Natural Flows Assessment and Creating Alternative Future Scenarios for Major River Basins of Peninsular India

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Summary

The current study focuses on the six major peninsular basins of India namely, Brahmani-Baitarni, Cauvery, Godavari, Krishna, Mahanadi and Narmada, for estimating natural flows and residual flows under different scenarios to investigate whether 'surplus' water is available in these basins and also to assess the limits of utilization of massive water transfers.

The first part of the study uses the recent historical flow and information, about water use and other anthropogenic changes in the water cycle, to establish a monthly 'Natural Flows' series for the basin. This is done by using a simple hydrologic model of the land phase, incorporating a linear groundwater reservoir, and incorporating the anthropogenic changes. The concept of natural flows is being used as a 'peg' while proceeding from the current condition to the likely future condition.

The second part, aims to assess the likely future alternate water situation and process the monthly time series of natural flows as established in the first part. The objective was to test the ability of the basin to support alternative possible development scenarios, while maintaining an acceptable level of residual flows. Therefore, different alternate development scenarios are worked out and incorporated in the model. The operation of the reservoir capacity is adjusted, to ensure the availability of a positive, or, if necessary, 'above a threshold' flow. Simultaneously, the water use is increased to a level where sustaining the use and maintaining the residual flows becomes impossible, and failures occur in some years. By adjusting the incidence of the failures (in meeting the specified demands) to an acceptable level, the 'limit of water use' under the scenario is established. The 'limits of utilization' is determined not only by natural flows and the engineering-agronomic constraints, but also by the manner in which the utilization is achieved, including the environmental constraints. Thus, according to the authors, a simple concept of a fixed 'utilizable flow' is inadequate.

The analysis was to be done for the hydrologic and developmental environments as expected in the year 2025. The natural flows as would occur in that year, as well as the initial conditions (the storage available at the beginning of the year) cannot be known. Since a series of natural flows for about 15 years (as established in the first part) was available, the analysis

was done for these years by holding the development level as stationary. This allows the depiction of the role of 'over the year' storages in dealing with the good and bad sequences of flows. For all the peninsular basins, covered in the study, the 'business as usual' condition was tested for 'low development' (completion of storage facilities under construction) and 'high development' (taking up and completing additional contemplated storage facilities), without any emphasis on any improved water management. In addition, tests were also conducted in scenarios in which the water management was improved by reducing waterlogging through improved drainage and its reuse (the WM-2 scenario), and also by efficiency improvement and large adoption of micro-irrigation techniques (WM scenario). Two additional environmental-friendly variants of the WM scenario in which a minimum 'low flow' is maintained throughout (EFR-Low scenario), and in which sizeable floods are also maintained (EFR L & H scenario) were also tested.

The study has brought out that considerable dependable surplus flows are available under all future scenarios in the Brahmani-Baitarni, Godavari, and Mahanadi basins, even after considering the current and committed imports and exports. These surpluses could be mopped up in planning the larger interbasin water transfers. The average annual natural flows, as established in the study, are shown in Table 1.

Table 1. Flows in 10^9 m^3 per year.

Basin	Brahmani-Baitarni	Cauvery	Godavari	Krishna	Mahanadi	Narmada
Average annual observed Flow	31.0	14.9	80.3	19.9	58.3	34.6
Average annual estimated natural flow	36.9	25.4	122.1	74.0	74.1	46.7

The uses, as projected for 2025, in regard to the domestic and industrial use, which were comparatively smaller, were not varied across the scenarios. The differences among scenarios were mainly in the agricultural uses and in the environmental flow requirements. The agriculture uses were limited, but were relevant because of the availability of the 'culturable land', the impracticability of irrigating the entire culturable land including high plateaus, and because of the limits imposed by cropping calendars on land occupancy. Table 2 illustrates the information of the limits of possible net irrigation areas (million hectares).

The maximum NIA possible indicates the physical limit imposed by land availability alone, without considering the constraints imposed by the available water. While considering the constraint on the land for agriculture, the impracticability of irrigating all the land including the high plateaus has been considered. The water availability constraint is considered later, through the modeling process as shown in the other columns.

The 75 % dependable surplus flows as available from the basin under the projected uses, is 16.03 $*10^9$ m^3 in Brahmani-Baitarni Basin, 14.55$*10^9$ m^3 in Godavari Basin and 19.19 $*10^9$ m^3 in Mahanadi Basin under WM-scenario. Thus, the study has brought out that considerable dependable surplus flows are available under all future scenarios in the Brahmani-Baitarni, Godavari, and Mahanadi basins, even after considering the current and committed imports

Table 2. Limits of possible net irrigation areas (NIA), in different scenarios (NIA in million hectares).

River basin	Present NIA possible	Maximum	BaU-LD	BaU-HD	WM	WM-2	EFR-LOW	EFR-L & H
Brahmani-Baitarni	1.27	1.74	1.71	1.71	1.71	1.71	1.71	1.71
Cauvery	2.27	3.78	3.37	3.40	3.75	3.75	3.62	3.45
Godavari	5.35	12.43	8.70	10.53	11.75	10.40	11.60	10.61
Krishna	3.31	13.94	4.76	5.25	6.92	6.08	6.35	4.98
Mahanadi	2.46	5.9	3.82	4.06	5.79	5.05	5.79	5.79
Narmada	1.94	4.08	2.95	2.95	2.95	2.95	2.95	2.95

and exports. These surpluses could be mopped up in planning the larger interbasin water transfers (Annexure 1 shows the flow duration curve).

The detailed results including the variable ‘limits of utilization’ across the scenarios, for the various concepts ‘utilizations’ are presented in the text. The main messages flowing out of the study are as follows.

1. In any water situation assessment, the concept of ‘utilization’ needs to be defined, and used consistently. The definition could be based on ‘withdrawals’ from the natural waters, the ‘evaporation- transpiration’, or any other factor. The quantum of the ‘returns’, and the possibilities of their use, and the quantum of the ‘inadvertent’ evaporation-transpiration also need to be assessed.
2. The concept of ‘maximum possible utilization’ for a basin is not good enough. It needs to be replaced by the concept of ‘limit of utilization’ under a specified set of possible actions and constraints.
3. In assessing future situations, a scenario building approach allows the investigation of these limits under alternate sets of actions and constraints; and thus aids in policy formulation.
4. In regard to agricultural water use through irrigation, the in-basin land availability and the limits on irrigated crop occupancy, and the practicability of trans-basin imports and exports, when considered together, would allow an assessment of the limits of utilization, as also the possibilities of additional interbasin water transfers.
5. In water-stressed basins, the ‘business as usual’ strategies are not sustainable. In basins with better water endowments, significant surplus waters would continue to be available, and these could perhaps be transferred.

