INDUS BASIN IRRIGATION SYSTEM: WATER BUDGET AND ASSOCIATED PROBLEMS

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Abstract

Around 74% of mean annual river flows (140 MAF) are diverted to the canal system and the rest flows to the Arabian Sea (19%) or contribute to the river system losses (7%). Efficiency of the canal irrigation system is extremely low, as 53% of water (55MAF) is lost in conveyance through canals, watercourses and field channels. Thus system conveyance efficiency is only 47%. The loss of 55 MAF of canal water in conveyance to the fields can be translated to a financial loss of around Rs. 3.3 billion per annum assuming a value of Rs. 60 per acre-foot of water based on existing *"Abiana"* rates. In terms of pumped water cost it will be around Rs. 55 billion per annum. In-efficient application of water in basin/flood irrigation contributes to around 25% of water losses in fields. This is mainly due to un-levelled fields and un-scheduled irrigation without considering the management allowed deficit based on crop and soil needs. Total loss of water in conveyance and field application (around 64% of canal diversions and 32% of groundwater) is not only loss of water but it also adds to waterlogging and salinity. Acute shortage of freshwater forced farmers to exploit groundwater by installing tubewells and thus use of marginal to brackish quality groundwater resulted in secondary salinization and increased dependence on energy. The loss of productivity in the IBIS due to waterlogging and salinity was estimated as 25% of total crop productions. The GNP of crops in Pakistan is over Rs. 355 billion per annum. Thus the production loss due to waterlogging and salinity can be estimated as around Rs. 88 billion per annum. Around 10% of the irrigated area within canal commands is severely affected due to waterlogging and salinity and value of land is now much lower than the productive lands and in certain cases it is only 10% of the problem free lands. This is a financial loss to farmers and their families and an economic loss to the country.

1. Introduction

1.1. Land, Climate and Water

The Indus river basin stretches from the Himalayan Mountains in the north to the dry alluvial plains of Sindh in the south. The area of Indus basin is 364515 miles^2. The vast alluvial plains of the Indus basin (the Indus plains) cover an area of 79959 miles^2. The relatively flat plain is largely made up of deep alluvium deposited by Indus River and its tributaries.

The climate in the Indus plain is mainly semi-arid to hyper-arid. In lower Indus plain, December to February is the cold season. The mean monthly temperatures vary from 14-20°C. Mean maximum temperatures during March to June vary from 42-44°C. In the upper Indus plain mean annual temperature ranges from 23-27°C. Daily temperature ranges from to 23-49°C during the summer months and from 2-23°C during winter.

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Average annual rainfall in the Indus plain is about 9 inches. In lower Indus, Larkana and Jacobabad areas receive on the average about 3.5 inches of rainfall annually. In the upper Indus plain, Multan receives 6 inches and Lahore about 20 inches of rain. Because of hot climate, evaporation rate is very high and mean annual evaporation in lower Indus plain (Nawabshah) is 80 inches while in upper Indus plain (Sargodha) it is 65 inches.

Primary source of surface water is precipitation in the form of rainfall and snow and the glacier melt. Glaciers in the upper Indus basin are the largest outside the polar region and serve as natural storage reservoirs that provide the snowmelt to river Indus and its tributaries.

Soils in the whole of the Indus plain consist of deep (mostly over 1000 feet) deposits of unconsolidated and highly permeable alluvium brought in by Indus River and its tributaries. The alluvium mass is mostly homogeneous and forms highly transmissive aquifer. Recharge to the aquifer in the Indus plain is through rainfall and deep infiltration from the irrigated fields and seepage from earthen irrigation channels. Presently, estimated groundwater extraction from the aquifer is almost equal to the recharge in fresh groundwater areas although the balance between recharge and abstraction is not uniform across the basin.

