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Water-use accounts in CPWF basins

Simple water-use accounting
of the Indus Basin

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1. ABSTRACT

This paper applies the principles of water-use accounts, developed in the first of the series, to the Indus River basin in South Asia. The Indus Basin covers 3 countries, rises in the Tibetan plateau in the vicinity of Lake Mansarovar in China. Irrigated agriculture in the Basin is extensive with the construction of dams, barrages, and link canals to distribute water, with modern engineering to support irrigation starting as early as the mid 1800s.

Net runoff is about 10% of total precipitation. Irrigated agriculture covers 20% of the basin and use about 31% of the precipitation. Grassland is the most extensive vegetation, covering 45% of the Basin, consuming about 36% of the precipitation. Rainfed agriculture covers 14% of the Basin and uses about 15% of the water.

Changing irrigation efficiency from the currently assumed 40% to 60% and increasing the irrigated area by 10% has relatively little impact on water availability overall, since the water thus made available can be consumed downstream.

Keywords: Water use accounts, Indus basin, top-down modeling, basin water use.

2. INTRODUCTION

In this note, we describe a simple water-use account for the Indus Basin.

The Challenge Program on Water and Food aims to catalyse increases in agricultural water productivity at local, system, catchment, sub-basin, and basin scales as a means to poverty reduction and improving food security, health, and environmental security. It does this in several priority basins: the Indo-Gangetic Basin, the basins of the Karkheh, Limpopo, Mekong, Niger, Nile, São Francisco, and Yellow Rivers, and a collection of small basins in the Andes.

A useful output for each basin, and a key element of the understanding of basin function, is an overview water use account. Water use accounts produced in the same way for each basin would have the further benefit of making easier the development of syntheses of understandings from all the basins.

Here, we describe a draft water use account for the Indus Basin, developed as an Excel spreadsheet. Water use accounting is used at national (ABS 2004; Lenzen 2004) and basin (Molden 1997; Molden et al. 2001) scales to:

- Assess the consequences of economic growth;
- Assess the contribution of economic sectors to environmental problems;
- Assess the implications of environmental policy measures (such as regulation, charges, and incentives);

- Identify the status of water resources and the consequences of management actions; and
- Identify the scope for savings and improvements in productivity.

However, these accounts are static, providing a snapshot for a single year or an average year. Furthermore, they do not link water movement to its use. In contrast to the static national and basin water-use accounts referred to above, our accounts are dynamic, with a monthly time step, and thus account for seasonal and annual variability. They can also examine dynamic effects such as climate change, land-use change, changes to dam operation, etc. The accounts are assembled in Excel spreadsheets, and are quick and easy to develop, modify, and run. We have applied this accounting method to several major river basins including the basins of the Murray-Darling, Mekong, Karkheh, and Limpopo Rivers (Kirby et al. 2006a, Kirby et al. 2006b). Here we describe the application to the Indus River.

As we shall describe below, the account has been developed using existing data, and gives an overview of water uses within the Basin. There are some problems with the data, which we shall describe, and the account can be improved with better data and calibration. We recommend that, should it be intended to use the account for any purpose beyond developing an understanding of the broad pattern of water uses in the Basin, that effort be directed to obtaining better data.

3. BASIC HYDROLOGY AND OUTLINE OF SIMPLE WATER ACCOUNT

3.1. BASIC HYDROLOGY, IRRIGATION, AND LAND USE

The Indus Basin covers 1,218,500 km², and is drained by the Indus River and its tributaries (Figure 1 and Table 1). There are six major rivers in the Basin, the Indus, Jhelum, Chenab, Ravi, Beas, and Sutlej. The Western Rivers (Indus, Jhelum, and Chenab) supply the majority of water to the Indus Basin Irrigation System in Pakistan, except a small amount supplied from Kashmir in India. Flow from the Eastern Rivers (Ravi, Beas, and Sutlej) was granted to India by the Indus Water Treaty of 1960. Irrigated agriculture in the Basin is extensive with the construction of dams, barrages, and link canals to distribute water, with modern engineering to support irrigation starting as early as the mid 1800s. There are four major dams and barrages in the Basin; the Mangla Dam on the Jhelum River, and the Tarbela Dam, Marala Barrage, and Kalabagh Barrage on the Indus River.

Table 1. Catchments in the Indus Basin with their areas.

Catchment	Area, km ²
Tarbela	188,378
Nowshera	87,614
Kalabagh	25,085
Gomal	98,395
Marala	30,461
Mandi Plain	19,522
Sutlej	64,972
Ravi	32,701
Mangla	32,345
Jhelum Chenab	41,717
Panjnad	88,607
Rajasthan	120,453
Sukkur	98,497
Kotri	186,779
Estuary	12,981
Total	1,128,508

Both precipitation and potential evaporation in the Indus Basin vary markedly both in their temporal and spatial distribution (Figure 2). The monthly maximum potential evaporation (ET_0) occurs in May or June, during the early part of the rainy season. A large part of the annual precipitation occurs later in rainy season during June, July, August and September (Figure 2). Both the latitudinal extent of the Basin and the mountainous terrain to the north create a gradient of increasing potential evaporation from north to south (Table 2). Mean annual ET_0 is lowest in the Tarbela catchment (744 mm) and greatest in the Sukkur catchment (1880 mm). In contrast, annual precipitation tends to decrease towards the south of the Basin, with the Kotri catchment having the lowest mean annual rainfall of 175 mm (Table 2). In catchments of the Upper Indus Basin and foothills, mean annual rainfall exceeds potential evaporation, but on the Indus Plains mean annual potential evaporation is greater than the rainfall.

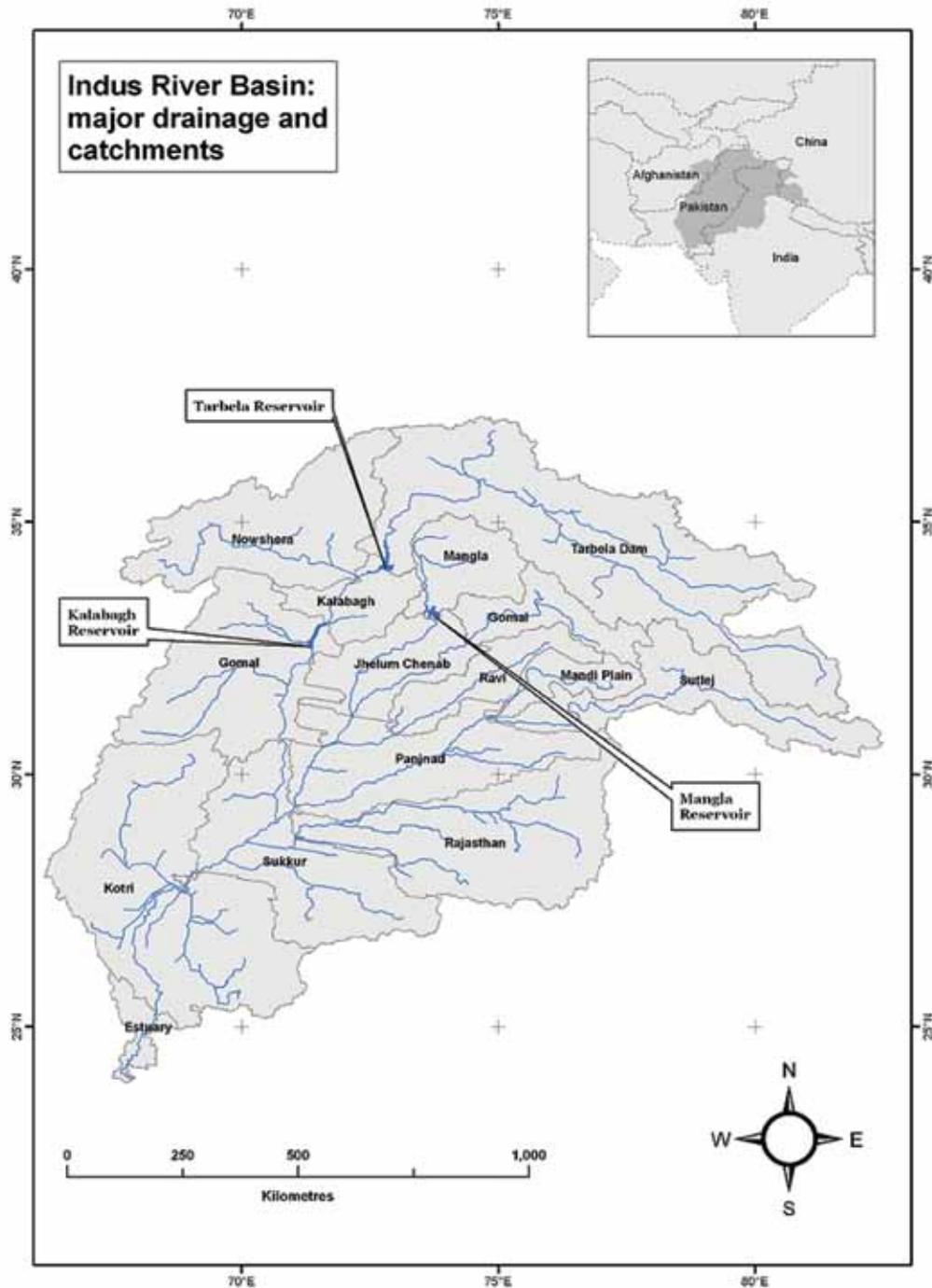


Figure 1. The Indus Basin, with the catchments used in the water-use account.