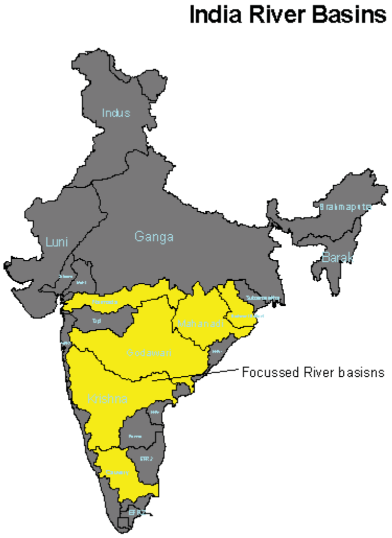
Introduction

India covers 2.4 % of the worlds land area. The fluvial water resources of India (1953*10^6 m^3) per year (Central Water Commission) are around 4.6 % of the global resource, whereas it supports 16 % of the world population. The distribution of water resources in the country shows variation over space and time. Over 80-90 % of the runoff in Indian rivers occurs in 4 months of the year, and there are regions of harmful abundance and acute scarcity (NCIWRD 1999). Managing the available water resources would be a great challenge for the country. Large consumptive use of waters, mostly for irrigation, both from the surface and the ground, is a distinctive feature of Indian water situation. The annual utilizable surface water and groundwater is estimated to be 690 km^3 and 432 km^3. (Amarasinghe et al. 2005). Future water management strategies rely both on in basin development and on large interbasin transfers.

This study[1] was undertaken for creating information that could be used in a later analysis of the proposed Indian strategy of large-scale interbasin water transfers. The immediate purposes were to demonstrate a methodology for estimating, from the available information, the 'natural' flows (annual, seasonal and monthly surface water and groundwater resources), and to use these for assessing the likely future scenarios, and the residual flows under each of these scenarios. Also, the development potential of the basins or the limits of possible use, through possible in-basin development, under different strategies, were sought to be established. Another purpose was to study how the limits of utilization, in terms of consumptive use, gets affected by the water management strategies. Inter-comparison of future water management strategies was also a purpose, which could support policy formulation. However, choice of a strategy was considered beyond the scope of the study.

The present study focuses on the six peninsular basins, (covering about 30 % of India's area, 29.2 % of its population and 17.6 % of its water resource.) in estimating the limits of utilization. The study covers the Brahmani-Baitarni, Cauvery, Godavari, Krishna, Mahanadi and Narmada basins (Figure 1). The salient features of the river basin are shown in Table 3.

Figure 1. Water resources – river basin-wise, NCIWRD1999.



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[1] The full text of this study is available on IWMI's website.

Table 3. Salient features of river basins studied.

Serial No.	River basins	Area (sq.km)	Percent of India's area	No. of states involved	Basin population (2001) (estimated)		Average annual water resources, (NCIWRD estimates)		Natural water resource per person.
					Thousands	Percent of Indian population	10^9 m^3	Percent of Indian resource	m^3/ person/ year
1	Brahmani-Baitarni	51,882	1.7	3	18,382	1.9	28.48	1.46	1,549
2	Cauvery Basin	87,900	2.7	3	35,097	3.5	21.36	1.09	608
3	Godavari Basin	312,812	9.5	5	85,351	8.6	110.54	5.66	1,295
4	Krishna Basin	258,948	8	3	73,968	7.5	69.81	3.57	943
5	Mahanadi Basin	141,589	4.3	4	29,690	3.0	66.88	3.42	2,252
6	Narmada Basin	98,796	3	3	19,144	1.9	45.64	2.34	2,384
Total for basin studied		951,927	29.2		261,632	26.4	342.71	17.55	1,310

The concept of 'an utilizable flow' is, much more complex than it appears to be. There is no uniformity in defining the use. The governmental sources in India, generally, define it in terms of 'withdrawals'. This is, however, less appropriate from a scientific-hydrologic viewpoint in view of the returns. The NCIWRD has realized this and has accounted for the returns while using withdrawals as a yardstick. The scientifically pleasing procedure of defining the use in terms of consumption (that is, the evaporationtranspiration) also does not solve the problem of a part of the return occurring into 'sinks' (or where, because of its quality, it has to be led to a 'sink'), and is not capable of future withdrawal and use.

Methodology

A good approach in the present and future water situation assessment is to model the complete land phase of the hydrologic cycle, through a model capable of depicting the likely future changes in the processes, caused by land use changes. Such an approach, as developed earlier (Gopalkrishnan et al. 2006) could not be followed in the present study in view of the large data requirements of that approach. In the present study, only the anthropogenic changes in the land phase of hydrologic cycle have been modeled and estimated.

The general hydrologic concept used by us is depicted below (Figure 2). This is for the 'Pseudo-Natural condition', under which human interventions through rain-fed agriculture are allowed, but other anthropogenic water cycle interventions through uses, including irrigation use, are not allowed. The hydrologic concept used in the current study under anthropogenically modified state of the basin is shown below (Figure 3).

In the present study therefore:

1. Rather than estimating the utilizable flow directly, broad development scenarios were conceptualized.
2. Scenarios were refined using the model, by adjusting the use (withdrawals) to a level which tests the limits of allowable use under the assumptions and constraints of the scenario. For all the scenarios so refined, we present both the (limiting) withdrawal and consumption (Figure 4).

Figure 2. Hydrologic concept used in the study (natural condition).

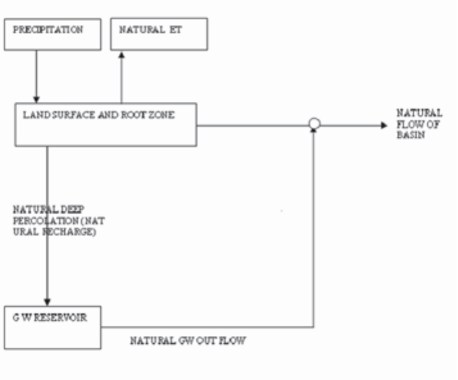
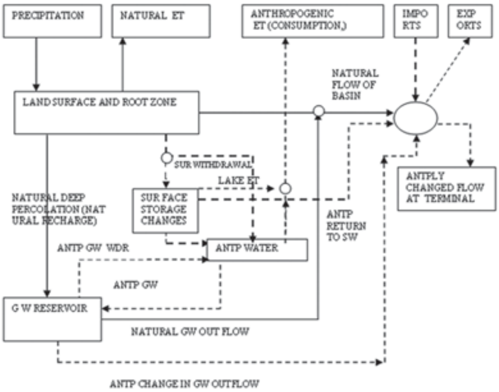
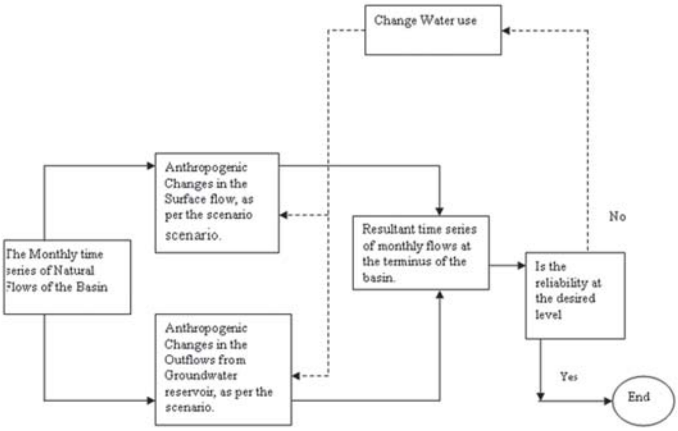


Figure 3. Hydrologic concept used in the study (anthropogenic condition).