Mainstay of Pakistan's economy is the irrigated agriculture in the Indus plain. At the time of partition in 1947, population of Pakistan was about 33 million with about 80% residing in the rural areas. The population of West Pakistan in 1965 was 51.2 million (18% urban, 82% rural). The present (1999) population of Pakistan is about 134.5 million with a rural ratio of about 67%.

1.2. River System

Indus river system can be divided into western rivers (Indus, Jhelum and Chenab) and the eastern rivers (Ravi, Beas and Sutlej). This division came into effect at the time of settlement of water dispute between India and Pakistan in 1960. Total flows of western rivers belong to Pakistan while India has the right to flows of eastern rivers. All the rivers of the Indus system are perennial. The first record of gauge heights was made on the Indus at Attock in 1848. The next was on Chenab at Alexandria Bridge in 1879. The most important river gauging stations, called the rim-stations have continuous discharge data from early 1920s when the Indus Discharge Committee was established for this purpose

1.3. Indus Basin Irrigation System

Indus Basin Irrigation System (IBIS) is the largest contiguous irrigation system in the world developed over the last 140 years. The lengths of main canals, branches, distributaries and minors are 2628, 4246,16073 and 11920 miles, respectively, servicing the IBIS through around 110,000 watercourses. The irrigation system is supported by 3 storage reservoirs, 19 diversion structures (headworks/barrages) and 12 link canals transferring water from western rivers to canals previously taking their supplies from eastern rivers now assigned to India. IBIS commands a cultivable commanded area (CCA) of about 34.5 million acres out of which about 12.25 million acres are under command of Mangla and the remaining 22.25 million acres under Tarbela command. IBIS layout is presented in **Figure 1**. Starting from early 1960s, IBIS was augmented/remodelled under the Indus Basin Project (IBP) as a consequence of the Indus Waters Treaty of 1960 (World Bank 1960).

2. River Flows and Canal Diversions

2.1. Variability of Inflows to the Basin

Variability in river flows is a major limitation in the development of run-of-river type irrigated agriculture in the Indus Basin, especially to meet crop irrigation requirements during low flow period of the *Rabi* season and early and late *Kharif* season.

Period of 1968-96 was considered to represent the post-storage scenario. This also helped to have at least 28 years of data for the probability analysis. The probability analysis for the *Rabi* season represents the period from October to March (6 months), whereas the period from April to September (6 months) represents the *Kharif* season. The annual probability analysis represents period from April to March (12 months) and in anyway it is not summation of the seasonal probabilities. The western rivers provided 131 million acre-feet (MAF) of surface water in an average year during the post-storage period (Mangla and Tarbela), that was 6.4% less than the pre-storage period. Bulk of the river flow was during the *Kharif* season, which was around five times the flows in the *Rabi* season. Variability in flows of the eastern rivers was even higher than the western rivers. After the construction of Mangla and Tarbela dams and major diversions by India, the eastern rivers contributed about 8.7 MAF of water to the Indus river system in an average year of which about 77% was in the *Kharif* season. Annual contribution of the eastern rivers to the Indus river system was about 6%, whereas it was 5.6% during the *Rabi* season (**Table 1**).

The mean inflows to the Indus River System are in the order of 140 MAF based on 50% probability of occurrence. The arithmetic average is not appropriate, as there is no average year prevailing in nature. Every year will behave either below, above or close to the average. Thus 50% probability was used as an average indicator of the river flows.

Table 1. Variability of inflows (Rim-station) to the Indus River System for post-Mangla period (1968-96)

Probability(%)	**Rim-station Inflows (MAF) for Post-Mangla Period 1968-96**						
	Western Rivers			**Eastern Rivers**			**Total Annual**
	Kharif	***Rabi***	**Annual**	***Kharif***	***Rabi***	**Annual**	
Minimum	**76.1**	**16.1**	**93.1**	**1.9**	**0.0**	**2.9**	**96.0**
10	90.4	16.5	109.8	3.0	0.7	4.3	114.1
25	100.6	19.4	124.1	4.1	0.9	5.8	129.9
50	110.2	22.0	131.3	6.6	1.3	8.7	140.0
75	120.3	23.9	146.5	10.3	1.9	12.5	159.0
90	129.4	26.6	153.6	15.0	2.8	16.3	169.9
Maximum	**147.4**	**30.6**	**166.9**	**16.5**	**6.2**	**19.3**	**186.2**

Data Source: Water Resource Management Directorate, WAPDA.

