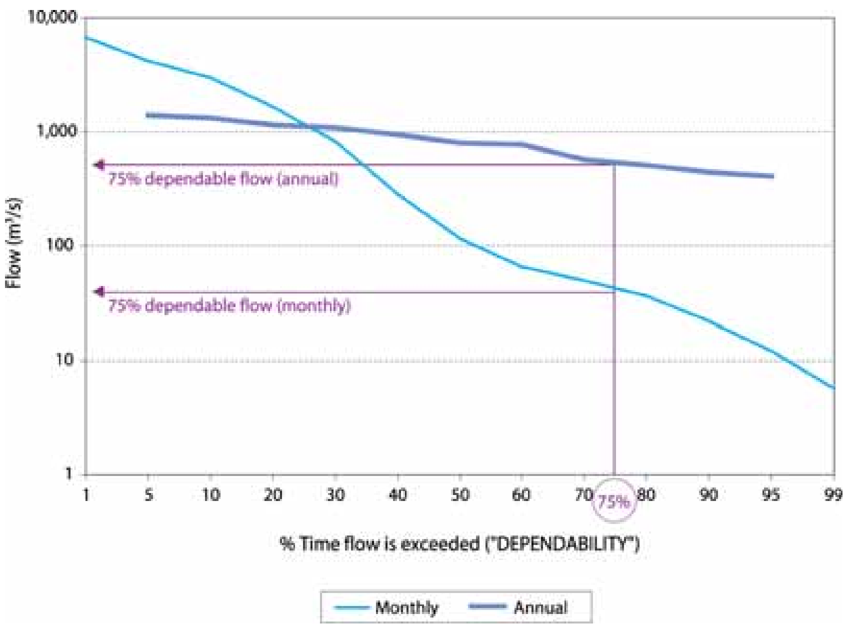
Figrure 3. An illustration of different temporal data resolution: yearly, monthly and daily flows recorded in the Krishna River at Agraharam Town during March 1990–February 1991.



used flow data types- annual, monthly and daily. The differences between daily and monthly flows in low-flow months are negligible due to minor variability of daily flows during these months. However, the differences between the mean flow for the 'year' and the 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 the 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 the annual and monthly flow time series for the same arbitrarily selected site on the Krishna River, for which certain observed flow data were available. The flow exceeded in 75 % of all years (75 % dependable flow- in Indian terminology) and is much higher than the flow that exceeded 75 % of all months. NDWA feasibility reports use *annual* flow values at 75 % dependability as a measure of surface water availability at the points of transfer (both Donor and Receptor sites). However, if monthly, more information 'rich' data are used instead of annual flow values, the flow available at 75 % dependability amounts to a smaller magnitude than when annual data resolution is used.

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 of the assessment of the water available for transfer at the links' 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 limitation of data available for this study prevented the carrying out of reliable calculations for all link points. Only very few data sets, primarily from the Internet, were available. The accuracy of these data sets is not possible to ascertain, but it is possible still to illustrate the abovementioned differences for certain links.

The link points for which dependable flows have been calculated are listed in Table 1. These are effectively the only link points which can be simulated with the limited data available.

To construct a FDC at Inchampali, the duration curve at Polavaram (both in the Godavari Basin) has been multiplied by the factor of 0.874 – the ratio of catchment areas at Inchampali (269,000 km2) and Polavaram (307,880 km2). The data period used was 1910-1960 (despite the availability of more recent observations) – to avoid the impact of missing data on both ends of the record, particularly after 1960 and in order to ensure that a less impacted, more natural flow time series was used. This record gives a long-term mean annual flow estimate at Polavaram of approximately 105 BCM, which is close to the 'official natural' flow estimate of 110 BCM (cited also in Smakhtin and Anputhas 2006).

To obtain a FDC at Vijayavada, which is representative of more natural and less regulated conditions, the curve at Vijayavada (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 and the 'official' estimate of the mean annual flow at the Krishna outlet, which is 78 BCM (cited also in Smakhtin and Anputhas 2006).

To obtain a FDC at Srisailam, the 'naturalized' duration curve at Vijayavada (Station 1 in Figure 2) has been multiplied by the factor of 0.84 – the ratio of catchment areas at Srisailam (221,657 km2) and Vijayavada (251,360 km2). The data period used was 1900-1965 (despite the availability of more recent observations) to avoid the impacts of the significant reduction of the Krishna flow observed in the last 50 years and to ensure a more or less 'unregulated' record.