Hydrologic Concept used in the study (Anthropogenic condition)

Figure 4. Scheme for refining a conceptual scenario.



Data Availability and Sources

Storage

Information about storage facilities under construction, storage facilities under consideration and ultimate irrigation potential in the basin was taken from CWC's water-related statistics (2004).

Runoff

The observed runoff, at or near the terminal site of the six basins, as a monthly time series from 1989 to 2003 was used in the first part to establish a monthly series of natural flows. In the second part, the natural flows so estimated were used for scenario analysis. For some basins, the series available was for a shorter period.

The period of minimum length data[2] required for assessing the reliability of a plan of development would depend on (i) the interannual variability of hydrologic data and (ii) the predominant type of the development, i.e., runoff of the river, within the year storage and over the year storage. Among the basins studied, the Krishna and Narmada have a predominant storage development with the carry over component as a significant proportion of the total. All other basins have predominantly a 'within the year storage'. Although a 40-year and 25-year long series of monthly flows would have been preferred for a planning exercise, for want of readily available data and in view of the time and resource constraints, the present study was based on a 15-year series.

Land Use and Irrigated Areas

This was obtained from the government statistics. However, a few changes had to be made in two basins, namely Krishna and Godavari, as the data from the government statistics were not consistent with the data obtained from other sources, e.g., remotely sensed data.

Reference Crop Evapotranspiration

The reference evapotranspiration figures for various locations in India and the rainfall figures for these locations were taken from www.iwmi.cgiar.org/WAtlas. Monthly information for 475 locations (districts) of India in regard to the following parameters was available. Penman ET- (minimum, maximum, mean, standard deviation) (mm/day for the month); Precipitation (50 %) (mm/day for the month); Precipitation (75 %) (mm/day for the month); and Moisture Availability Index (mm/day for the month).

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[2] The general Indian practice, in regard to the minimum length of data necessary for project planning is as follows: runoff of the river development -10 years, in weekly or 10 daily time units; within the year storage development - 25 years, in 10 daily or monthly time units; over the year storage development - 40 years, in monthly or seasonal time units.

The following procedure was adopted for analysis purpose,

A. Location-wise analysis

The mean value of the ET_0 (reference crop evapotranspiration) and the mean value of the precipitation (50 %) were chosen. The effective rainfall for the month was estimated from the mean monthly precipitation, using the USDA soil conservation service method. (FAO 1992).

The irrigation water requirements at the field level were calculated for K-crop (crop coefficient) values from 0.5 to 1.1 the location-wise analysis for multiple locations within each basin was important, since the irrigation water requirement computations are non-linear, and at each location, have a lower bound of zero. Lumping of these over a basin would ignore the requirements of those parts of the basin, where the potential evapotranspiration exceeds the effective rain, in situations in which the average requirement is less than the effective rain.

B. Basin-wise analysis

A list of districts which were relevant to each of the basin was prepared. For each month and for each K-crop value, the average irrigation water requirement for the basin was calculated using the list. As an illustration, the irrigation water requirement at the field for the Krishna Basin as a whole, as averaged from the 38 numbers of stations for crop coefficient 0.5 is shown in Table 4.

Table 4. Monthly irrigation water requirements for Krishna (millimeter).

Crop coefficient	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	June-Sept.	Oct-Jan	Feb-May
0.5	61.8	68.7	88.1	82	70.8	11	1.76	1.55	0	3.97	43	56.4	14.3	165	310

The predominant crop and its stage of growth guided the aggregated crop coefficient for any month, over all crops. As explained, the basin-wise aggregation was made after a distributed estimation of irrigation water requirements.

Lake Evaporation

Monthly lake evaporation depths for 19 stations within India (not very evenly distributed) were obtained from Central Water Commission (CWC). Using the data of the appropriate (generally, the nearer) station, and using the estimated lake area, the monthly quantities of reservoir losses (in the historical period) were estimated.

Estimating Total Live Storage Capacity

For major and medium reservoirs, which are the main source of storage facilities, live storage capacity data was readily available (CWC). For minor tanks, the storage capacity was estimated by an approximate analysis, which indicated that for irrigating thousand hectares, a live capacity of 3.5 $*10^6$ m^3 would have been built. When building up the future scenarios, the likely loss of capacity due to sedimentation was considered. As per our estimates, the total live capacity of the Indian reservoirs (2003) was 262.87 $*10^9$ m^3, and, the six basins under study had a total live storage of 125.9 $*10^9$ m^3.

Estimating Monthly Live-storages and Lake Areas

Of the total live storage of 125.9 $* 10^9$ m^3 available in the study area, about 67 $*10^9$ m^3, available in 36 of the comparatively larger reservoirs, is being monitored by the Central Water Commission (CWC). The monthly water level and live capacity information for each of the monitored reservoirs in the six basins were obtained from the CWC and were used to fit a logarithmic reservoir height-capacity curve for each. By differentiating this, a logarithmic area reservoir height-curve was also obtained. In the absence of the readily available data, the values of dead storage and elevation of the reservoir bottom were determined by trials and by using secondary information as available. In general, a very high coefficient of correlation around 0.99 could be achieved through trials. It was also ensured that, in general, the value of exponential in the reservoir height-capacity curve was within the normally acceptable range of 1.5 to 5.

Scenarios

The model built comprised five scenarios, namely BaU-LD; BaU-HD; HD-WM; HD-WM2; EFR-L; and EFR-L&H. None of the scenarios considered massive interbasin transfers beyond those existing at present, which are shown in the table below. The BaU-LD scenario considered a low level of future storage development, whereas other scenarios consider that most of the possible storages would be built by 2025. All the scenarios (except BaU LD and BaU HD) considered a massive drainage improvement to reduce waterlogging, and reuse of the drained water for irrigation as a future strategy. In addition, the HD-WM, EFR L and EFR L&H scenarios considered improvements in surface water distribution efficiency through canal lining etc. The provision of environmental flows in the low-flow season was included in EFR L. Additional environmental flows during the flood period were provided in EFR L & H.

Irrigation Efficiencies and Returns

The irrigation efficiencies (combined conveyance, distribution and application) and the distribution of excess withdrawals, based on the general experience in India, as assumed in the various scenarios, are abstracted below.