The wettest parts of the Basin are the Himalayan foothills of the Upper Indus Basin, with the Mandi Plain catchment receiving the greatest annual precipitation of 2140 mm. Annual variability in precipitation is greatest in the south of the Basin since the Indus Plains receive most of their precipitation during the monsoon from July to September.

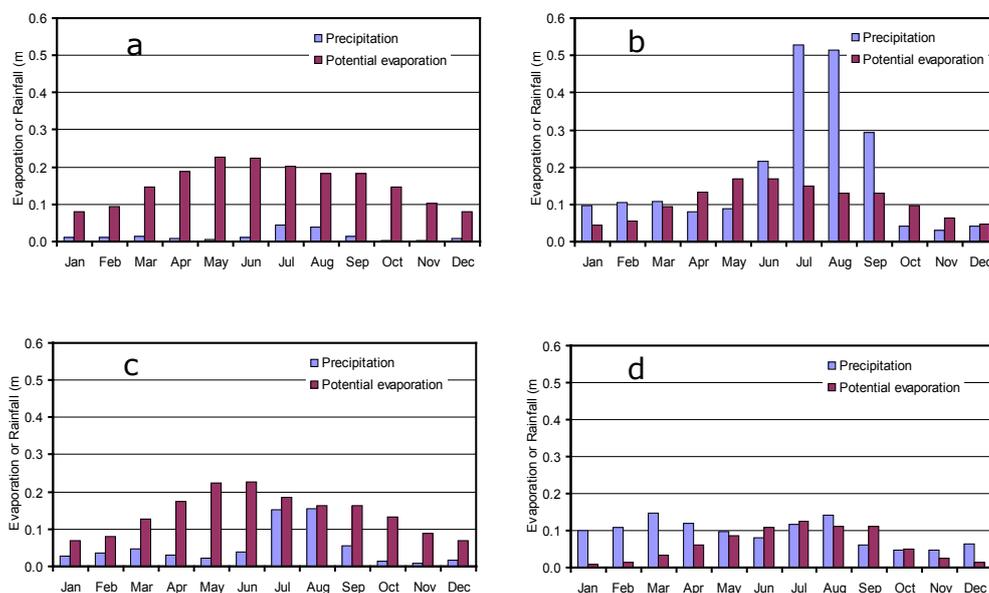


Figure 2. Monthly average precipitation and potential evaporation in the Indus Basin. a). Tarbela catchment in the north of the Basin; b). Mandi Plain in the east; c). Jhelum Chenab in the centre; and d). Kotri in the south.

Table 2. Mean annual precipitation and potential evaporation for Indus Basin catchments.

Catchment	Precipitation, mm	Evaporation, mm
Tarbela*	1130	740
Nowshera*	1450	1040
Kalabagh*	790	1560
Gomal	390	1530
Marala*	2100	1020
Mandi Plain*	2140	1280
Sutlej	640	970
Ravi	650	1550
Mangla*	1980	1070
Jhelum Chenab	600	1700
Panjnad	380	1780
Rajasthan	450	1770
Sukkur	220	1880
Kotri	180	1850
Estuary	190	1730

* Denotes modified precipitation (see Section 3d.)

The contrasting climatic conditions of the hotter, drier south of the Basin compared with the cooler, wetter north give rise to a strong contrast in the origin of flows leaving the northern and southern catchments. In the wetter, northern catchments, locally-derived runoff forms an important portion of flow from the catchment. In contrast, in the drier south, flows from upstream predominately contribute to discharge from the

catchment, and locally-derived runoff is less important. In all catchments there is a marked seasonal variation in flow, with peak flows occurring in the wet-season months June to September. The seasonality of flow derives partly from the monsoon rainfall, but also from ice and snowmelt in the mountainous areas of the Upper Indus Basin and the Himalayan foothills. Large variability between years in annual precipitation causes important variation in annual flows from the Indus catchments and hence in the Indus River itself.

3.2. SIMPLE WATER ACCOUNT

The simple water account has two parts:

- A hydrological account of the water flowing into the Basin (primarily rain), flows and storages within the Basin, and water flowing out of the Basin (primarily as evapotranspiration and discharge to the sea); and
- A further partitioning of the evapotranspiration into the proportion of evapotranspiration accounted for by each vegetation type or land use, including evapotranspiration from wetlands and evaporation from open water.

The simple hydrological account is based on a monthly time step, which we consider adequate for our purpose.

The account is a top-down model (Sivapalan et al. 2003), based on simple lumped partitioning of rainfall into runoff and infiltration into a generalised surface store. This is done at the catchment level, with no attempt to model the spatial distribution of hydrological processes and storages within a catchment. Total catchment evapotranspiration is estimated from potential evaporation and water supply from the surface store, and partitioned between rainfed and irrigated land uses based on the ratio of their areas. The rainfed component of evapotranspiration is further partitioned between land uses/vegetation types (agriculture, forest/woodland, grassland, other) based on the ratio of their areas and using crop coefficients to scale their evapotranspiration relative to other rainfed land uses.

Runoff flows into the tributaries and thence into the Indus River, with downstream flow calculated by simple water balance. We assume that the base flow in a catchment comes from a notional groundwater store whose monthly discharge is a fraction of the quantity of water it contains. Deep drainage to the groundwater store is estimated as a proportion of the surface water store. For more details see Kirby et al. (2010). Channel storages and losses from the river are estimated as a function of flows. Inflows are stored in reservoirs, and are balanced by evaporation and discharge at the dam. Water is spilled if the capacity of the dam is exceeded.

Crops in each catchment may be irrigated from surface water and groundwater sources. Extractions from groundwater and surface water diversions for irrigation are based on crop water requirements calculated from cropped areas, crop coefficients, potential evaporation and irrigation efficiencies. Maximum irrigated areas are defined based on land-use data, but the area irrigated from surface water may be reduced in any year to match the supply if the volume stored in the reservoir at the beginning of the cropping season is insufficient to meet crop water requirements. If reservoir storage becomes

insufficient to meet crop demand during the cropping season, irrigation applications are reduced to match supply. Irrigation is assumed to be inefficient, and a proportion of the water applied returns to the groundwater store, and a further amount lost by evaporation.

The model is described in detail in a companion report *Water-use accounting in CPWF basins: Model concepts and description* (Kirby et al. 2010). Here we describe only that part of the model that differs from the general set of equations.

3.3. UNITS

Rain, evapotranspiration and potential evapotranspiration are given in mm.

River flows and storages, and lake storage, are given in mcm (million cubic metres). 1 mcm is equivalent to one metre over one square kilometre. $1000 \text{ mcm} = 1 \text{ bcm}$ (billion cubic metres) = $1000 \text{ m over } 1 \text{ km}^2 = 1 \text{ km}^3$.

4. DATA SOURCES

The datasets used in this water-use account were all readily available on the internet.

4.1. RAINFALL

The rainfall and other climate data were taken from the Climate Research Unit at the University of East Anglia (specifically, the dataset CRU_TS_2.10). They cover the globe at 0.5° (about 50 km) resolution, at daily intervals for 1901 to 2002. The dataset was constructed by interpolating from observations. For recent decades, many observations were available and the data show fine structure. For earlier decades, few observations were available and the data were mostly modelled and lack fine structure. We sampled the rainfall and other climate surfaces for each catchment within the Basin, to calculate catchment area-means of rainfall and potential evapotranspiration for each month. The method is described in more detail in Kirby et al. (2010).

4.2. FLOW

Reach flows were taken from the dataset ds552.1, available on the internet (URL: <http://dss.ucar.edu/catalogs/free.html>) (Bodo 2001). The dataset also gives contributing drainage areas for each flow gauge. Flow records were not available for all the catchments.

4.3. LAND USE

Land use was taken from the 1992-3 AVHRR dataset (IWMI 2006), which has more than 20 land-use classes, many of which have similar patterns of water use. The land-use classes were therefore aggregated into rainfed agriculture, irrigated agriculture, grassland, woodland and other. The aggregated class of grassland contains important areas of other land uses including shrubland and barren land.