To obtain a FDC at Almatti, the duration curve at Agraharam (Station 3 in Figure 2 – the nearest to Almatti with usable data) has been multiplied by a factor of 0.25 – the ratio of catchment areas at Almatti (33,375 km2) and Agraharam (132,920 km2). 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 have lead to the underestimation of means and dependable flows. Observed data at Agraharam 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 tiny compared to the assurances of 50 % or 75 % of flows in Table 1 taken from NWDA. It is clear that such a mean flow is not accurate and the error is transferred to the estimates of dependable flows at Almatti.

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 for example, differences in estimates from annual and monthly time step data. It has to be noted that should more reliable data become available, then the estimates in this study can be revised to ensure more 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 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 the water available 75 % of the time, given the high

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 /Receptor 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 Vijayavada	Not available	11,808	Not available	1,964

Source: Annual data are from the feasibility reports in http://nwda.gov.in/indexab.asp? langid=1. Monthly data are authors' estimates.

variability of flow within a year in the Godavari, and also that a year contains a large number of low-flow months (the case similar to that shown in Figure 3)

The Use of Spell Analysis for the Re-assessment of Surface Water Availability

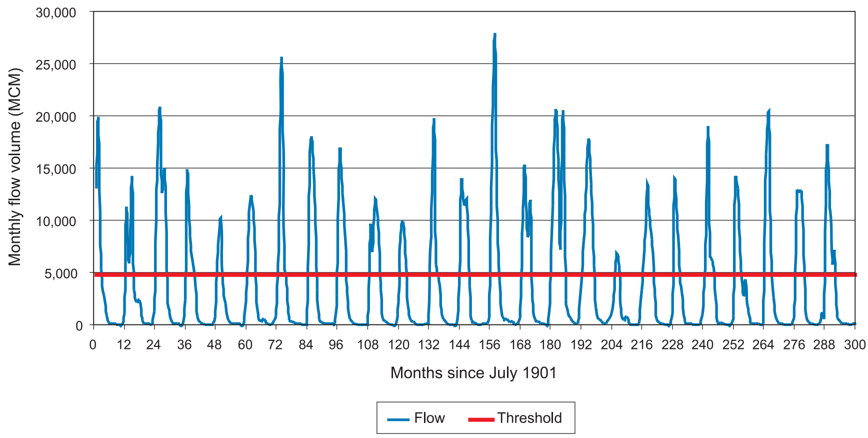
The two different data resolutions (annual and monthly) used to assess water availability effectively represent two different ways of thinking about the level of possible flow regulation. Annual flow data ignores within-year flow variability and, therefore, indirectly suggests that the river may be almost 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 the extreme cases in water availability i.e. the 'annual' one unjustifiably pushes up water availability estimates while the 'monthly' one significantly reduces them. Neither of these approaches and their results is 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 a form of water resources storage-yield analysis to establish the maximum possible draft (reservoir yield) at the donor point of each transfer. This analysis can be used to establish either the possible reservoir yield if a given/ planned storage is constructed, or the reservoir storage necessary for the required yield. In the context of estimating water availability (including water availability for transfers), a reservoir (or a system of reservoirs) could to an extent provide feasible maximum storage that will be used to make the water actually 'available'. The 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 however, 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 a river flow *continuously* stays below or above a certain threshold flow level. Each spell is characterized by the duration and excess or deficit of flow volume. For example, deficit flow volume is characteristic of a low-flow spell. Depending on the type of flow regime and the flow threshold, there may be one or several low-flow spell(s) in one year. Two transfer sites from Table 1—Krishna (Srisailam) and Godavari-Polavaram—are used below as examples to illustrate this alternative method of assessment of water availability. Other points were not or could not be considered either due to the lack of certain data, or the unreliability of available data or closeness to other gauging points.

In the case of the transfer at the Srisailam site, the NWDA estimated an available annual yield of 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, this figure 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 MCM 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.

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



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 there are dams with larger percentages than that, 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 become 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 take up a large proportion of the total storage.
- No major additional storage construction is actually planned

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 realistically be 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 elevated to 20 BCM to allow for 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 below 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 water 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 they are found in the relevant NWDA reports. The environmental flow requirements have, however, been estimated and added to the tables (these estimates have been prepared using the method developed by Smakhtin and Anputhas [2006] for the least acceptable environmental management category called 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.