The overall surface water irrigation efficiency in the wet season (*kharif*—June-September) was assumed as 0.4 for the BaU conditions and was increased to 0.5 for the scenario with improved distribution. For the other non-wet seasons (*rabi*—Oct-January and hot weather—February-May) the corresponding values were 0.3 and 0.4. For groundwater irrigation, higher efficiencies, ranging from 0.6 to 0.7 (June-October and November-January seasons) and 0.5 to 0.6 for the hot season (February-May) were assumed. Depending on the overall efficiency and irrigation water requirements the withdrawal from the surface or groundwater was computed. The excess of withdrawal over the additional evapotranspirational needs was accounted by dividing it in three parts, namely that lost as additional ET from anthropogenic swamps, that which returns to the surface water system ,and that which returns to the groundwater system. In the BaU scenarios, the distribution ratios were 0.4, 0.15 and 0.45, respectively; whereas in the other scenarios, which involved drainage improvements, the ratios were changed to 0.2, 0.2 and 0.6, respectively.

Domestic and Industrial Uses

The domestic uses depend on the population projections for 2025. For the present, we estimated these as follows. The averages of the ‘All India’ projections, low and high, as projected by NCIWRD for 2025 were used. These were segregated statewise, and also into rural and urban components. In doing so, the differences in the processes of population growth and urbanization, within the states were considered. The state-wise figures were converted to basin-wise figures, in the proportion of the state areas in each basin. Domestic and industrial uses were calculated by changing the current norms to more reasonable norms for 2025 situation.

The industrial requirements were projected through an approximate but elaborate study, which separately worked out the requirements for 11 types of major industries plus the general small-scale industries. The requirements for each type were partly related to the natural resource distribution and partly to the population growth. An overall increase of more than 400 % for the all India withdrawal figures between 2000 and 2025 was assumed in the BaU type scenarios. In the scenario depicting improved water management, the consumption levels were kept the same as that of BaU type, but with improved water use efficiency, the withdrawal and the return figures were reduced.

The Model Operation, Including the Reservoir Operation

1. The approach was to decide, beforehand, the development parameters of the scenario (storage capacity, imports and exports), the agro-climatologic parameters (ET_0, ETcrop, Effective rainfall), the water management parameters (efficiencies and distribution of excess withdrawals) and also the ecology-related constraints (environmental flows—both low flows and floods), and then to vary the use-related parameters, (target irrigation areas) to estimate the limits of use within the acceptable reliability. Even within the use-related parameters of a scenario, the domestic and industrial uses were held at a prescribed level, and only the irrigated areas were changed in the ‘trial and error’ procedure for investigating the limits of development. Each basin would be having a large number of major, medium, and minor reservoirs, however, in this generally lumped model of the basin, all reservoirs were lumped into a single reservoir. The approximations involved in such lumping were dealt separately as described in (5) below.
2. The reliability: As per the prevalent Indian practice, the failures in meeting the targets of irrigation, on an annual basis, of less than 25 %, was allowed. The failure percentage, on a crop-year basis was also computed. Irrigation failures were managed by reducing irrigated areas during a failure.
3. The storage facilities were so operated that as much water as possible is held back for future use, after meeting the requirements for uses, and also the requirements for

EFR (Low Flow) and EFR(High Flow) as specified in the scenario. The storage operation was done in a recursive way.

4. Failures were imposed mostly in surface irrigation, and even in these, failures in *rabi* and hot weather were imposed before imposing failures in the subsequent *kharif* and in perennials.

5. The maximum practicable value for the transient storage has the upper bound in terms of the available live capacity, in 2025, under the scenario. However, the limiting storage was assumed to be at 90 % of the live capacity. Similarly, the minimum practicable live storage may not reach the physical bound of zero live capacity. An integrated operation, across political units, may not be fully achieved. Even within a unit, isolated reservoirs may not be operated to cater to deficits much downstream. A small carry-over to cater to a delayed monsoon may be preserved even in the face of a current overall deficit. Considering all these, we kept a small minimum live storage limit of around 1,000 million cubic meters in all scenarios, in the studies. Both these corrections represent an attempt to overcome modeling limitations involved in considering a single lumped reservoir, instead of the distributed reservoirs within the basin.

6. The suggested operational pattern was then used to compute the residual flows for the basin, as also the residual flows at a critical point near the basin outlet. Often, initially, the residual flows included some monthly flow values, which were below the EFR threshold, or were negative. In such cases:

    - Cuts on irrigation areas were applied from the earlier post-monsoon period .Cuts in other seasons were also imposed, if necessary, until the physically impossible negative flows were eliminated. As the hydrologic and storage situation improves with time, beyond the bad run, the cuts in forthcoming seasons become unnecessary.

    - Considering the short period of simulation, it was necessary to leave an ‘end of the period’ storage at a level not far below the average storage for that month. Apart from the number of failures, this became an important consideration.

    - The irrigation area targets were increased or decreased, if the failures were too few or too many, as compared to the criterion of 75 % annual reliability of irrigation. . An account of the cuts, as imposed, was kept, to work out the reliability.

    - The ‘critical point’: All balances were done for the basin as a whole. However, the availability of non-negative (or above threshold) flows at the basin outlet does not imply such conditions at all places in the upstream. Balances had to be worked out at one or more points which may be critical from the water depletion considerations. The decision about which point is to be considered as ‘critical’ would require some knowledge of the basin. For most studied basins, the withdrawal-related stresses occur in the middle and lower portions, since upper parts are comparatively wet, and have less withdrawal. Hence, critical conditions would be occurring at points downstream of the last large withdrawal, and balances at such points were worked out.

Environmental Flows

The environmental flows, as used, were more for demonstration, and a qualitative depiction. No scientific studies based on the ecologically desirable hydrologic regime were available. In the two scenarios, EFR-Low and EFR-L&H, an environmental flow corresponding to about 10 % of the lowest average monthly flow was provided as the low flow which needs to prevail throughout. In addition, a high season EFR that caters to maintain the flood regime of the river to a limited extent, and thereby maintain the geomorphology of the river is also provided for, in the EFR-L&H scenario. The total volume of this High Flow EFR in all wet months in a year was kept at 40 % of the maximum of the average monthly flows. Environmental flows, as used for the various basins are shown in Table 5.

Table 5. Monthly environmental flows, $10^6 m^3$.