4.4. DATA LIMITATIONS – CLIMATE DATA

For several catchments of the Indus Basin, the mean annual precipitation data are less than the mean annual observed discharge from the catchments over the period from 1951-2000. The discrepancy occurs for catchments that include high altitude (mountainous) areas; the Tarbela, Nowshera, Marala, Mandi Plain, and Mangla catchments. The precipitation data for the Kalabagh catchment is unrealistically low to generate the discharge observed, and evapotranspiration values derived from the normal model-fitting procedure are also unrealistically low. We assumed the anomalies observed in these catchments were caused by underestimation of precipitation through inadequate measurement at high altitudes. We are unable to evaluate whether precipitation data used for other ungauged catchments may also underestimate actual annual precipitation.

Since discharge exceeds inputs by precipitation into these catchments, we could not apply our normal method of partitioning precipitation into runoff and infiltration in the water-accounting spreadsheets. Instead we estimated discharge from monthly precipitation using relationships between observed discharge and precipitation for each month, derived empirically for each catchment. We assumed monthly evapotranspiration from these catchments were at an upper limit, equal to potential evaporation. We adjusted monthly precipitation using a multiplying factor that matched the mean annual precipitation with the sum of the mean annual discharge, losses, storage changes, and water uses in each catchment (assumed an upper limit for precipitation). Whilst the capability of the model to predict discharge can not be evaluated through comparison of observed and modelled flow in these catchments, the uncertainty in estimates of evapotranspiration, losses, and storage changes is unknown. Improved climatic data for these catchments are needed to reduce this uncertainty and improve the water account.

4.5. DATA LIMITATIONS – FLOW DATA

We have been unable to access flow data for 6 of the 15 catchments of the Indus Basin, including Gomal, Sutlej, Ravi, Jhelum Chenab, Rajasthan, and the Estuary catchments. Where data were unavailable, we selected model coefficients that gave parity in calculated and observed flow in downstream catchments, using rainfall-runoff coefficients similar to nearby catchments with similar climatic and physiographic characteristics.

5. COMPONENTS AND RESULTS IN DETAIL

5.1. FLOW

5.1.1. THE UPPER INDUS BASIN AND HIMALAYAN FOOTHILLS

Flow from catchments in the Upper Indus Basin and Himalayan foothills (Figure 3) show annual flow peaks in summer months and low flows during winter. Although an important proportion of precipitation falls in winter months, it falls mostly as snow and generates little flow at the time. Flows generated by rainfall during summer months are supplemented by snowmelt from these catchments.

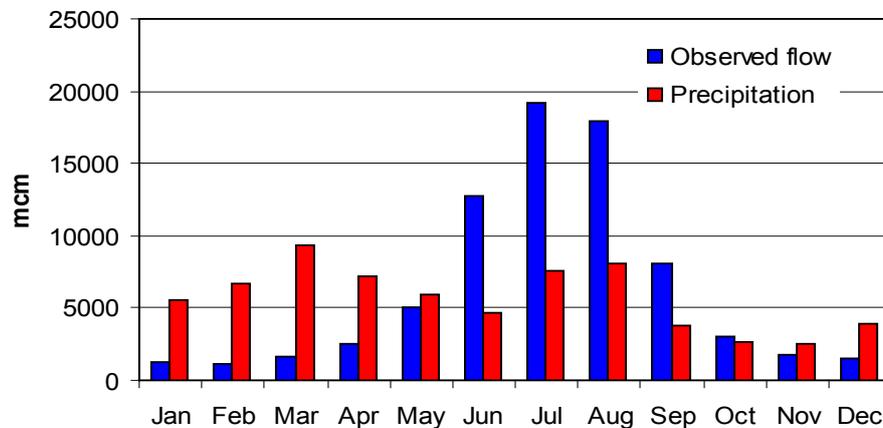


Figure 3. Mean monthly precipitation (modified) and observed flow in the Tarbela catchment (Upper Indus Basin).

Many of the catchments of the Upper Indus Basin and Himalayan foothills are headwater catchments (Tarbela, Nowshera, Marala, Mandi Plain, and Mangla catchments) with flow derived solely from runoff generated locally within the catchments. Of the Indus catchments, only Kalabagh has important contributions from upstream inflows (94%) to its discharge (Figure 4).

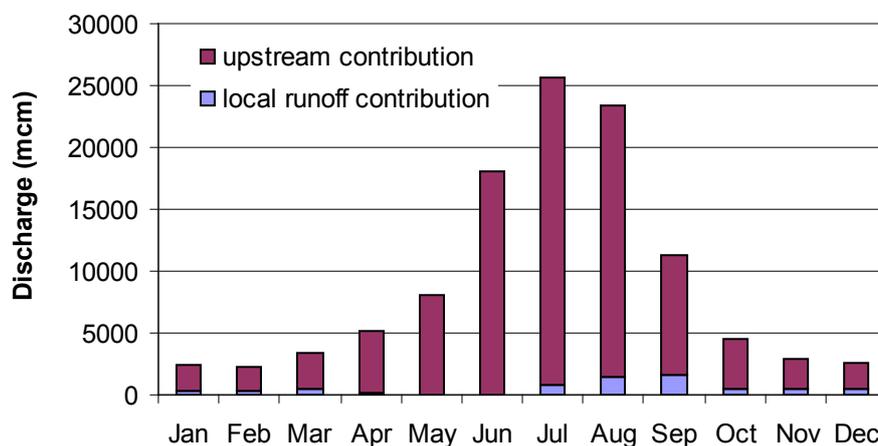


Figure 4. Contribution of upstream inflows and locally generated runoff to flows from the Kalabagh catchment.

Figures 5 to 10 show flow from the catchments of the Upper Indus Basin and Himalayan foothills. The catchments all show annual peak flows during the wet-season months when snowmelt augments runoff generated by rainfall. Minimum flows occur in the dry-season months when low temperatures cause snow and ice to accumulate. The area of irrigated cropping can be relatively large in these catchments, and ranges from 747 km² in the Tarbela catchment to 5,594 km² in the Nowshera catchment. However,

diversions of surface water for irrigation are less than 10% of the runoff generated in all catchments. Thus for catchments in the Upper Indus, irrigation has only a relatively small impact on discharge.

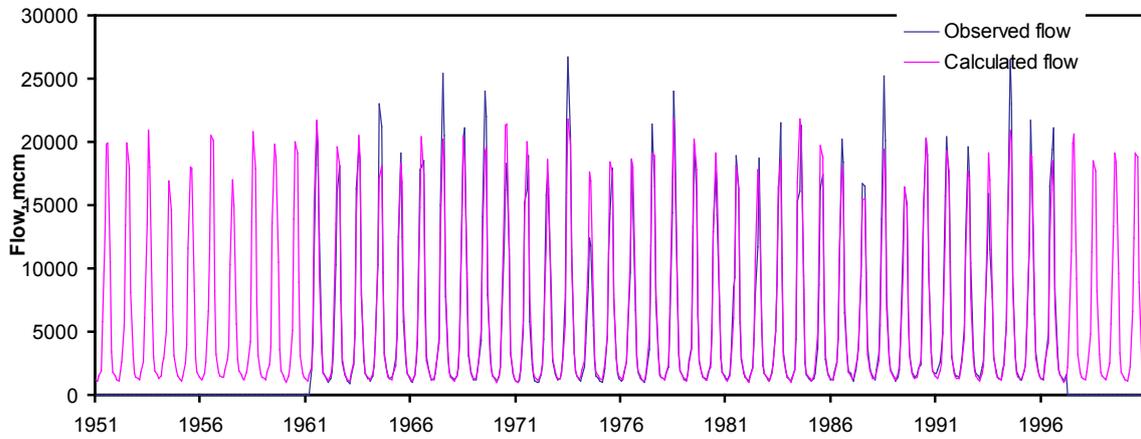


Figure 5. Observed and modelled flow at Tarbela.