Table 2. Surface water balance (MCM) at the Srisailam Dam site, 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		
Sub-total	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
Sub-total	52,678	(-) 52,678	(-) 57,978
Surface water balance		(+) 6,017	(-) 24,281

Source: Annual data are from the feasibility reports in http://nwda.gov.in/indexab.asp? langid=1. Monthly data are authors' estimates.

Table 3. Surface water balance (MCM) at the Polavaram Dam site, Godavari (307,880km^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 from (+)			
Domestic use	1,512		
Industrial use	2,402		
Irrigation use	3,138		
Sub-total	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
Sub-total	62,621	(-) 62,621	(-) 70,821
Surface water balance		(+) 15,171	(-) 37199

Source: Annual data are from the feasibility reports in http://nwda.gov.in/indexab.asp? langid=1. Monthly data are authors' estimates

As the tables above illustrate, after significant reductions in surface water availability, which is the starting point in planning for inter-basin water transfers, the overall water balance of each basin has changed dramatically from being essentially 'water surplus' to seriously 'water deficit'. It is important to note that this change would occur regardless of whether environmental flow requirements are included as a component of water demand or not. In the first place, it is acknowledged that the estimates suggested here may not be very accurate due to severe data limitations. However, the change itself cannot be attributed to data inaccuracies or limitations, but clearly to the approach used for the assessment of surface water availability. It is envisaged that if the original data used by NWDA were available, it would still result in a similar change in water balance. 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, a more transparent process as well as by accepting environmental water requirements as a legitimate demand similar to other water demands.

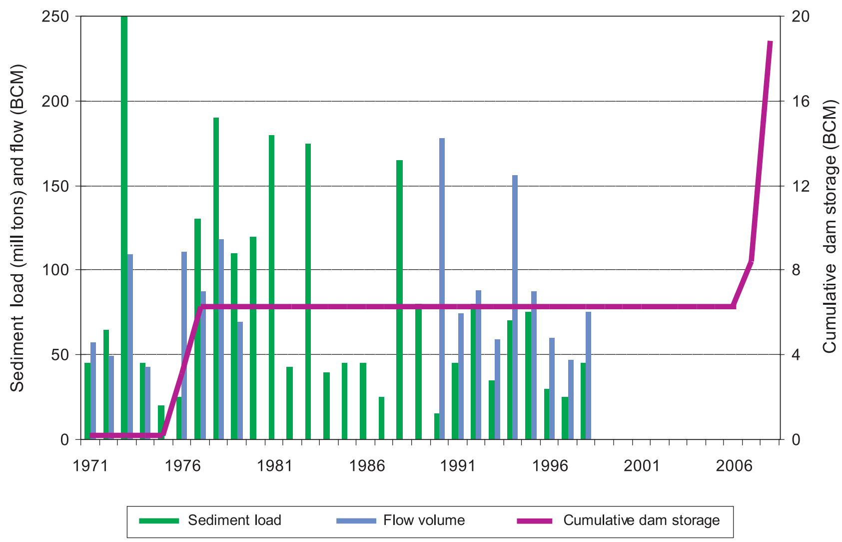
Environmental Impacts of Reservoir Construction on the Godavari and Krishna Deltas

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

Coastal Erosion: Godavari Delta

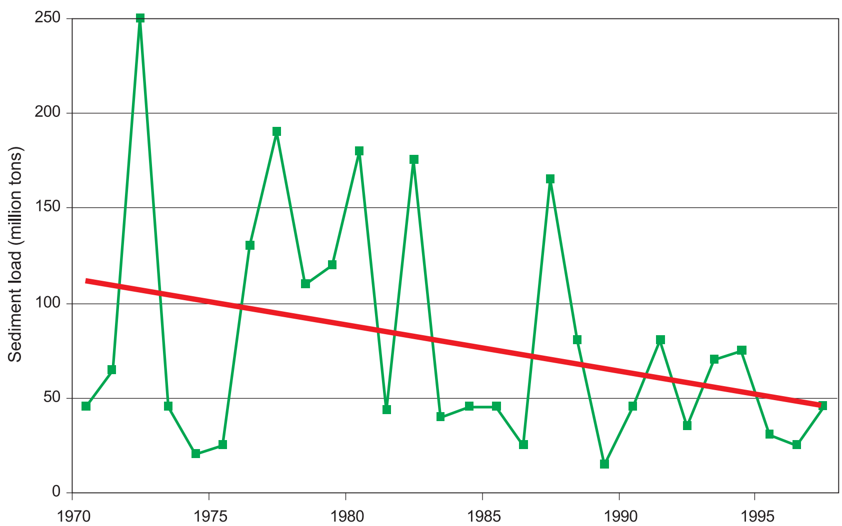
Malini and Rao (2004) examined the recent changes in the Godavari River delta, called the 'rice bowl of AP', using remote sensing images. They discovered that the delta has regressed landward with the total net land loss of 1,836 ha over the period of 1976-2000 (at rate of 73.4 ha/year). It was suggested that the reduced inflow of sediments, associated with upstream reservoir construction are the main causes of reduced vertical accretion at the delta. At the same time, coastal subsidence, probably promoted by neotectonic activity and consequent relative sea level rise, continued and led to a shoreline retreat. Figure 6 illustrates the dynamics of flow and sediment load at the outlet of the Godavari (at Polavaram) and the reservoir storage growth in the entire Godavari Basin since 1970. The flow time series has been taken from Internet sources, and the sediment load data have been read off similar sediment graph published by Malini and Rao (2004), while the storage data are derived from the ICOLD dam register. The flow time series does not include data during the period 1980-1990, and neither flow nor sediment data were available after 1998. Cumulative dam storage (including large and medium dams) increased significantly in the early 1970s and remained relatively constant for the last 30 years. However, it will increase abruptly again after the construction of the Polavaram barrage and the major Inchampali Dam (the growth of the total storage in the basin after the dam construction is shown in Figure 6 —an arbitrarily assumed completion date for the Inchampali Dam is the year 2010).