2.2. Indus Basin Canal Diversions

The canal diversions in the IBIS represent total amount of water diverted at all the barrages constructed on rivers of the IBIS. Considerable increase in canal diversions of about 7.3 MAF was observed during the post-Mangla period. Further substantial increase of around 9.8 MAF was observed during the post-Tarbela period. Out of this, the major increase was in the *Rabi* season (7.7 MAF per annum) as shown **Table 2**. The increase in the *Kharif* season in represents increased diversions in the early when river flows are relatively less (April period and May).

Table 2. Historical canal diversions to the IBIS under key-influences (1940-98).

Key Influences	Period	Canal Diversions (MAF)		
		Kharif	*Rabi*	Annual
Pre-Partition	1940-47	47.4	20.2	67.6
Partition	1947-48	46.2	22.4	68.5
Dispute	1948-60	51.4	24.6	76.0
Pre-Mangla	**1960-67**	**60.1**	**27.5**	**87.7**
Post-Mangla	**1967-75**	**65.1**	**30.1**	**95.1**
Post-Tarbela	1975-80	67.8	38.1	105.9
Post-Tarbela	1980-85	68.1	37.2	105.3
Post-Tarbela	1985-90	66.1	37.6	103.7
Post-Tarbela	1990-95	66.0	38.3	104.3
Post-Tarbela	1995-98	67.7	37.9	105.6
Post-Tarbela	**1975-98**	**67.1**	**37.8**	**104.9**

Data Source: Water Resource Management Directorate, WAPDA.

The average annual canal diversions were around 105 MAF in the IBIS during the period of 1975-98. The canal diversions are based on the capacity of the canals and the available river flows at a particular instance.

There was variability in the canal diversions in both the seasons. The percent variability between the highest and lowest post-Tarbela canal diversions was 25 and 17 % during the *Kharif* and the *Rabi* seasons, respectively. Tarbela dam was designed to provide more secured *Rabi* diversions by transferring the *Kharif* season water to the *Rabi* season in a given year. Therefore, the variability for the *Rabi* season was lower than the *Kharif* season. However, given the relatively small size of the reservoir compared to the annual discharge of the river, it is not possible to carry over the water of a wet year to a dry year. This shows that stochastic nature of the river flows also has an effect on the canal diversions, in addition to the reduced storage capacity of Tarbela (**Table 3**). The canal diversions at 50% probability were around 103 MAF, and the same was used in this study instead of the average value of around 105 MAF.

Table 3: Variability of post-Tarbela canal diversions in the IBIS (1975-98)

Probability (%)	Canal Diversions (MAF)		
	Kharif	*Rabi*	Annual
Minimum	**57.3**	**34.8**	**94.4**
10	58.5	35.4	96.3
25	61.6	36.0	98.9
50	65.6	38.0	102.4
75	68.2	38.6	105.8
90	71.0	39.4	109.0
Maximum	**71.3**	**40.7**	**109.7**

Data Source: Water Resource Management Directorate, WAPDA.

3. Irrigation System's Losses

3.1. River System Gains and Losses

Indus rivers flow through alluvial plains and thus the phenomenon of losses and gains assumes significant importance (Ahmad 1993a). In the Indus river system, losses generally occur in the rising stage during the period from April to July. During the falling flows, covering the periods from end of July to September and from October to March, the rivers usually gain water from base-flow. Analysis of annual historic gains and losses was conducted using the data between the period from 1940-41 to 1997-98 for the *Kharif* and the *Rabi* seasons (**Table 4**).