Basin	Brahmani-Baitarni	Cauvery	Godavari	Krishna	Mahanadi	Narmada
EFR-L in all months	68	49	150	106	66	49
EFR-L and H (Increased flow in July-Sep, were relevant)	1,157	644	4,915	2,704	3,558	2,134

Results

Natural Flows and Residual Flows

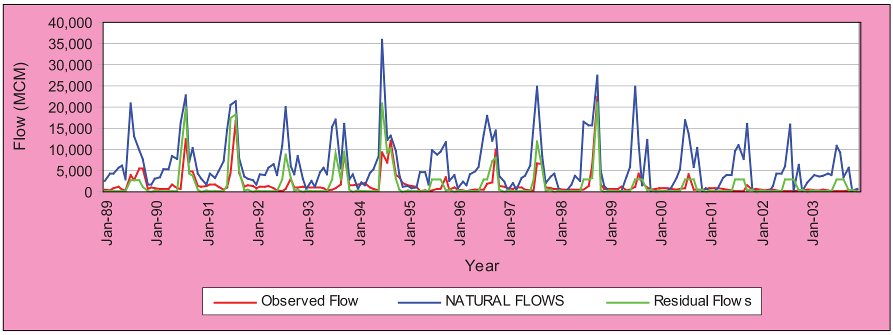
The natural flow series was combined with the expected 2025 development condition under different scenarios to work out the likely flows available at the critical point. The residual flows were worked out after considering the environmental flow requirement as also the needs for reducing utilization by inducing failures of an acceptable nature, in the low-flow years. The results in terms of averages are shown below (Table 6).

Table 6. Observed, natural and residual flows estimated.

Basins	Observed flows, average (1990-2004), 10^9 m^3			Estimated natural flows, average, 10^9 m^3			Estimated residual flows, average,(EFR-L and H) 10^9 m^3		
	Monsoon	Non-monsoon	Total	Monsoon	Non-monsoon	Total	Monsoon	Non-monsoon	Total
Brahmani-Baitarni	20	11	31	26	11	37	17	4	21
Cauvery	6	6	12	13	15	28	2	2	4
Godavari	62	18	80	90	32	122	41	9	50
Krishna	9	10	19	45	29	74	17	5	22
Mahanadi	44	14	58	53	21	74	30	7	37
Narmada	26	8	34	36	10	46	13	3	16

As an illustration, depicting the monthly variability, the estimated natural flow and the estimates of the residual flows under the EFR-L&H scenario for the development condition of 2025 in regard to the Krishna Basin is shown in Figure 5. Similar comparison, under the EFR-L&H scenario for other basins were also carried out.

Figure 5. Comparison of observed, natural and residual flows (EFR-L&H) (2025 condition), $10^6 m^3$, Krishna Basin.



Limits of Utilization

Limits on Land Utilization: In Indian river basins where water utilization is largely linked to agricultural development and utilization of the land resources, the limits of utilization can flow out of either the land resources available in the basin or the water-related endowments of the basin. The basin-wise constraints are depicted in Table 7.

Table 7. Constraints on net irrigated area (NIA) (Mha) as used in the study.

Basin	Present			Max possible NSA in 2025*	Unavoidable rain-fed area++	Max possible NIA in 2025+
	Culturable area	NSA	NIA			
Brahmani-Baitarni	2.00	1.94	1.27	1.94	0.20	1.74
Cauvery	5.22	4.07	2.27	4.18	0.40	3.78
Godavari	18.04	14.39	5.35	14.43	2.00	12.43
Krishna	19.29	13.19	3.31	15.44	1.50	13.94
Mahanadi	8.37	5.98	2.46	6.70	0.80	5.90
Narmada	5.00	4.68	1.94	4.68	0.60	4.08

Notes: * Max possible NSA in 2025 was calculated as the Max of the present NSA and 80 % of the culturable area

++ Unavoidable rain-fed area, figures are based on the impracticability of irrigating the high plateau and cutup lands devoid of groundwater and, are not related to water availability constraints

\+ Max possible NIA in 2025, as shown in this table represents the physical upper limit, without considering the constraints imposed by water availability

The Limits on Water Utilization:

The limits of utilization in terms of withdrawals for in-basin use, in-basin consumption and in-basin useful consumption for the six basins for all the scenarios are presented in Table 8.

Table 8. Limits of annual utilization – 2025 ($10^9 m^3$).

	Basin	Brahmani-Baitarni	Cauvery	Godavari	Krishna	Mahanadi	Narmada
BaU-LD	As withdrawal for ‘in-basin’ use	20.3	41.0	95.1	68.3	49.3	39.5
	As ‘in-basin` consumption	13.4	25.6	64.8	52.8	32.9	27.0
	As ‘in-basin’ useful consumption	8.6	16.1	41.6	28.3	21.1	15.4
BaU-HD	As withdrawal for ‘in-basin’ use	23.1	41.4	107.9	76.3	63.0	39.5
	As ‘in-basin` consumption	15.5	25.9	74.2	57.7	42.1	27.0
	As ‘in-basin’ useful consumption	9.8	16.3	47.6	31.0	25.7	15.4
WM	As withdrawal for ‘in-basin’ use	21.3	40.5	106.0	79.3	61.3	38.7
	As ‘in-basin’ consumption	13.8	25.3	73.6	57.7	40.0	27.0
	As ‘in-basin’ useful consumption	10.9	19.7	46.0	39.7	31.5	21.1
WM-2	As withdrawal for ‘in-basin’ use	28.4	50.1	109.4	85.2	73.6	45.5
	As ‘in-basin` consumption	15.6	26.3	75.1	54.9	40.3	27.4
	As ‘in-basin’ useful consumption	11.5	19.3	48.1	35.3	29.2	20.0
EFR-L	As withdrawal for ‘in-basin’ use	21.3	39.2	105.3	75.1	54.2	35.6
	As ‘in-basin` consumption	13.8	24.6	73.1	54.8	34.9	25.1
	As ‘in-basin useful consumption	10.9	19.2	45.6	37.1	27.0	19.5
EFRL & H	As withdrawal for ‘in-basin’ use	21.3	37.0	94.2	58.3	62.3	27.7
	As ‘in-basin consumption	13.8	23.4	65.9	45.38	39.1	20.10
	As ‘in-basin’ useful consumption	10.9	18.2	41.0	29.56	30.3	15.17

Dependable Surpluses: The model yields monthly water balances for each year of simulation for each basin and under each scenario. This also includes the water available in each month, at the critical point near the end of the basin, over and above that required to meet the demands (including the curtailed demand in failure years) and the environmental flow requirements. From this monthly information, the annual surpluses have been computed and this information has been further abstracted as the 75 % dependable annual surpluses. These are presented in Table 9. Seventy-five percent dependable annual surplus flows at critical stations, over and above environmental thresholds is also depicted graphically in Figure 6.

Water Balances: As stated above, monthly water balances, year-wise, basin-wise and scenario-wise are available. As an illustration, useful abstraction, the annual water balances for the WM scenario for Narmada Basin for one year (1992) is shown in Table 10.

Table 9. Seventy-five percent dependable annual surplus flows at critical stations, over and above environmental thresholds (10^9 m^3).

Basin	BaU-LD	BaU-HD	WM	WM-2	EFR-LOW	EFR-L & H
Brahmani-Baitarni	16.62	14.40	16.03	14.53	15.09	11.83
Cauvery	0.12	0.12	0.12	0.12	0.12	0.12
Godavari	21.61	13.29	14.55	12.55	13.39	5.26
Krishna	0.12	0.12	0.18	0.12	0.12	0.12
Mahanadi	29.20	19.79	19.19	21.13	23.94	13.47
Narmada	0.12	0.12	0.12	0.12	0.12	0.12

Figure 6. Limits of use out of total endowment of 37 BCM, Brahmani-Baitarni Basin.