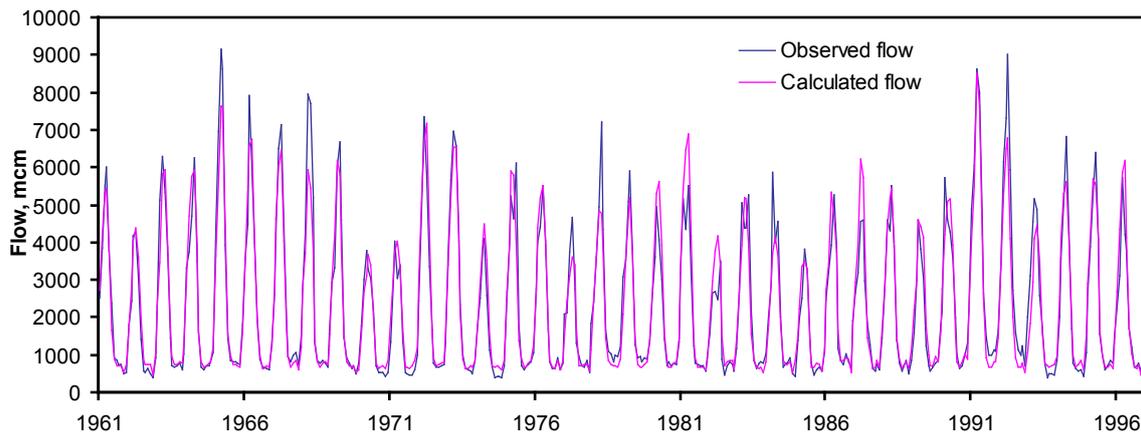


Figure 6. Observed and modelled flow at Nowshera.

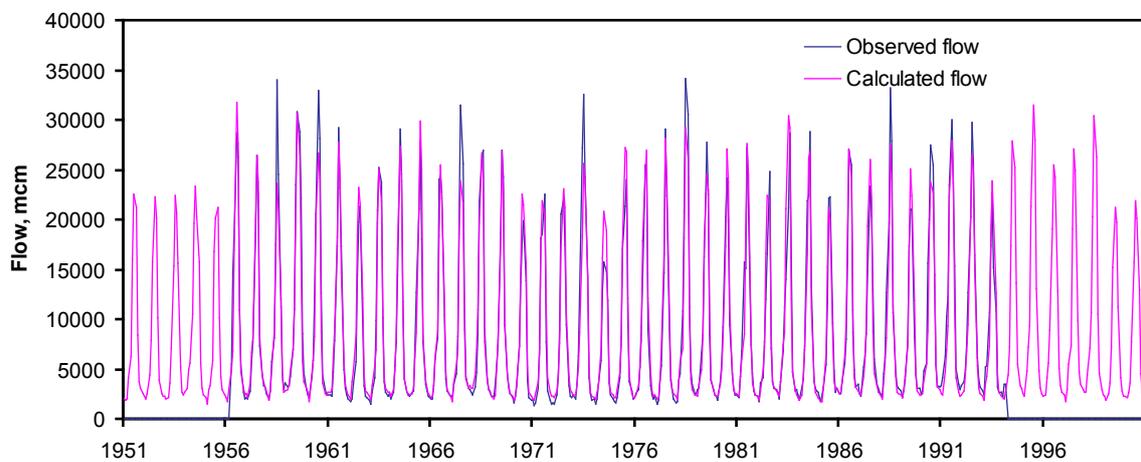


Figure 7. Observed and modelled flow at Kalabagh.

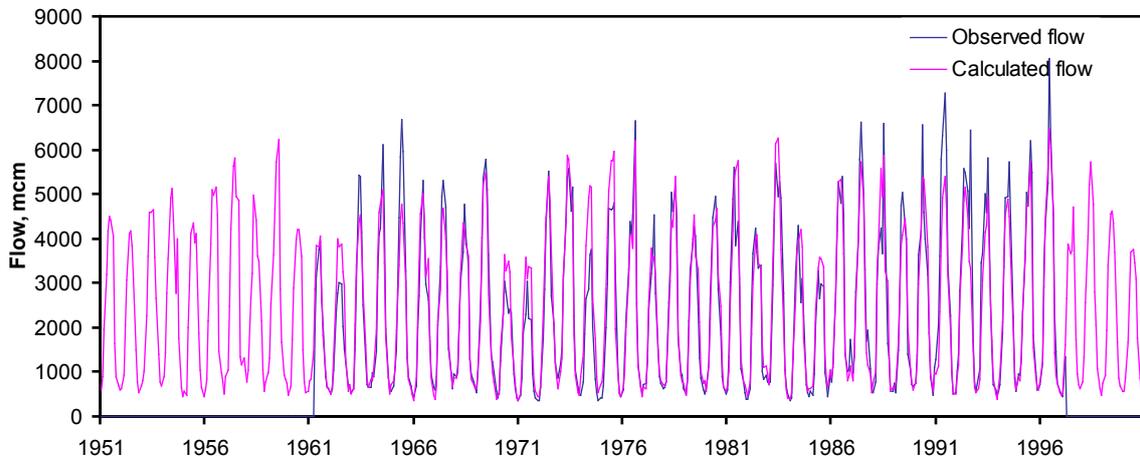


Figure 8. Observed and modelled flow at Mangla.

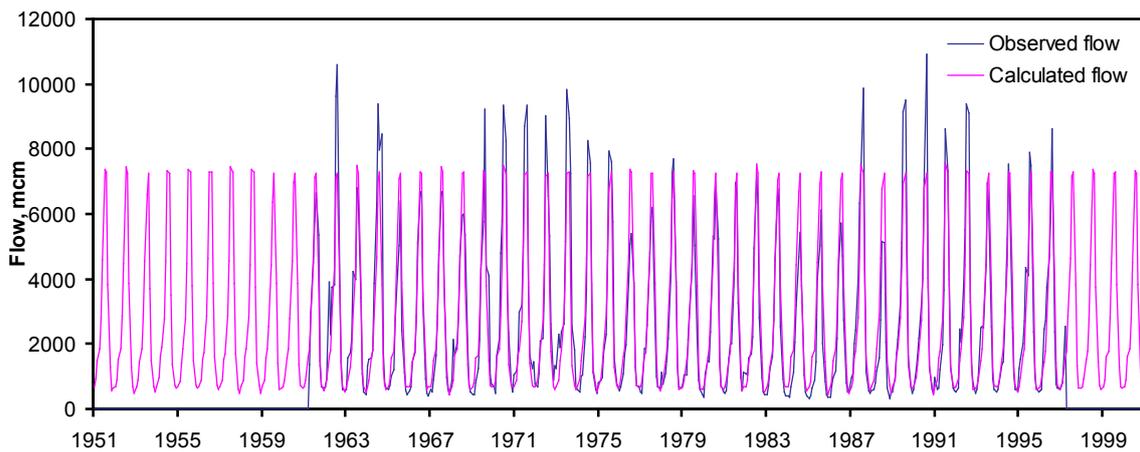


Figure 9. Observed and modelled flow at Marala.

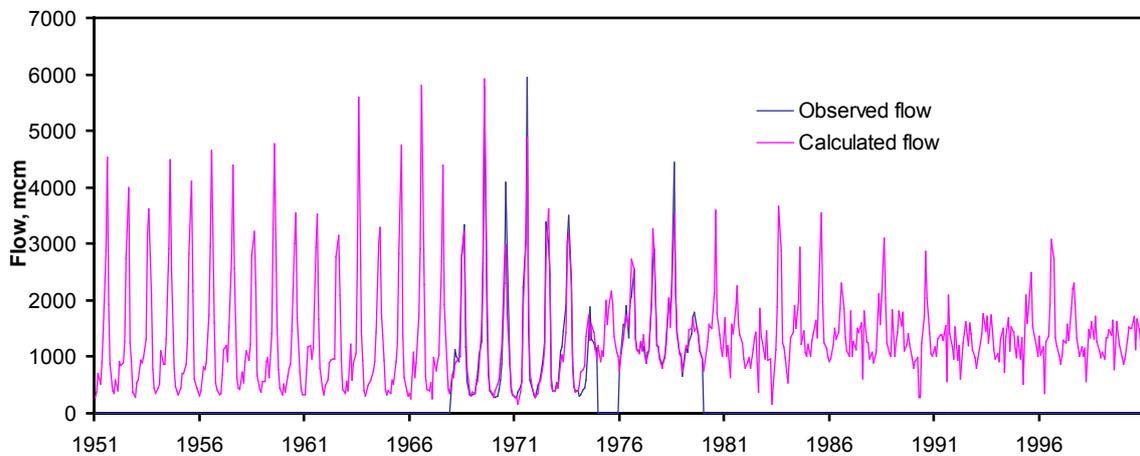


Figure 10. Observed and modelled flow at Mandi Plain.

5.1.2. INDUS PLAINS

Apart from the Sutlej, Ravi, and Rajasthan catchments, which have no catchments upstream, discharge from catchments of the Indus Plains is largely dominated by upstream inflows. Local runoff contributes 19% or less to the discharge from these catchments (Figure 11). The relative contribution from local runoff tends to decrease on moving downstream towards the estuary, being greatest in the Panjnad catchment (19%), and smallest in the Estuary (2%).