Table 4: River gains and losses in the Indus River System

Period	River Gains and Losses (MAF)		
	Kharif	***Rabi***	**Total**
Pre-Mangla 1940-67	-16.4	4.6	-11.8
Pre-Tarbela 1967-76	-8.7	3.0	-5.7
Post-Tarbela 1976-98	-11.6	0.8	-10.8
Average 1940-98	-13.2	2.9	-10.3

Source: Water Resource Management Directorate, WAPDA

3.2. Canal Command Losses

Kennedy (1895) was the first to report, quantitatively, the seepage loss in the irrigation canals in the Indian subcontinent. He stated that 47% of the total water supplied to the irrigation system is lost before it reaches the farmers. Kennedy estimated seepage losses from main canals to be of the order of 9.9 cfs/mft^2.

Earlier studies revealed that conveyance losses in canals varied between 15-30% (Ahmad 1993a; Harza 1963; IACA 1966; LIP 1966). The Water Sector Investment Planning Study (WSIPS) of 1990 provided a synthesis of the work done by WAPDA (1979) on annual canal conveyance losses for 24, 5 and 14 canal commands in the Punjab, NWFP and Sindh provinces, respectively. The average annual canal losses computed were 23, 12 and 20% for the canal commands of the Punjab, NWFP and Sindh provinces, respectively. These losses were around 21% for the whole basin. The losses to the canal system become gains to groundwater in a global context, otherwise energy is required to pump water. In addition to this it is not possible to retrieve the canal loss from the aquifer with same quality of freshwater.

Systematic work on watercourse loss measurement was initiated jointly by the Colorado State University, USA and WAPDA. Based on the two systematic studies of 40 and 61 watercourses, the actual watercourse losses were 47 and 45%, respectively. The field application losses were around 25% (Ashraf *et al.,* 1977; WAPDA 1979; Trout and Kemper 1980; PARC-FAO 1981). Thus, the overall irrigation efficiency of the IBIS was around 36% (Ahmad 1993b).

4. Water Budget

Seasonal and annual river flows in the Indus river system are highly variable (Warsi, 1991; Kijine *et al.,* 1992; Ahmad, 1993b; Mohtadullah, 1991). The analysis of the daily and monthly flows also indicated a similar trend (Bhatti, 1999). This variability in river flows affects the diversion of water to the canal system even in the post-storage period of 1968-99 (WCD 2000). This variability further complicates the assessment of water budget for the Indus basin. Even with this high variability in river flows and canal diversions, the experts have presented the water budget considering the average values of flows and canal diversions (Ahmad 1993a; Ahmad 1993b; WSIP 1990).

Due to the stochastic nature of river flows, the concept of probability of river flows and canal diversions at 50% level was used in formulating the water budget for the Indus basin. The 50% probability means that at this probability there is 50% chance of having flows of less than the predicted value.

Annual river flows to the Indus basin are around 140 MAF at 50% probability. This shows that there is 50% chance that annual river flows will be less than 140 MAF. The river system losses are around 10 MAF. At 50% probability, around 103 MAF are diverted to canals per annum. This leaves 27 MAF, which flow to Arabian Sea at the 50% probability level. The flow to Arabian Sea would reduce to 17 MAF at 25% probability. Furthermore, there would be hardly any flow to Arabian Sea at 10% probability, if 103 MAF are diverted to the canals. These are the physical limitations for further development of water in the IBIS.

The canal conveyance losses are around 25% and therefore 26 MAF is lost in the canal system. Thus only 77 MAF is available at the watercourse head. The "Watercourse" refers to the "*Sarkari Khal*" only and does not include the farmers' channels. The average watercourse losses are assumed to be around 30% (23 MAF) leaving only 54 MAF available at the farm gate. This means that out of the canal diversions of 103 MAF, 49 MAF is lost in the conveyance of canal water. The loss of 49 MAF of water although not available for crops but it helps to recharge the groundwater.