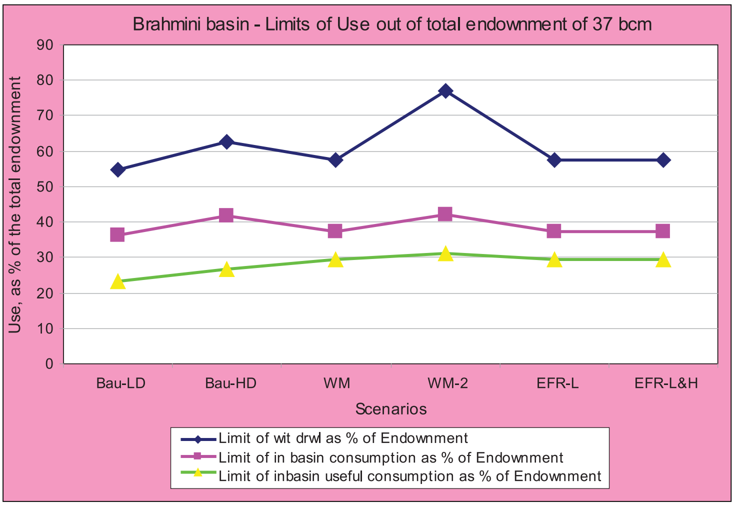


Table 10. Overall water balance for one year (year like1992) (WM scenario), for Narmada Basin (all fig. in $10^6 m^3$).

Basin	Natural flows	Imports	Total resource	Surface with-drawls	Return to surface	Surface storage filling	Reservoir evaporation	Exports	Subtotal, reductions in resource through surface water	Reduction in resource through GW	Total reduction in resource	Residual outflow
Narmada	34,059	0	34,059	18,143	3,668	-4,479	2,487	11,000	23,483	8,490	31,973	2,086

The anthropogenic changes in the groundwater regime are also revealed in the body of the results. Under the anthropogenic changes there would be both additional anthropogenic recharge and additional anthropogenic withdrawals (by pumping) for use. This has quality and quantity implications. On the quantitative side, if the anthropogenic recharge is less than anthropogenic withdrawals, the average GW regime will change by making corresponding reductions, as compared to the natural state, in its outflows. If the GW outflows decrease a new dynamic steady state will be achieved through a reduction in GW level and storage, to strike a new balance through a reduction in the base flow. This will have both social and environmental implications, since some deep-rooted trees may be drawing water from the GW reservoir. To understand this in comparative terms, we compared the anthropogenic changes in the groundwater inflows and withdrawals for each scenario. Any plan of water use in any scenario that required large reductions in GW base flow, as compared with the natural situation, were not accepted. The comparison in regard to the Krishna Basin for a year like 1992 under the 2025 situation is shown in Table 11.

Table 11. Krishna Basin—anthropogenic changes in groundwater regime (all fig. in $10^6 m^3$) for 2025 development condition and 1992 natural hydrologic situation.

Scenario	BaU-LD	BaU_HD	HD-WM	HD-WM2	EFR-L	EFR-L&H
Annual anthropogenic GW withdrawal	26,037	26,037	23,561	31,855	20,386	19,333
Annual return to GW, including anthropogenic returns	16,799	19,158	22,509	27,920	21,952	16,006
Consequent reductions in base flow, as compared with 'natural'	9,238	6,879	1,052	3,939	-1,206	3,327

Note: The scenarios were so adjusted that these regime changes do not appear unacceptably large.

Target Irrigation Areas and Failures in Irrigation

As stated, the target irrigation areas for different scenarios, for each of the basin along with the distribution of these areas in the seven crop seasons, were decided by trial and error. This was done so as to obtain the following:

- acceptable residual flows on the downstream;
- acceptable number of failure years in which the targets are required to be reduced (around 25 % of the total years in the simulation);
- acceptable level of the storage at the end of the simulation; and
- acceptable anthropogenic changes in the groundwater table.

The summarized results for all basins and scenarios are given in Table 12.

The net irrigation possible in each basin under each scenario, as compared with physical limit on the net irrigation possible is depicted in the Table 13. This clearly brings out that for the Krishna Basin, its endowment in terms of land does not get utilized in any scenario because of the limited water endowment; whereas in Cauvery, Narmada, as also in the Godavari , much of the land endowment can be effectively used in the WM scenario. In all these four basins, the irrigation area has to be reduced significantly if environmental constraints are added to the WM Scenario. As a contrast, the Mahanadi Basin, where again, improved water management

Table 12. Target irrigation areas (1,000 hectares) by scenarios basin-wise.

	BaU-LD	BaU-HD	HD-WM	HD-WM2	WM-EFRL	EFR-L &H
Brahmani-Baitarni						
Total GIA	2,500	2,600	2,800	2,800	2,800	2,800
Total NIA	1,708	1,708	1,708	1,708	1,708	1,708
Cauvery						
Total GIA	3,835	3,874	5,110	4,810	4,940	4,650
Total NIA	3,365	3,398	3,750	3,750	3,620	3,450
Godavari						
Total GIA	10,440	12,340	13,920	12,528	13,800	12,392
Total NIA	8,700	10,525	11,745	10,397	11,595	10,614
Krishna						
Total GIA	5,750	6,364	8,381	7,375	8,291	6,034
Total NIA	4,760	5,250	6,920	6,080	6,350	4,980
Mahanadi						
Total GIA	5,780	6,360	9,180	8,180	8,216	8,216
Total NIA	3,818	4,064	5,789	5,050	5,789	5,789
Narmada						
Total GIA	4,000	4,000	5,200	5,100	4,755	3,850
Total NIA	2,951	2,951	3,830	3,830	4,024	3,442

Table 13. Limits of possible irrigation areas, in % of max possible NIA.

Basin	Presen-t	BaU-LD	BaU-HD	WM	WM-2	EFR-LOW	EFR-L & H
Brahmani-Baitarni	73	98	98	98	98	98	98
Cauvery	60	89	90	99	99	96	91
Godavari	43	70	85	94	84	93	85
Krishna	24	34	38	50	44	46	36
Mahanadi	42	65	69	98	86	98	98
Narmada	48	72	72	94	94	99	84

is necessary for the full use of the land endowment, no irrigation is required to be given up while imposing environment-related restrictions. The Brahmani Baitarni Basin is so richly endowed with water, that all land can be irrigated in all scenarios.

The incidence of failures could be computed in two ways. There are seven possible crop seasons, which we have considered. These are the three 4-monthly crop seasons, three possible 8- monthly crop seasons and the perennial crops. These seven crop seasons irrigated from two sources (SW and GW) in the 15 years of simulation represent 210 source season years.