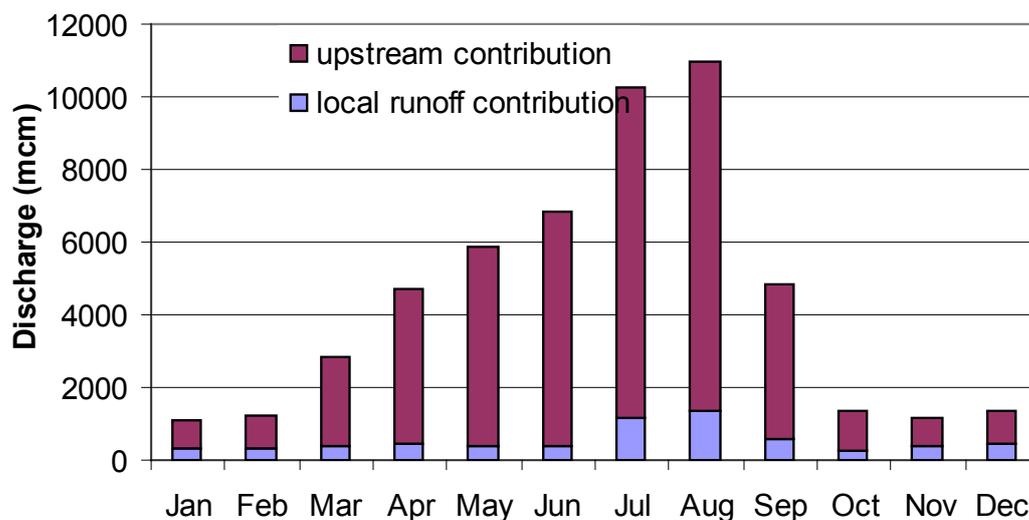


Figure 11. Contribution of upstream inflows and locally-generated runoff to flows from the Jhelum Chenab catchment.

As in the Upper Indus Basin, the areas under irrigation in each catchment are large, and range from 5563 km² in Sutlej to 57,683 km² in Panjnad. However, in strong contrast with the Upper Indus catchments, diversions for irrigation in many of the Plains catchments exceed the amount generated by local runoff. Diversions on the Plains catchments ranged from 5% to 75% of the annual inflow from upstream for the Gomal and Panjnad catchments respectively. Thus the major influences on the flows from downstream catchments on the Plains catchments are rainfall and snowmelt from the Upper Indus Basin and local diversions for irrigation.

Flow from catchments on the Indus Plains that receive inflows from upstream generally show annual flow peaks in wet-season months and low or zero flow during dry-season months (Figure 12), reflecting flows in the Upper Indus catchments (Figure 3).

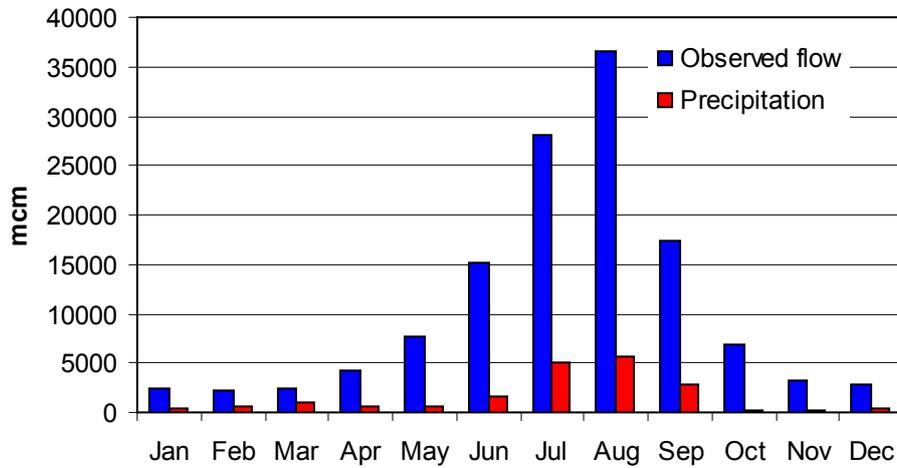


Figure 12. Mean monthly precipitation and observed flow in the Sukkur catchment (Indus Plains).

Flows in the Ravi and Rajasthan catchments on the Plains are largely ephemeral since local runoff is low, and they have no upstream catchments to sustain flow (Figures 13 and 14).

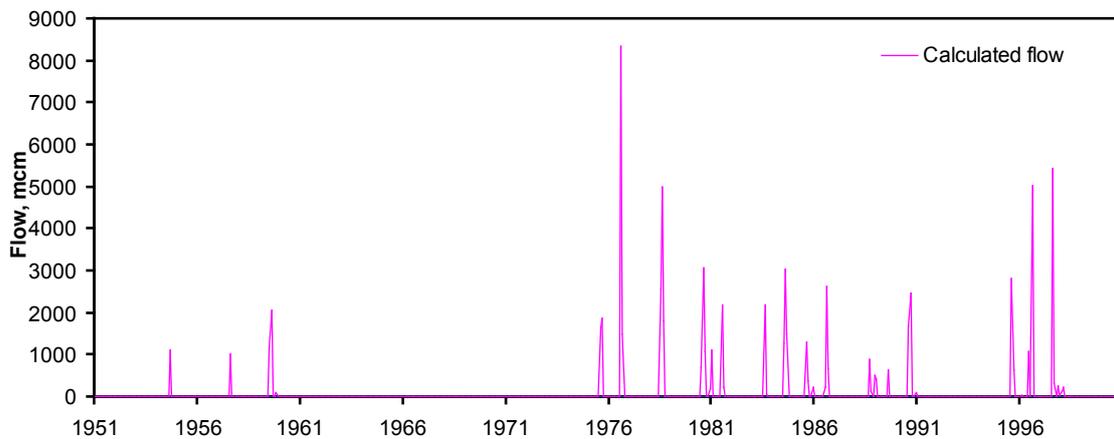


Figure 13. Modelled flow from the Ravi catchment.

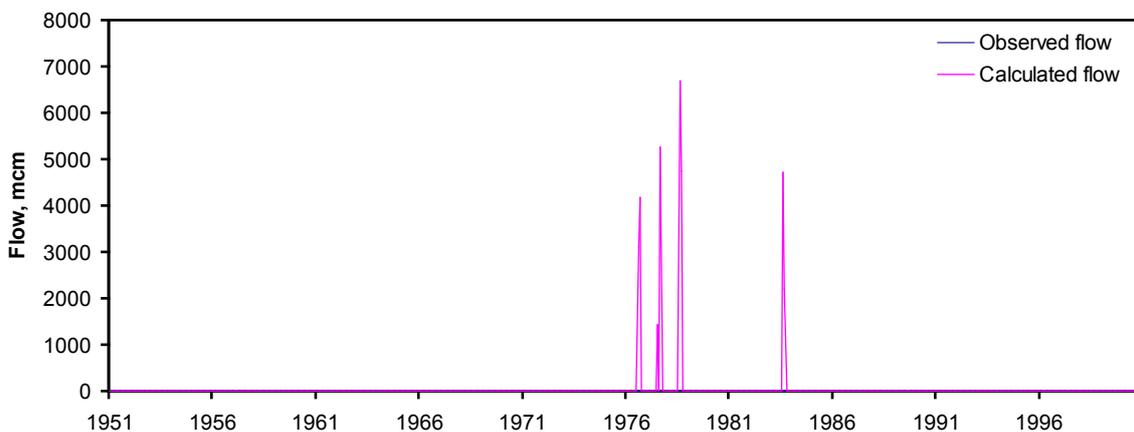


Figure 14. Modelled flow from the Rajasthan catchment.

The Gomal catchment is the only downstream catchment on the Plains with continuous flow throughout the year (Figure 15). However in the remaining downstream catchments on the Plains, irrigation diversions and other losses can reduce flows to zero. This occurs periodically in the Panjnad and the Jhelum Chenab catchments (Figures 16 and 17), and more frequently at Kotri (Figure 18).

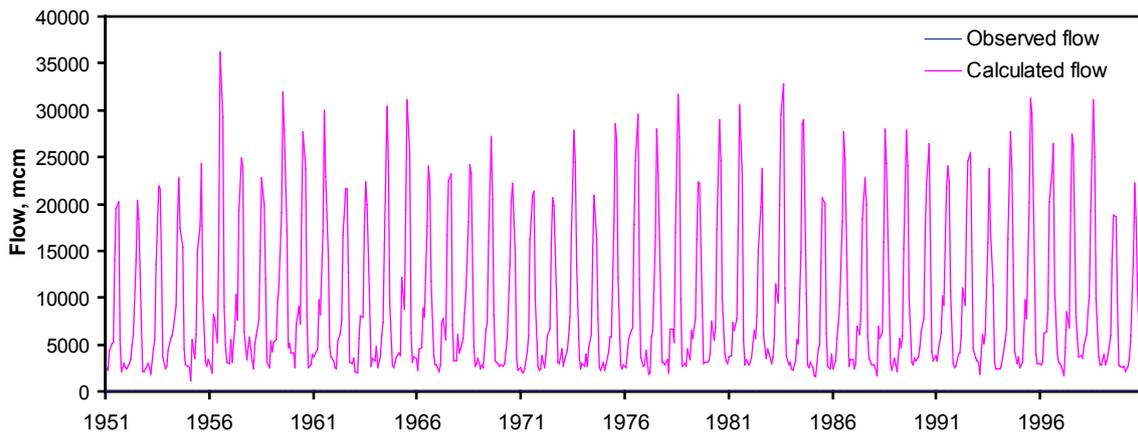


Figure 15. Modelled flow from the Gomal catchment. Note that there are no zero flows.