Groundwater in the Indus basin is now extensively used through over 500,000 private tubewells and pumping around 50 MAF even after the transition of the public tubewells (GOP 1999). This makes 104 MAF available at the farm gate. Conveyance losses in farmer's field channels are assumed to be around 10% primarily due to shorter channel lengths. Therefore, around 10 MAF is lost in the field channels. Thus 94 MAF is available for meeting field gross irrigation requirement.

Basin irrigation is predominantly practised in the Indus basin. The fields are normally not levelled and irrigation is not scheduled based on the management allowed deficit. Thus the field application losses are around 25% (24 MAF). This leaves only 70 MAF available at field level for crop consumptive requirement. This can be considered as net irrigation water available for crops consumptive needs.

The contribution of effective rainfall in the Indus basin is estimated as 13 MAF (Ahmad 1993b). Therefore, total water available for crop consumptive requirement is 83 MAF, which contributes to meet water requirement of around 35 million acres in the Indus basin. The flowchart of the water budget of the Indus basin is presented in **Figure 2**.

5. Irrigation Efficiency

Irrigation efficiency of the Indus basin irrigated agriculture is described in segments covering canals, watercourses, field channels and field application sub-systems. The research studies conducted in Pakistan in the last three decades measured basin-wide efficiencies for various sub-systems (WAPDA 1979; PARC-FAO 1981). The acceptable efficiencies of various sub-systems at basin-wide level are described as under:

- Ø Basin-wide canal conveyance efficiency is around 75% covering main canals, branch canals, distributaries and minor canals.
- Ø Watercourse conveyance efficiency of the "*Sarkari Khal*" is around 70%. This value is assumed against the overall conveyance efficiency of 60%, accepted both for watercourse and field channels. This change would help to have more precise estimates for the farm level sub-system, especially after the transition of the SCARP tubewells.
- Ø Field channel conveyance efficiency is around 90% for farm level channels used for both canal and tubewell supplies. Length of farm channels is a function of farm size and normally small compared to watercourses. Thus higher efficiency is assumed for the basin. However, for larger farms, this efficiency will be relatively lower.
- Ø Field application efficiency is around 75% covering application and uniformity losses within the field.

For estimation of overall irrigation efficiency of the Indus basin, efficiencies of the four sub-systems can be multiplied using the relationship:

$$E_I = E_C * E_{WC} * E_{FC} * E_A$$

E_I = Irrigation Efficiency at the basin level

E_C = Canal Conveyance Efficiency at the basin level

E_{WC} = Watercourse Conveyance Efficiency at the basin level

E_{FC} = Field Channel Efficiency at the basin level

E_A = Field Application Efficiency at the basin level

Using the above relationship, the basin-wide overall irrigation efficiency is:

$$E_I = 0.75 * 0.70 * 0.90 * 0.75$$
$$E_I = 35.4 = 36\ \%$$

Overall irrigation efficiency at the basin level is around 36%, which is low as 64 % water is lost before it is consumptively used by crops.

6. Problems Associated with Irrigation

Low irrigation efficiency of canal irrigation system is one of the major causes having low productivity of agriculture in the Indus basin. The major problems and constraints affecting productivity of the Indus basin are:

- Ø High water table due to seepage from canals, watercourses, field channels and fields is affecting productivity of around 42% of the basin area (WAPDA 1979). There is seasonal and temporal variability due to occurrence of wet years. The extent of waterlogging and salinity was reduced in 1999-2000 due to severe drought and extensive pumping of groundwater.
- Ø Rise of water-table in the basin area also resulted in accumulation of salts in surface and profile affecting 26 and 39% area due to surface and profile salinity, respectively, in 1980, which to some extent was reduced in the last two decades.
- Ø Secondary salinization is prevailing in the basin, which is due to the use of marginal quality (saline and/or sodic) groundwater. It is a major cause for salt buildup in the basin and situation will deteriorate further due to the enhanced use of brackish groundwater.
- Ø The loss of productivity in the IBIS due to waterlogging and salinity was estimated as 25% of total crop productions, whereas 10% of the irrigated area within canal commands is severely affected and value of land is now much lower than the productive lands. The GNP of crops in Pakistan is over Rs. 355 billion. Thus the loss due to waterlogging can be estimated as around Rs. 88 billion per annum.