The percentage of source season years involving failures among these is one measure. Without considering the seasons, and the source, the number of years would be 15 and the percentage of failure years in another measure. The computations have been done using both measures. As an illustration, the failures for Krishna are depicted in Table 14.

Table 14. Failures in all scenarios, Krishna Basin.

Summary of failures	BaU-LD	HD	HD-WM	HD-WM2	WM-EFRL	EFR-L &H
KRISHNA						
Percentage by source-season-years	6.19	7.14	8.10	8.57	6.19	6.67
Percentage by years	20	20	20	20	20	33.33

Basin-wise Results

As an illustration, some details of the results for Brahmani-Baitarni Basin are presented below. The Brahmani-Baitarni Basin has an estimated average natural flow of 37x 10^9 m^3. No imports and exports are contemplated in the present study and thus the total endowment is 36.9x 10^9 m^3. The Figure 6 shows that in terms of useful in-basin consumption, only 30 % of this water can be used in WM, WM-2, EFR-L and EFR-L&H and the consumption would be lesser in other scenarios. In terms of total in-basin consumption only about 40 % of the endowment would get consumed as evapotranspiration. In terms of withdrawal, the WM-2 scenario would be able to withdraw around 77 % of endowment, whereas the scenarios with better water management (WM, EFR-L, and EFR_L&H) would require a withdrawal of 57 % of the withdrawal.

The basin has a current net sown area 1.94 Mha, which we assume would continue upto 2025, with some 0.2 Mha as the unavoidable rain-fed area in plateau lands without enough groundwater, the maximum NIA would be around 1.74 Mha against the present NIA of 1.27 Mha. The full available area has been proposed to be irrigated in all future scenarios. Thus land and not water is the constraint for in-basin use in the Brahmani-Baitarni Basin. In terms of GIA, we have assumed that for the NIA of 1.7 Mha the GIA cannot exceed 2.8 Mha. With the assumed cropping pattern having perennial and two seasonal crops hardly any irrigable land would be lying unoccupied in the *kharif* season. The occupancies as resulting from assumed cropping pattern are shown in Figure 7.

As mentioned, the land and not water is the restriction in the in-basin use in Brahmani-Baitarni Basin. Table 15 shows the 75 % dependable surplus flows at critical station over the environmental flow for Brahmani-Baitarni Basin and different scenarios.

Thus for Brahmani-Baitarni Basin a dependable surplus of 16.68*10^9 m^3 is available in the BaU (low development) scenario which decreases to 14.46 * 10^9 in the BaU (high development) scenario. With more efficient water use through water management activities, the surplus can be increased to 16.09*10^9 in WM scenario. However, when the low-flow EFR constraint is used, the surplus reduces to 15.15*10^9 m^3 when both low-flow and high-flow constraints for environmental flow are imposed, the surplus reduces to 11.89 * $10^9 m^3$.

Figure 7. Brahmani-Batarni: WM scenario—occupancies under assumed cropping pattern.

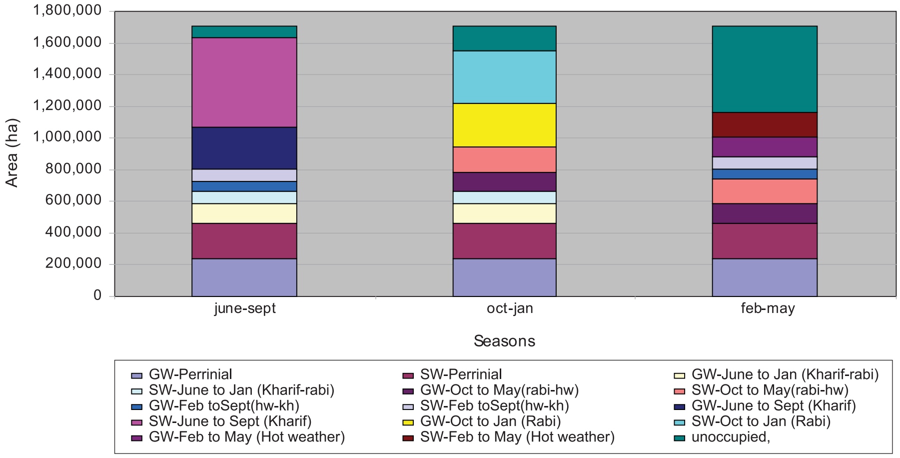


Table 15. Seventy-five percent dependable surplus flows at critical station, over and above environmental thresholds.

Basin	BaU-LD	BaU-HD	WM	WM-2	EFR-LOW	EFR-L & H
Brahmani-Baitarni	16.68	14.46	16.09	14.60	15.15	11.89

Concluding Remarks

The main purpose of the study was to demonstrate the process of scenario building, and of the assessment of the basin water situation for the scenarios. The process involved a conceptualization of the scenario, and its refinement to obtain the desired reliability in meeting the water use and environmental targets, through trial and error.

Another purpose of the study was to build alternate developmental scenarios for the six peninsular basins. This was to be done both for the purpose of a demonstration purpose, and also for generating good information about the capability of the basins in supporting in-basin development, with and without additional large interbasin transfers.

An important purpose of the study was to investigate the utilizable resources of the basins without considering additional interbasin transfers. As stated in the paper, the authors feel that the 'utilizable resource' is a complex concept, which depends, among other considerations, also on how the utilization is done and, therefore, the concept of the variable, 'limits of utilization' needs to be preferred. These limits would depend both on the basin characteristics and on the developmental strategies. The limits on both the withdrawals and the consumption under each scenario have been presented in Tables 8, 12 and 13 and they show a large variation among the scenarios.

The studies clearly bring out that the water resources of the Brahmani-Baitarni, Mahanadi and Godavari basins, and that their water endowments are far more than what could be used in the basins even after considering the current and committed imports and exports, and possible future uses. Thus, these basins are candidates for supporting additional water transfers without reducing the in-basin use possibility.

In regard to the Narmada Basin, where large exports from the basin are already envisaged, the studies bring out that the full potential of in-basin development for irrigation cannot be achieved, particularly in the low-development and high-development scenarios of the 'business-as-usual' strategy. Almost the full development can be achieved in the scenarios involving improved water management (The WM, WM-2, EFR-L and EFR-L&H scenarios). Thus for the full in-basin development of Narmada, either improved water management practices need to be installed or some reduction in the already committed export needs to be considered.

The studies establish that for Krishna and Cauvery basins, the water endowments are not enough to reach the full in-basin development potential. The Krishna Basin, even under these circumstances, is currently an exporting basin. Considerable water is being exported to Pennar and other east flowing rivers. The current study has not covered these basins which import the Krishna waters and it is likely that both equity and marginal productivity considerations would justify such exports even from a basin, which is not rich in water endowments. The basin also exports water for hydroelectric purposes, to the already water-rich west-flowing rivers. Thus there is a case for either reducing the exports from or increasing the exports to the Krishna Basin. Similarly, there is a strong case in considering new imports to the Cauvery Basin.