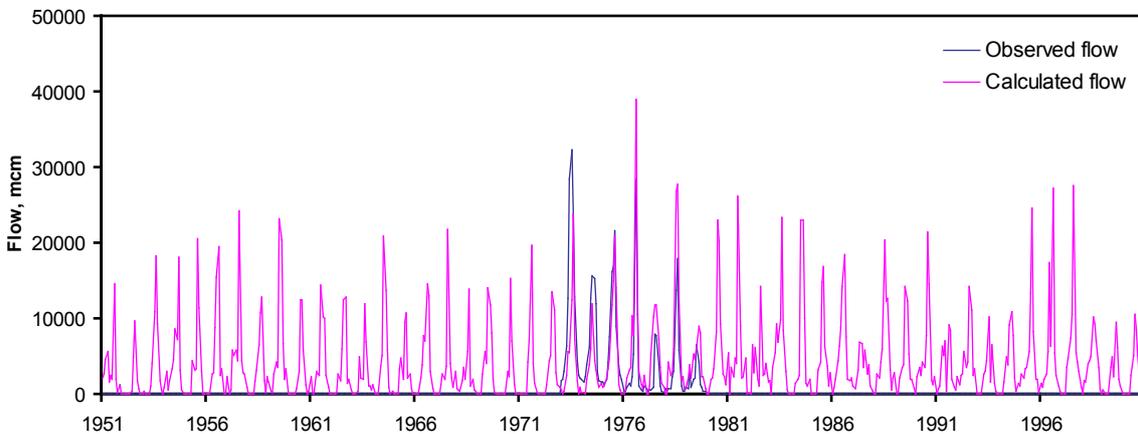


Figure 16. Observed and modelled flow from the Panjnad catchment. Note that there are periods of zero flow in many years.

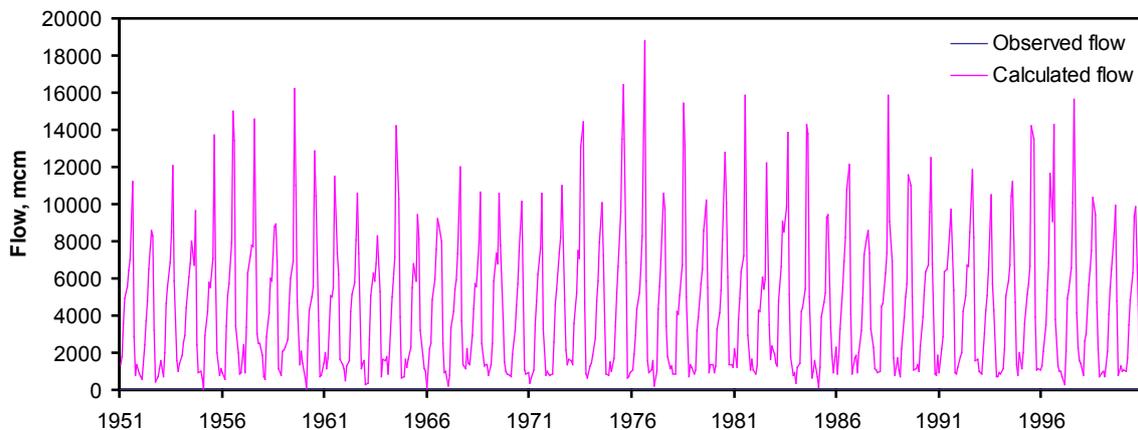


Figure 17. Observed and modelled flow at Jhelum Chenab. Note that there are only occasional periods of zero flow.

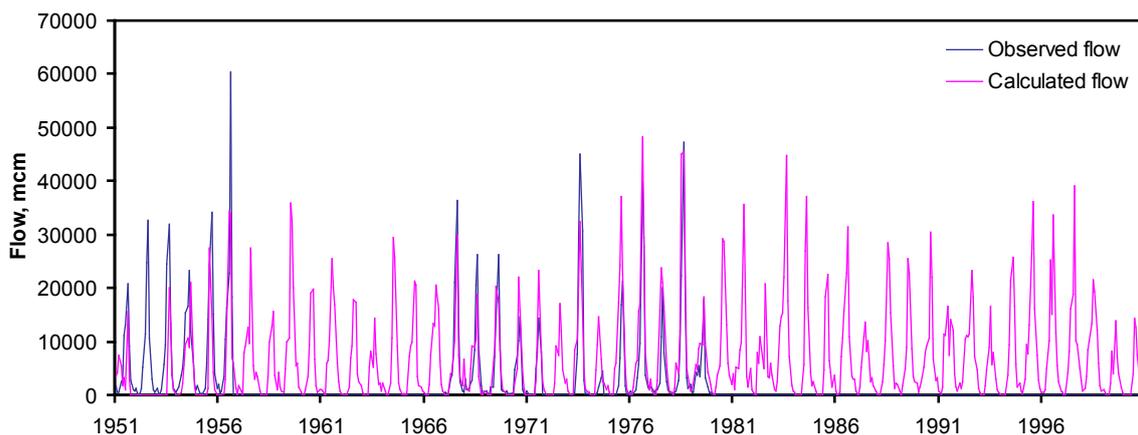


Figure 18. Observed and modelled flow at Kotri. Note that there is zero flow in most years.

The discharge at the estuary of the Indus River is ungauged, but the losses and gains to the flows from upstream of the Kotri gauge are unlikely to be large, since the catchment is relatively small, annual rainfall inputs are low (220 mm), and the irrigated area is relatively small compared with other catchments of the Indus Basin.

5.2. WATER USE

The mean annual input by precipitation to the Indus Basin totals 824,000 million cubic meters (mcm). Figure 19 summarizes how this water is partitioned amongst the major water uses in the Basin. Net runoff comprises the runoff remaining after all the water uses in the Basin have been satisfied, and includes all other storage changes and losses. Net runoff from the Basin is about 80,000 mcm or 10% of the total precipitation input.

The aggregated class grassland, which includes shrubland and barren land, is the most extensive vegetation, covering 45% of the Basin. Its water use is correspondingly high, with a mean annual water use of 315,000 mcm (Figure 20).

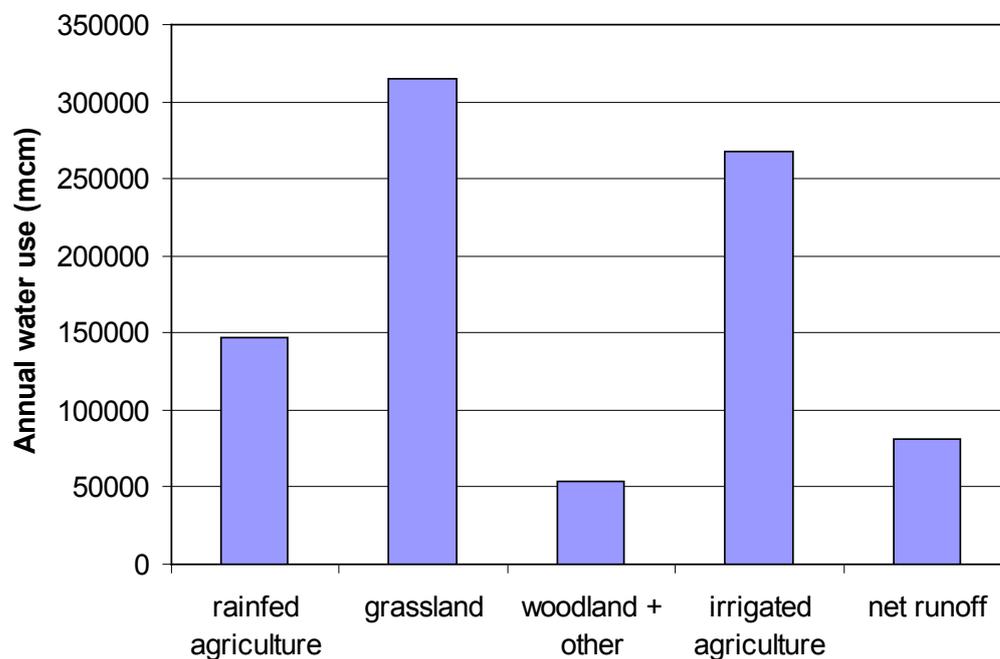


Figure 19. Summary of major water uses in the Indus Basin. Grassland included shrubland and barren land (see Section 4.3)

Irrigated agriculture, which covers 20% of the Basin, has the second highest water use at 268,000 mcm. Most of the irrigated land in the Basin (92%) receives irrigation water from surface water resources, and the remaining 8% from groundwater. A correspondingly high proportion (94%) of the water use by irrigated agriculture is from crops irrigated by surface water.