The waterlogging and salinization of soils was mainly due to either inefficiency of the irrigation system or associated shortages of freshwater which has forced farmers to start using marginal to brackish quality groundwater. Out of 103 MAF diverted to canal system only 37 MAF is available for crop consumptive use. Out of the losses of 66 MAF, about 50 MAF is recovered through groundwater and thus only 16 MAF can be considered as a loss based on global context of efficiency. These losses in high water-table areas also contribute to crop water requirement as sub-irrigation.

Canal water must be seen in the context of a resource, which is highly valuable as irrigation in the IBIS is practiced through gravity and without using any energy. In addition to this, any loss of canal water is not retrievable in quality terms through pumping. The energy input required for pumping adds to the production cost. Energy in Pakistan is costly and tariff on electricity and prices of diesel fuel will further increase in the future.

Analysis made by the author in a recent study based on the electricity rates provided by the National Electric Power Regulatory Authority (NEPRA) indicated that cost of pumped water to grow wheat is around Rs. 1750 per acre compared to the *Abiana* of Rs. 60 per acre of wheat grown. This comparison clearly highlights the need to save canal water to maintain profitability of canal irrigated agriculture. Any further inefficiency in the canal irrigation system would force farmers to increase their dependence on groundwater. Recently, the government has drawn back the subsidy on electricity for tubewells, therefore, cost of pumping will further increase in the near future.

The IBIS is characterized as a continuous-flow and fixed-rotation irrigation system. Problems and constraints related to the system's operational management are:

- Ø Adequacy is a serious concern as water available from canals is generally not sufficient to support cropping intensity of more than 70% within existing framework of management.

- Ø Equity is a primary concern as availability of water at the tail-end reaches is extremely low compared to head reaches primarily due to seepage and operational losses.
- Ø Reliability is affecting the system due to shortage of water and thus fixed-rotation is practiced in a continuous-flow system. In addition to this, the water allocation made for the perennial canals is not sufficient to meet peak demand of prevailing cropping patterns.

The most critical factor is the concept of *'Warabandi'* practiced for allocation of water to farmers on a particular watercourse. The formula of *'Warabandi'* is based on time equity, because conveyance loss function was never considered. Same time is allocated per acre for farmers located both at head and tail reaches. This formula is based on the assumption that canals are completely sealed for zero seepage to have volume equity in water distribution. Time equity does not ensure availability of allocated water to tail end reaches.

7. Conclusions

Around 74% of mean annual river flows (140 MAF) are diverted to the canal system and the rest flows to the Arabian Sea (19%) or contribute to the river system losses (7%). Efficiency of the canal irrigation system is extremely low, as 53% of water (55MAF) is lost in conveyance through canals, watercourses and field channels. In-efficient application of water in basin/flood irrigation contributes to around 25% of water losses in fields. This is mainly due to un-levelled fields and un-scheduled irrigation without considering the management allowed deficit based on crop and soil needs. Total loss of water in conveyance and field application (around 64% of canal diversions and 32% of groundwater) is not only loss of water but it also adds to waterlogging and salinity. Acute shortage of freshwater forced farmers to exploit groundwater by installing tubewells and thus use of marginal to brackish quality groundwater resulted in secondary salinization and increased dependence on energy.