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



While trends in the Godavari River flow cannot be ascertained from the available disrupted flow time series, the decreasing trend in annual sediment loads are manifest in the sediment data (Figure 7, also shown by Malini and Rao 2004). The mean annual sediment load has decreased from 100 million tonnes in 1978 (effectively an ending point in noticeable reservoir growth in the basin) to 46 million tonnes 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 of the reservoir is not the only significant indicator of the volume of water transferred, as much of the water is also diverted from barrages, which are structures without storage. The fact that the sediment load remains at a noticeably decreasing trend in relatively small basin storage implies that the basin sediment regime is very sensitive to reservoir growth, if the reservoir growth 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 basin storage to the natural flow ratio in the basin to 19 %.

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



Coastal Erosion: Krishna Delta

In this study, an attempt has been made to examine whether similar trends exist in the Krishna Basin, where the proportion of storage viz., annual flow is much larger than in the Godavari. The observations on sediment loads at the Krishna outlet at Vijayavada 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 of 1991–2000 (CWC 2006), which is a rather limited time series for any meaningful conclusions on trends to be made. The comparison of the two short time series of sediment loads at Agraharam (upstream of major reservoirs, Figure 2) and at Vijayavada (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 the high-flow years (1994, 1999), when more sediment reaches Agraharam from the relatively unregulated upstream basin. However, all sediments are likely to be trapped by the existing reservoir system

(Srisailam, Nagarjunasagar) upstream of Vijayavada. The absence of sediment data prior to 1991 does not allow further conclusions to be made about sediment regime changes, even though, these changes are most likely to be 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.