Rainfed agriculture, which covers 14% of the Basin, has water use of 147,000 mcm, or 15% of the available water. Land uses included in the 'woodland + other' class are woodlands and forests, urban land, bare ground, barren and sparsely vegetated land, and snow and ice. This land-use class, covering 19% of the Basin, is largely dominated by barren and sparsely vegetated land, and has the lowest water use of 54,000 mcm, or 5% of the available water. Net discharge from the Basin is small, in large part because of the diversions for irrigation.

The distribution of the different water uses across the Basin is shown in Figure 20. The figure depicts the water uses in each catchment, and the distribution of water uses across the Basin. It does not, however, represent the water balance at the basin level. Irrigation in the lower part of the Basin, for example, uses the runoff water from the upper part, and thus this water is double counted at the basin level; the net runoff from the whole Basin is shown in Figure 19. The figure shows the different behaviour of the runoff-generating catchments in the Upper Basin and those of the Lower Basin where much of the flow is consumed by irrigation.

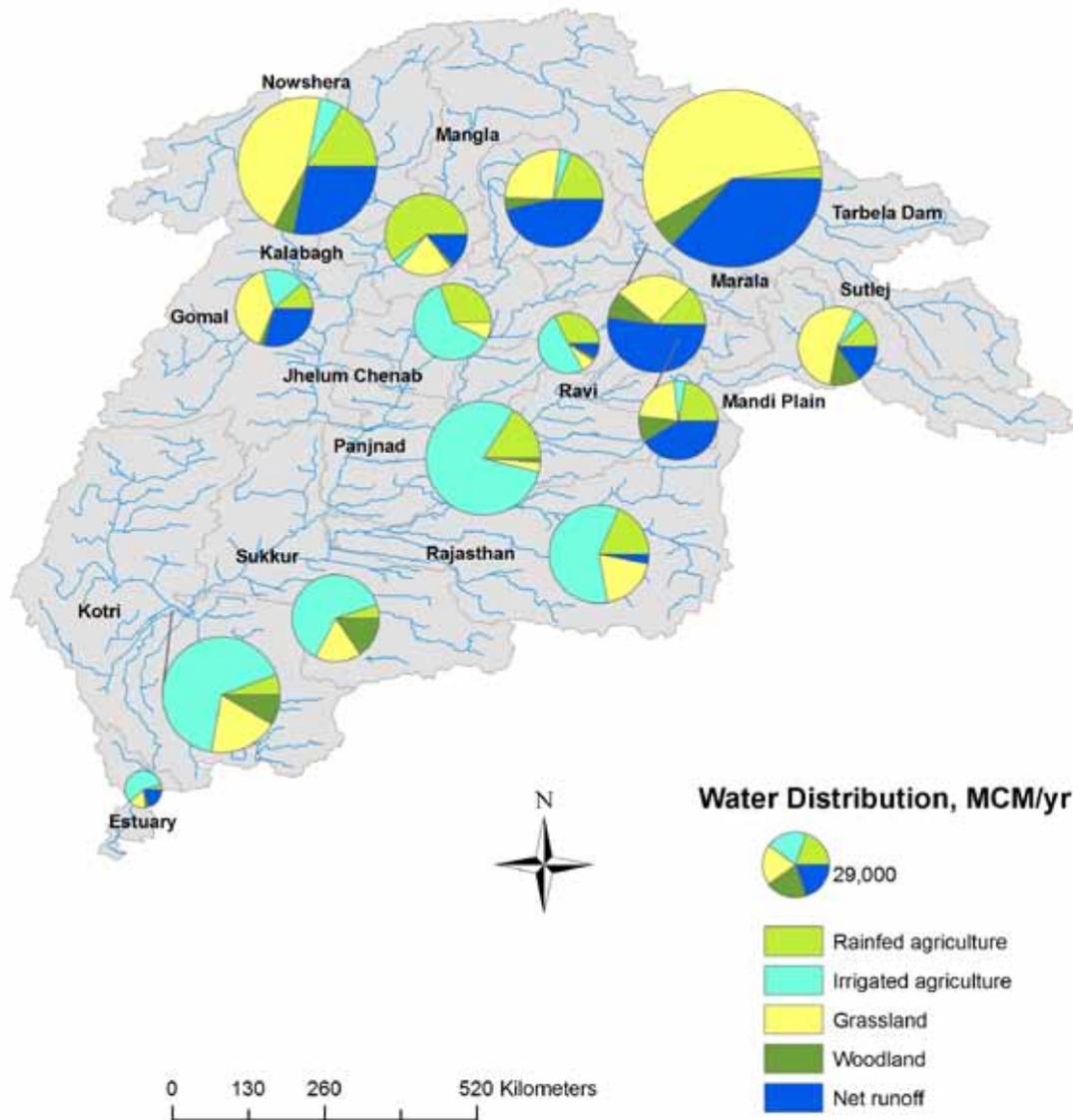


Figure 20. The spatial distribution of major water uses in catchments of the Indus Basin. Grassland includes shrubland and barren land (see Section 4.3).

Irrigated agriculture dominates the water used in the lower catchments of the Indus Plains, the Ravi, Jhelum Chenab, Panjnad, Rajasthan, Sukkur, Kotri, and Estuary catchments. In these catchments the irrigated water use ranges from 50% of the water used in the Ravi catchment to 80% used in Panjnad catchment. In all other catchments of the Basin except the Gomal, irrigated agriculture consumes less than 6% of the total water used. In the Gomal catchment, irrigated agriculture uses 18% of the water.

Rainfed agriculture is the major water use in only the Kalabagh and Mandi Plain catchments where it contributes 61 and 22% respectively to the water used in them.

The woodland + other land-use class is the smallest water use in eight catchments (Nowshera, Kalabagh, Gomal, Ravi, Jhelum Chenab, Panjnad, Rajasthan, and the Estuary), using 5% or less of their available water. Water use of the woodland + other land use is most important in the Sukkur catchment, accounting for 16% of the water used.

All the Upper Indus catchments generate important net runoff, ranging from 13% of the water used in the Kalabagh catchment, to 52% in Marala. Of the catchments on the Indus Plains, the Gomal, Sutlej, Ravi, and Estuary catchments generate important net runoff, ranging from 8% of the water used in the Ravi catchment to 29% in the Gomal catchment. In the remainder of the Plains catchments, net runoff is zero in all but the Rajasthan catchment, where it is 3% of the total water used. Thus we may consider the low-altitude catchments as net users of water, and the high-altitude catchments as net contributors of water to the Basin. This is well illustrated in Figure 20.

The crop coefficients and calendars we have used for estimating the water use of irrigated crops are based on Ullah et al. (2001). Their study divides the major areas irrigated by water taken from the Indus River into 11 groups to accommodate variations in cropping patterns and periods within 7 agro-climatic zones. We identified their agro-climatic regions and the associated major crops within each of our catchments, and used their crop coefficients and calendars for the two major crops in our water account.

The major crops in the Basin included rice, wheat, maize, cotton, and sugarcane. The crop coefficients of Ullah et al. (2001) represent their estimate of the crop water requirement for irrigated crops across the Basin. The amount of water diverted and applied at any location in any season may not match this theoretical water requirement, so our model may under- or over-estimate actual irrigation diversions. The area of irrigated land is relatively large, and the amount of water used for irrigation is a large component of the water used in many of the catchments of the Basin. The results from the spreadsheet modelling would be much improved by local information on crop seasonality and crop coefficients. Crop coefficients used for partitioning catchment evapotranspiration between the different rainfed land uses (agriculture, grassland, woodland, other) were our best estimates for their relative water use. These may be improved by local information on vegetation types and water uses.

5.3. CATCHMENT AND BASIN HYDROLOGICAL CHARACTERISTICS

Selected hydrological characteristics will be useful for comparing the Indus Basin hydrological function and its vulnerability with those of other basins under study in the Challenge Program. Some of these hydrological characteristics are outlined briefly below.