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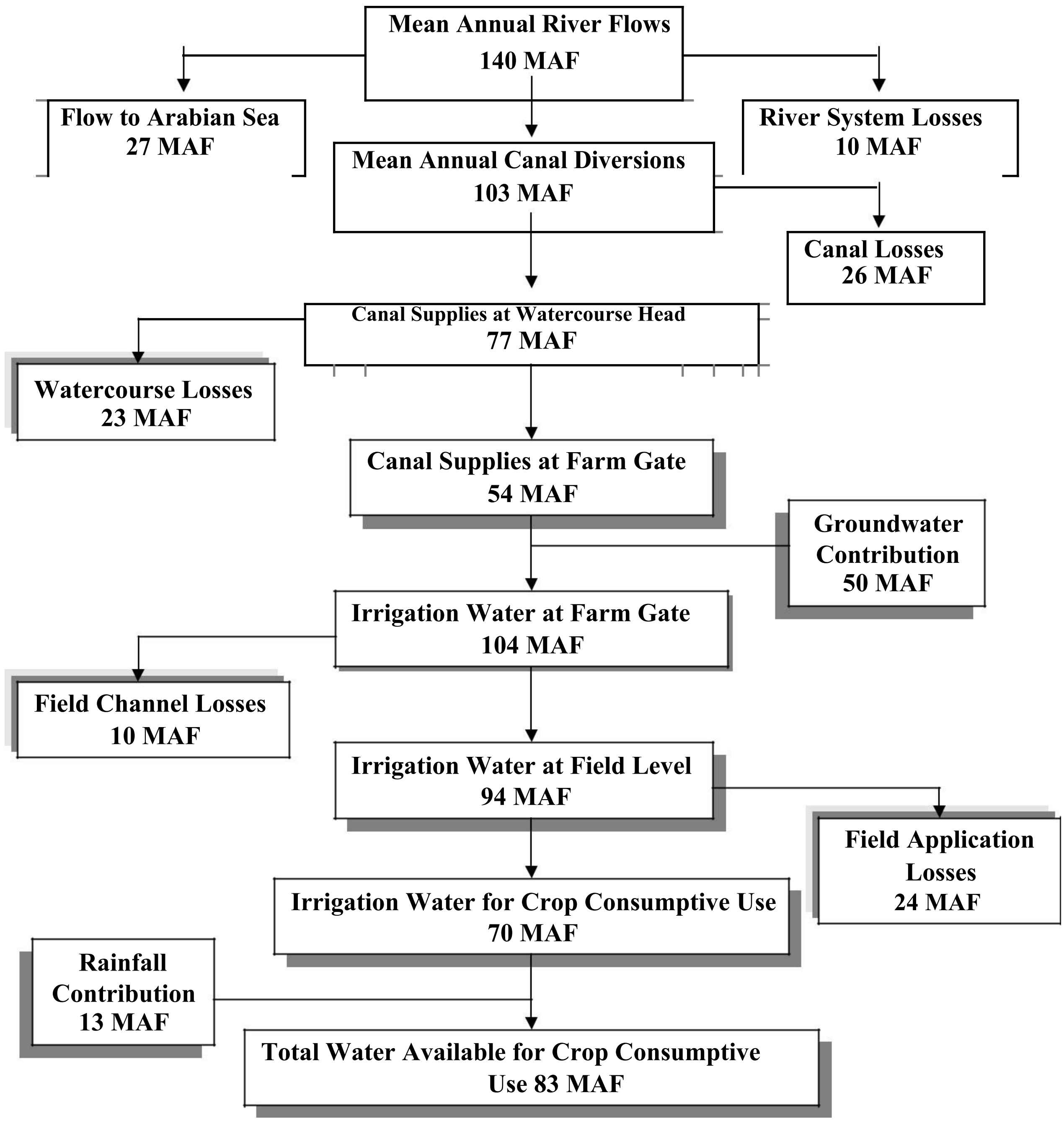

Figure 2. Water Budget of the Indus Basin Irrigation System, Pakistan, based on 50% Probability of both Annual River Flows and Annual Canal Diversions.