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

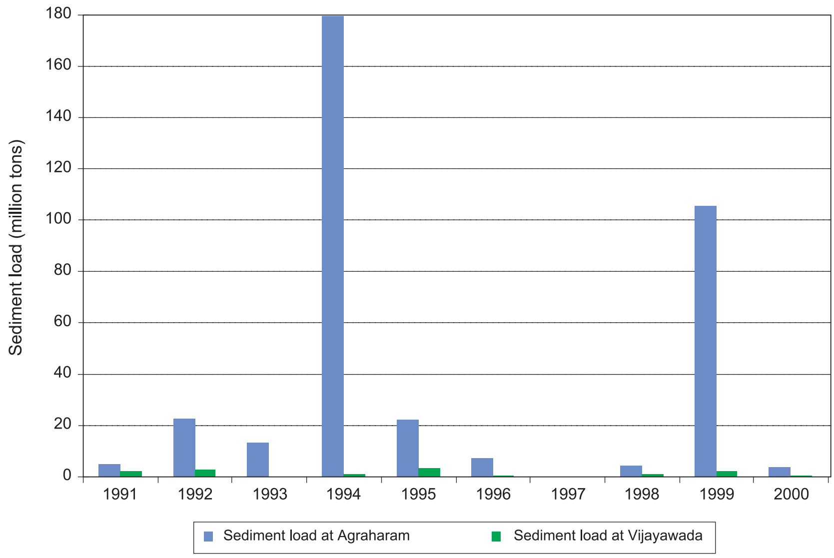
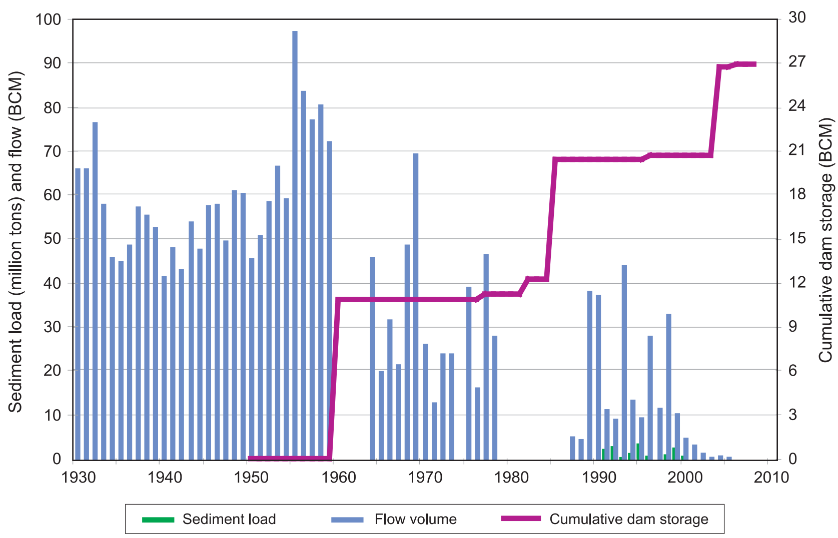


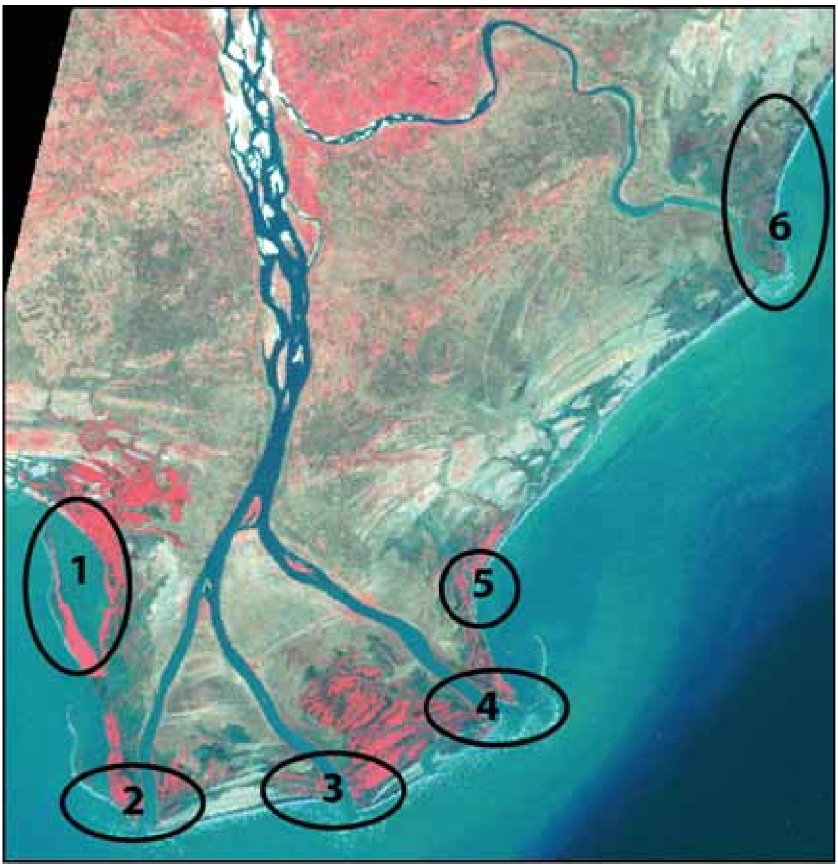
Figure 9. Time series of annual flows, sediment loads and cumulative storage in the Krishna Basin outlet at Vijayawada.



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 the Earth Science Data Interface (ESDI) at the Global Land Cover Facility (GLFC), found at http://glcfapp.umiacs.umd.edu:8080/esdi/index.jsp and were selected from the period between 1977 and 2000 to form a 'time series'. The images included:

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

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



Three basic layers were used to detect morphological changes in the delta: (a) band 4 (NIR); (b) band 2 (Red); and (c) band 1 (Blue). These layers have characteristics that are suitable for coastal mapping, differentiation of vegetation from soil, reflectivity of denseness of vegetation and delineation of water bodies. The first, 'oldest' image was assumed to be the reference condition against which changes in 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 in between two consecutive dates (i. e., at 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 point. The image of the Krishna delta showing selected areas where the 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 certain 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.