Runoff characteristics for different basins may be compared by comparing their annual percentage runoff ratios (total basin runoff/total basin precipitation). The runoff ratio for the Indus Basin is nearly zero (i.e. mean annual discharge is nearly 0% of mean annual precipitation). Differences in runoff characteristics for the different catchments in the Basin can be seen by comparing their annual runoff ratios (Table 3).

Table 3. Annual percentage runoff ratios (runoff/precipitation) for catchments in the Indus Basin.

Catchment	Runoff ratio
Tarbela	37
Nowshera	28
Kalabagh	13
Gomal	31
Marala	52
Mandi Plain	41
Sutlej	16
Ravi	9
Mangla	47
Jhelum Chenab	0
Panjnad	0
Rajasthan	4
Sukkur	0
Kotri	0
Estuary	76
Whole Basin	0

Note that the large value for the estuary catchment is almost certainly an error and should be disregarded. It probably derives from calculating it as the difference between catchment inflow and outflow, both of which are large numbers. A small error in one will result an apparent runoff, which is divided by a very small rainfall total to give the large runoff ratio.

Catchments in the higher-altitude catchments of the Basin (Tarbela, Nowshera, Marala, and Mangla) show the greatest ratios of runoff to precipitation. In the lower-altitude catchments of the Basin, the ratios are less, falling to near zero towards the estuary. Greater runoff ratios in the high-altitude catchments are associated with greater slopes, higher rainfall and lower rates of potential evaporation than are found at lower altitudes.

Annual average runoff from each catchment per unit area is simply related to annual precipitation (Figure 21). As expected, runoff/area increases with increasing precipitation.

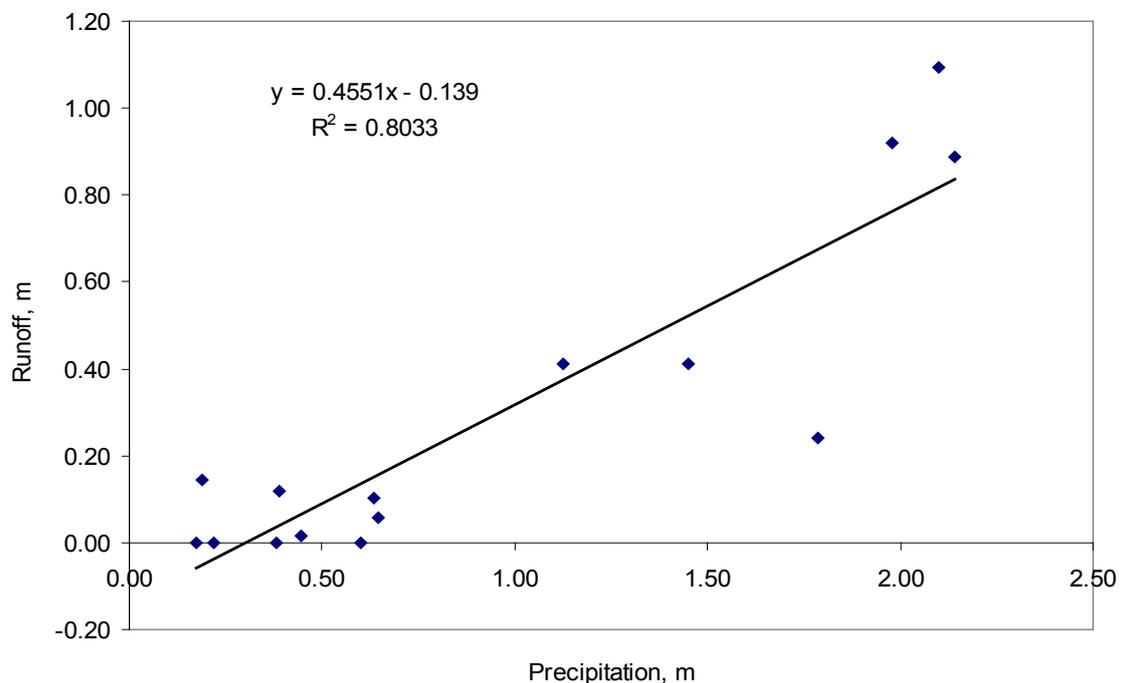


Figure 21. Annual average runoff/area as a function of annual average precipitation (or modified precipitation). See Section 3d and Table 2 for catchments of the Indus Basin.

6. EXAMPLE USE

6.1. IMPACT OF CHANGED EFFICIENCY OF IRRIGATED CROPPING IN THE INDUS BASIN

To demonstrate the application of the spreadsheet, we ran a scenario on the impact of changed irrigation efficiency on irrigated agriculture in the Indus Basin. In the base case, described above, we assumed an irrigation efficiency of 0.4, that is, 40% of water diverted from rivers or pumped from groundwater was assumed to be effective in growing a crop. The other 60% was assumed to be lost to evaporation, seepage to groundwater or return to the River. Mandavia (1998) suggested that many irrigation systems in India have irrigation efficiencies of 40% or less, and that 60% efficiency is a goal to which India should aspire. In the scenario, we assumed that these figures are also appropriate for the Indus Basin, and that the irrigation efficiency increased to 0.6. We also assumed that the area of irrigation increased by 10%.

In this scenario, less water needs be diverted or pumped to grow the crop, but there will also be correspondingly smaller quantities seeping to groundwater or returning to the River. The impact of the two assumptions is that flows are reduced marginally in the Indus River at Kotri (Figure 21). Thus, locally-reduced irrigation demand does not translate to a reduction of water used in the Basin, and the small overall reduction in flows result from the increased area of irrigated crop. Molle and Turrall (2004) made a

similar point about the water supply to New Delhi (which is within the Ganges Basin): capturing “losses” in irrigation water supplies and diverting the “savings” for New Delhi simply denied the water to other uses downstream. The predicted water use by irrigated crops under the scenario increases from about 122,000 to 140,000 mcm per year.

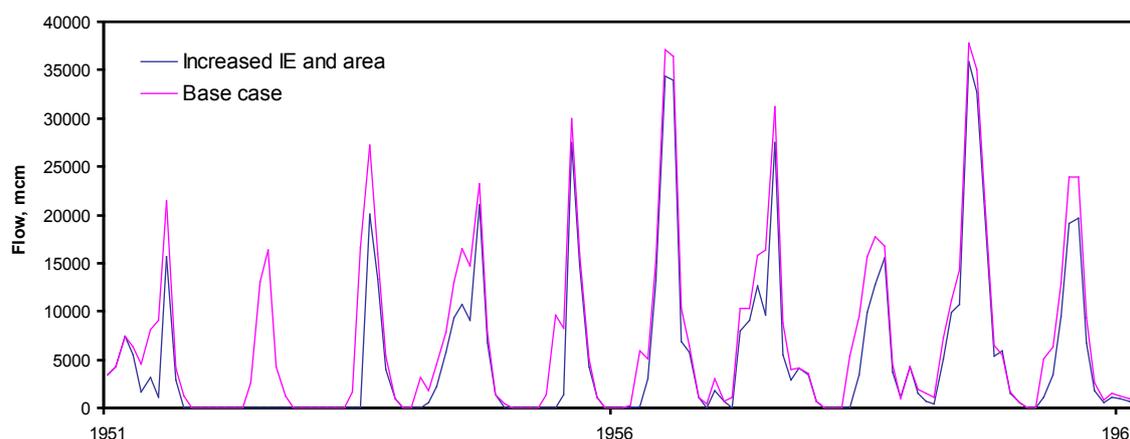


Figure 21. Impact of increasing irrigation efficiency from 0.4 to 0.6 and increased irrigation area by 10% on flows at in the Indus River at Kotri.

7. CONCLUSIONS

A very simple spreadsheet model with a few adjustable parameters has produced plausible runoff and river-flow behaviour in the Indus Basin. It must be further developed to give a better representation of water use by different land uses.

The Indus Basin has moderate annual average precipitation of about 750 mm spatially averaged across the Basin, and 2000 mm or more in the northern Himalayan catchments. Much of the precipitation in many of these catchments falls in the monsoon season of June to September, and leads to river flows that vary greatly from peak flows in the wet season to low flows in the dry season. Net discharge from the Basin is about 10% of the total rainfall. Grassland is the most extensive land use, and hence the largest water user, followed by irrigated agriculture. About 8% of irrigation water is pumped from groundwater.

We have undertaken a preliminary scenario that simulates the impact of increasing both irrigation efficiency (from 0.4 to 0.6) and the area irrigated by 10% on both water availability and productivity of irrigated cropping in the Basin. The intent was to demonstrate the application of the spreadsheet model. The results suggest that changing irrigation efficiency has relatively little impact on water availability overall, since the water thus made available can be consumed downstream. The main effect is the increasing irrigated area, which leads to a net increase in water consumption overall.

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