The study brings out the impracticability of continuation of the 'business as usual' approach in the water-stressed basins, by bringing out the effects on the limits of utilization, as also the effects on groundwater regime and on residual flows.

The study has also shown that the scope for in-basin development only through construction of additional storage-based projects is rather limited in the Krishna, Cauvery and the Narmada basins. This is because on one hand the basins of Krishna and Cauvery already have built a large number of storage facilities so that the marginal utility of additional storage facilities would be comparatively less (in both cases the terminal reservoirs hardly ever spill and the basins are effectively closed), and on the other hand because there are hardly any significant storage facilities remaining to be built. For the Narmada also, large storage projects are under construction and these would be completed in the next few years; after which there is hardly any scope for in-basin storage facilities.

The current studies have been done under some data limitations and assumptions. While the studies may have to be repeated when better data and information becomes available, the authors believe that the overall conclusions are unlikely to change substantially.

The limits of development of all the six basins under the six scenarios have been established, and the surplus water available in the three well endowed basins of Brahmani-Baitarni, Mahanadi and Godavari have been computed. However, large-scale plans for further water transfers, somewhat on the lines of the current plans of the National Water Development Agency (NWDA) have not been investigated in the current studies. While the dependable surpluses can be exploited, however, these are available mostly in the monsoons. Their use may require the construction of additional storage facilities in the surplus basin or the transfer of floodwater into additional storage facilities elsewhere, as well as changes in the current reservoir operation and in-basin uses. These possibilities may constrain the use of all the surplus water. This aspect requires a separate study as a continuation of the present one.

A separate scenario HD-WM2 which focuses only on drainage improvement and reuse has been created, and one of the main purposes of water development is to increase the useful consumption of water within the hydrologic, engineering, land-availability-related, and environmental-related constraints. The comparison of the WM and WM2 scenarios is presented in Table 8.

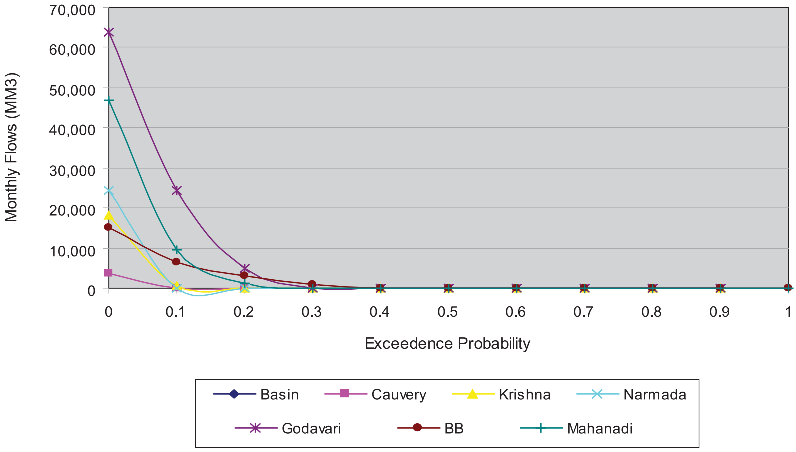
The study shows that it is difficult to maintain the environmental flows and, in particular, the environmental flows for maintaining the flood regime, in the relatively stressed basins, without reducing other uses. For example, in the Krishna Basin a useful in-basin consumption through irrigation $35.3*10^9 m^3$ is possible in the WM scenario and this gets reduced to $29.6*10^9 m^3$ for the EFR-L&H scenario. The desirability of providing a large environmental flow requirement is to be considered against these consequent reductions in in-basin consumptions. The societal preferences in this regard need to be established through studies, debates and trade- offs in a multi-stakeholder and multidisciplinary environment.

The study allows a comparative analysis of the scenarios, by developmental and environmental objectives, for each of the studied basin. While the choice of appropriate scenarios is considered outside the scope of the present study, such an analysis will allow the decision maker to reach the decision, or at least to shortlist a few scenarios for further socioeconomic analysis. To illustrate this point, a comparative analysis for the Krishna Basin has been included in the detailed report (www.nrlp.iwmi.org) and is abstracted below.

- The BaU LD scenario for Krishna involves an unacceptable groundwater regime and indicates that a large fall in groundwater table would take place under this scenario.
- The BaU HD scenario for Krishna indicates that with increased storage, and increased surface irrigation, without corresponding increase in groundwater irrigation, a slightly better groundwater regime can be expected.
- The HD-WM scenario for Krishna indicates, that with improvements in drainage as also water distribution efficiency, a still better groundwater regime can be obtained along with the largest possible irrigated area among the scenario. However, low flows would be too low.
- The HD-WM2 scenario for Krishna indicates, that if only the drainage improvements is done without canal efficiency improvements the irrigated area would have to be some what lower than the HDWM scenario.
- The EFR-L scenario for Krishna indicates, that as compared to WM scenario, significant irrigation has to be given up for maintaining the low flows. In the process, the groundwater regime, in this scenario is the best among all. However, the incidence of spills is the least among all scenarios and this may have adverse effects on the ecology and morphology.
- The EFR L & H scenario for Krishna indicates, that both in terms of consumption and possible irrigation, this scenario, indicates a situation in between the BaU LD and BaU HD scenarios. Thus, all the effort in improved water management through the drainage improvements and distribution efficiency improvements, and a part of the efforts in creating additional storage, go only towards the maintenance of environmental flows in both the low flows and high flows. The groundwater regime, is not as good as in the WM scenarios. However, spills or controlled flushing floods would be available each year.

Annexure-1.

Residual flows at critical point above threshold for WM scenario-flow duration curve.



Annexure 2.

Terminology

In India, due to marked seasonality in rainfall, seasonal crops are very common. These are roughly 4-month crops; the wet season (south-west monsoon, June-Sept, *kharif*), the autumn season (Oct-Jan, *rabi*) and the dry-hot season (Feb-May, hot weather) are common. Nomenclatures and the calendar can vary. Also, apart from perennial, some two season crops also prevail.

The 'gross cropped area (GCA)' indicates the total cropped area (rain-fed and irrigated) and includes the area which is cropped more than once. If and only the irrigated area is so counted the nomenclature used is 'gross irrigated area (GIA)'.

The 'net sown area (NSA)'is the geographical area which is under crop, at least for some time, during the year. If only irrigated area is counted the geographical coverage is known as 'net irrigated area (NIA)'. (Note that these intensity-related parameters do not really depict the intensity of occupation. For example, if the whole area of 100 ha were fully occupied in an year under sugarcane, the GCA would have been only 100 ha and the cropping intensity would have been 1.0, but if the land was fully occupied in June-September, occupied to 50 % in October - January, and occupied to 10 % in February-May, under seasonal crops, the GCA would have been higher at 160 ha.

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