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.

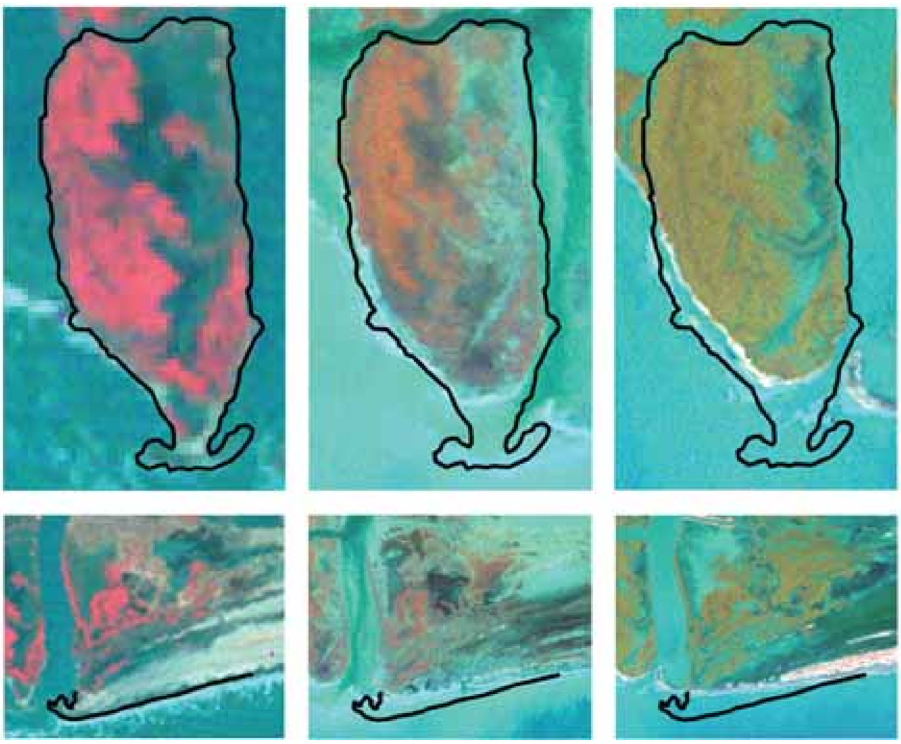


Figure 12. The changing morphology of the selected area 4 in 1977, 1990 and 2000. The top and bottom rows of images show the dynamics of the southern and northern parts of the area, respectively.

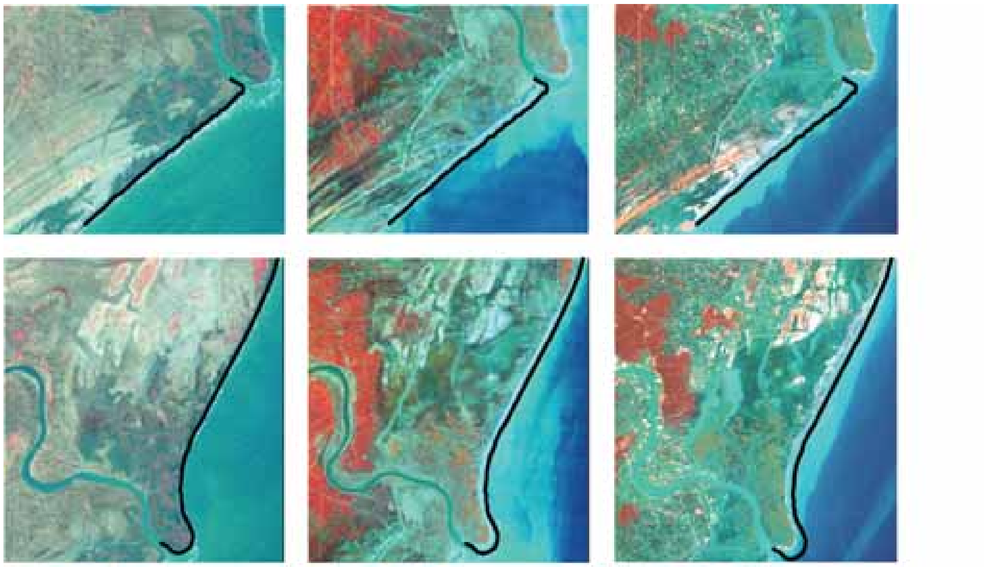


Figure 13. A contour of the Krishna Delta showing areas of erosion and deposition during the period between 1977 and 2000.

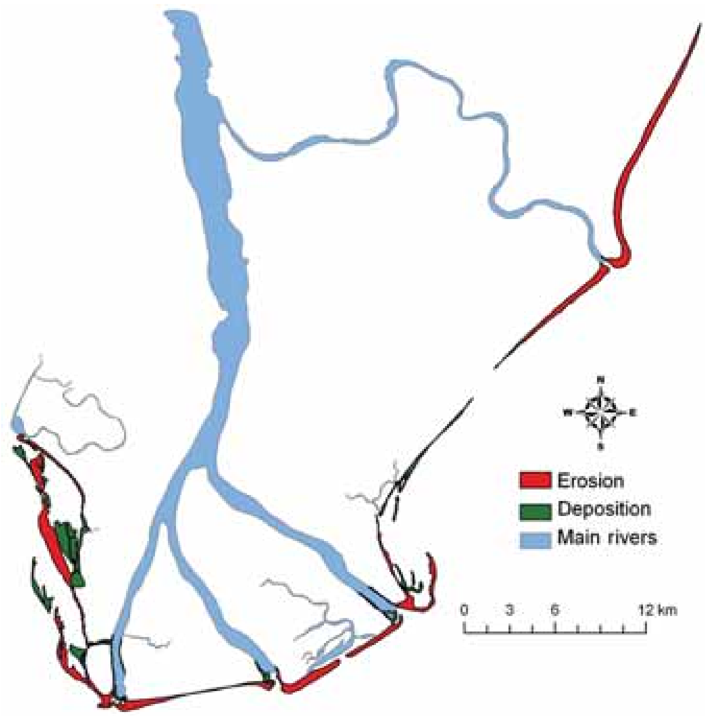


Table 4. Areal extent of erosion and deposition in the Krishna Delta over a period of 23 years (1977-2000).

Point #	Erosion (ha)	Deposition (ha)	Net Loss (ha)	Rate of Loss/Gain (ha/yr)
1	598	483	115	5.0
2	478	178	299	13.0
3	275	31	243	10.6
4	326	74	251	10.9
5	79	98	-19	-0.8
6	894	3	890	38.7
Total (23 Yrs)	2,650	867	1,770	77.4

The results suggest that while areas of predominant erosion and deposition interchange, the overall tendency is towards landward regression with losses of land to the sea - a situation similar to that in the Godavari delta. The annual net loss rate of 77.4 ha 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 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 delta, despite the slightly smaller area (4,700 km2 versus 5,100 km2) and shorter shoreline of the former (134 versus 160 km). Erosion is also a dominant process through most of the coast line, while deposition is limited to certain sections only (Figure 13).

Possible Causes and Implications of Coastal Erosion

The regression of both the Krishna and the Godavari 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 the daily tide gauge data at 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 reduced sediment supply that is illustrated above, which, in turn, is due to upstream flow regulation. In addition, human activities in the delta regions (e.g., conversion of cropland and mangrove swamp areas into aquaculture ponds) may also be responsible for sea transgression, which in turn lead 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 a 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, and in terms of delta changes, between upstream storage growth and man-induced changes in deltas on the one hand, and between the erosion and retreat of deltas, on the other. Such studies could also specify the environmental flow releases that need to be made for the maintenance of delta sediment regimes.

Coastal erosion may be seen as a slow process, but it does entail few aspects which promote negative environmental impacts. One such impact is the salt-water 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 reduce freshwater inflow (the authors could not identify a similar published study for the Krishna delta). Coastal erosion, caused by similar factors, facilitates salt-water intrusion deeper into the delta, adversely affecting land productivity. An additional factor, although highly uncertain in quantitative terms, is the potential sea level rise in the future 50 years due to climatic changes, although the limited available observations have not as yet detected it. This rise can lead to even more coastal erosion and deeper salt-water 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 developing, even limited environmental flow releases from existing reservoirs in the Krishna and the Godavari will delay the adverse environmental processes in both deltas. New storage reservoirs need to be planned in order to allow sediments to reach the deltas. Construction of the most downstream reservoirs however, particularly ones as large as Inchampali, will definitely not serve this purpose.

Conclusions

- All NRLP transfers are justified on the premise that ‘natural’ annual flow volume is exceeded 75 % of the time (e.g., 30 out of 40 years), and is available for water utilization. This does not consider the flow variability *within a year*, which is extremely high in monsoon-driven Indian rivers, and as a result, more water is perceived to be originally available at a site of transfer. Alternative techniques, based on low-flow spell analysis and, more importantly - storage-yield analysis may be used to re-evaluate the surface water availability at proposed transfer sites.

- All NRLP transfers are further justified on the basis of the maximum plans for irrigation (for 2025 or 2050), adopted by each state within each river basin. These plans boost 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 in Krishna (e.g., Almatti, Srisailam) are classified as ‘surplus’ points 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 lower Krishna can 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 differently 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. However, it is envisaged, that even such minimal allocation will make certain transfer plans less feasible, as was illustrated in this paper. The main point, however, is that environmental water demand should be explicitly considered in water resources planning, similar to the water demands of agriculture, industry, hydropower and domestic needs.

- In this paper, for the donor and receiver points on the Polavaram- Vijayavada 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 the detailed water resources modeling of this link. The results of this modeling are described in a companion paper (Bharati et al. 2007).

- Locating reservoir sites (particularly as large as the planned Inchampali Dam) in the most downstream, normally flat, areas of river basins is problematic from an engineering perspective. Such reservoirs have large surface water areas that drastically increase evaporation and incur large dead volume, which reduces the active storage and makes the reservoir inefficient. They also capture 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 river flow and sediment flow to the deltas. Environmental flows need to be provided to at least partially arrest/delay this ‘shrinking of deltas’, which is currently threatening agricultural production and mangrove ecosystems, despite the slowness of the shrinking process.

- It is not possible to properly re-evaluate 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 the 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 paper. 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 the time frame of 2-3 years. However, policies of free data access could and should be reinforced before that. Without such reinforcement in data availability, it will remain difficult to resolve the water controversies in India.

Acknowledgements

The study forms part of the research project on the assessment of the National River Linking Plan (NRLP). The project is funded by the Challenge Program for Water and Food. Some of the Figures for this paper have been produced by S. Gunasinghe and M. Anputhas (both of IWMI-Colombo). Continuing data acquisition efforts by Dr. A. Gaur and Mr. K Anand (both of IWMI-India) are gratefully acknowledged. The authors are grateful to Dr H. Turral (IWMI- Colombo) and to Prof. T. McMahon (University of Melbourne, Australia) for constructive comments on this paper.

References

Agricultural Finance Corporation Ltd. 2005. Indirasagar (Polavaram): A multipurpose major irrigation project. Vol 1: Environmental Impact Assessment (EIA) and Environmental Management Plan (EMP). Hyderabad, India.

Bharati, L.; Anand, B.K.; Smakhtin, V. 2007. Simulating water management scenarios for Godavari – Krishna inter-basin water transfer: The example of Polavaram-Vijayavada link. (in prep)

CWC- Central Water Commission. 2006. Integrated Hydrological Data Book (non-classified river basins). New Delhi, India.

Dams, Rivers and People. 2004. Vol. 1-2. South Asia Network on Dams, Rivers and People (SANDRP). www.narmada.org/sandrp

Bobba, A.G. 2002. Numerical modeling of salt-water intrusion due to human activities and sea-level change in Godavari delta, India. *Hydrological Science Journal*, 47 (S): S67-S80.

Inter-basin Water Transfer. 1999. Proceedings of the International Workshop. UNESCO, Paris, April 25-27, 1999. IHP-V Technical Documents in Hydrology. Document No. 28. UNESCO Paris.

Malini B.H.; Rao K.N. 2004. Coastal erosion and habitat loss along the Godavari delta front – a fallout of dam construction. *Current Science*, 87(9) 1232-1236.

McMahon, T.A.; Adeloye, A.J. 2005. Water Resources Yield. Water Resources Publications, LLC, Colorado, USA.

Sarma, V.V.L.N.; Murali Krishna, G.; Malini, B.H.; Rao, K.N. 2001. Landuse / land cover change detection through remote sensing and its climatic implications in the Godavari delta region. *Journal of Indian Society of Remote Sensing* 29: 85-91.

Smakhtin, V.U. 2001. Low-flow hydrology: a review. *Journal of Hydrology* 240 (3/4): 147-186

Smakhtin. V.U., Anputhas, M. 2006. *An assessment of environmental flow requirements of Indian river basins.* Research Report 107, International Water Management Institute, Colombo, Sri Lanka: IWMI.