XX

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CPWF WORKING PAPER

Water-use accounts in CPWF basins:

2. Simple water-use accounting of the Ganges Basin.

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THE WATER USE ACCOUNTS SERIES:

The twelve papers in the Series Water-use Accounts in the CPWF Basins are:

1. Model concepts and description (CPWFWP xx).
2. Simple water-use accounting of the Ganges Basin (CPWFWP xx).
3. Simple water-use accounting of the Indus Basin (CPWFWP xx).
4. Simple water-use accounting of the Karkheh Basin (CPWFWP xx).
5. Simple water-use accounting of the Limpopo Basin (CPWFWP xx).
6. Simple water-use accounting of the Mekong Basin (CPWFWP xx).
7. Simple water-use accounting of the Niger Basin (CPWFWP xx).
8. Simple water-use accounting of the Nile Basin (CPWFWP xx).
9. Simple water-use accounting of the São Francisco Basin (CPWFWP xx).
10. Simple water-use accounting of the Volta Basin (CPWFWP xx).
11. Simple water-use accounting of the Yellow River Basin (CPWFWP xx).
12. Spreadsheet description and use (CPWFWP xx).

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The Challenge Program on Water and Food (CPWF), an initiative of the Consultative Group on International Agricultural Research (CGIAR), contributes to efforts of the international community to ensure global diversions of water to agriculture are maintained at the level of the year 2000. It is a multi-institutional research initiative that aims to increase water productivity for agriculture—that is, to change the way water is managed and used to meet international food security and poverty eradication goals—in order to leave more water for other users and the environment.

The CGIAR Challenge Program for Water and Food's Working Paper series captures the Program's work in progress that is worthy of documentation before a project's completion. Working papers may contain preliminary material and research results - data sets, methodologies, observations, and findings that have been compiled in the course of research, which have not been subject to formal external reviews, but which have been reviewed by at least two experts in the topic. They are published to stimulate discussion and critical comment.

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1 Abstract (to be completed)

This paper applies the principles of water-use accounts, developed in the first of the series, to the Ganges River basin in South Asia. The Ganges Basin covers six countries, the River rises in . A unique feature is .

Net runoff is about xx% of total precipitation. Forest and woodland cover xx% of the basin and use about xx% of the precipitation. Grassland covers much of the upper part of the Basin, consuming about x% of the precipitation. Irrigated agriculture covers x% of the Basin and uses about x% of the water (excluding runoff).

Climate change, using an assumed change in rainfall distribution, shows that with the expected shorter and more intense rainy season, and longer and more intense dry season, both floods and seasonal water shortages may be exacerbated.

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

2 Introduction

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

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 for 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 its application to the Ganges Basin.

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 an outline of the simple water account

3.1 Basic hydrology, irrigation, and land use

The Ganges Basin covers 981,371 km^2 shared by India, Nepal, China (Tibet), and Bangladesh (Figure 1 and Table 1). There are large variations in the temporal and spatial distribution of water in the basin. The River Ganges originates in Uttar Pradesh, India, and many important tributaries including the Mahakali, Gandak, Kosi, and Karnali originate in Nepal and Tibet. A large proportion of the total flow in the Ganges, particularly during the dry season, originates from the tributaries in Nepal. Water is plentiful during the monsoon period and flooding may occur, particularly in downstream reaches in India and in Bangladesh. In contrast, during the dry period between monsoons, areas become water stressed and flows may be inadequate to supply the demand for irrigation .

The basin has a series of barrages that perform several functions including water storage, flood control, and hydropower generation. The Sarada (Mahakali), Kosi, and Gandak barrages have historically been the major barrages controlling water coming from the Nepalese catchments. More recently the Tanakpur barrage has been constructed 8 km upstream of the Sarada barrage. The Farakka barrage in India was constructed in 1974, 17 km upstream from Bangladesh. The barrage diverts water from the Ganges to the Hooghly River via a feeder canal. The magnitude of both wet and dry season flow at Paksey is important for preventing floods and water shortages in Bangladesh. Agreements exist for the sharing and control of water across national boundaries in the basin, although these have largely been inadequate to prevent both flooding and water shortages.

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

Catchment	Area, km^2
Chisapani nr Dondajri	46,942
Ghaghara	110,049
Chambal	148,212
Upper Yamuna	26,944
Yamuna	166,262
Ganges source	84,469
Middle Ganges	74,872
Son	75,371
Devghat	32,560
Lower Ganges	71,124
Kampu Ghat nr Udaypur	18,863
Everest	41,577
Farakka	40,814
Paksey	43,312
Total	981,371

The Ganges Basin shows strong seasonal variation in both precipitation and potential evaporation. Potential evaporation is greatest prior to the monsoon and lowest during the cooler part of the dry season Most of the annual precipitation (83%) falls in the monsoon between June and September (Figure 2), with monthly precipitation exceeding potential evaporation each month except June. For the remainder of the year, precipitation is low and monthly potential evaporation exceeds precipitation. Rainfall and potential evapotranspiration vary spatially, from the drier and hotter west (Figure 2a) to the wetter and cooler Himalayan regions (Figure 2c).

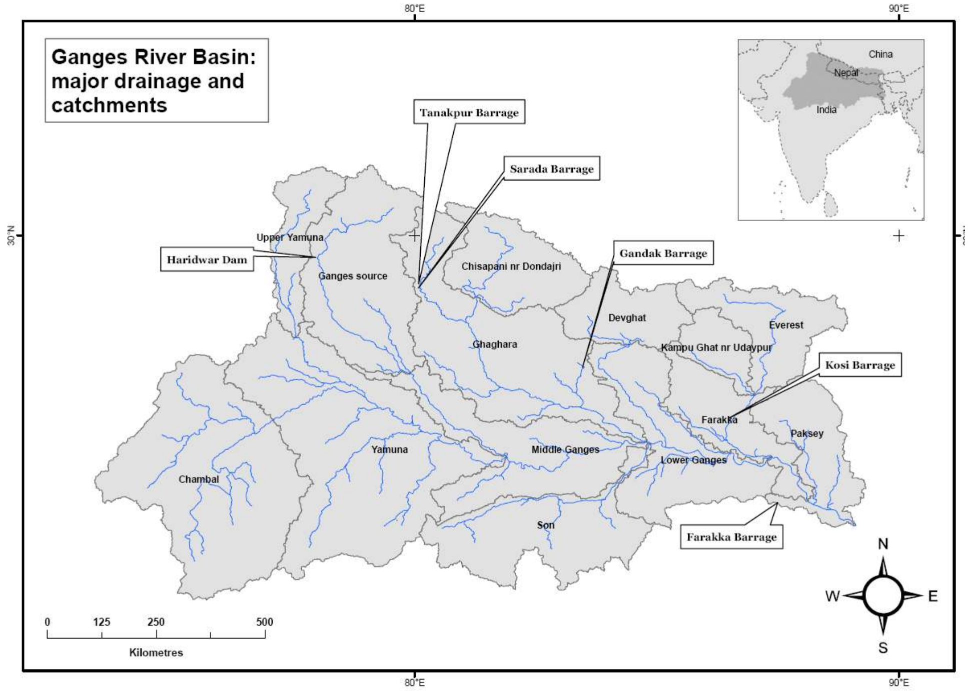

Figure 1. The Ganges Basin, with the catchments used in the water-use account.

As well as the marked seasonal variation in climate, there is large variability in annual precipitation (Figure 3), which causes important variation in annual flows from the Ganges catchments. Whilst mean annual rainfall in the basin (1951-2000) is 1200 mm, rainfall between 1951 and 2000 varied from a minimum of 860 mm in 1965 to a maximum of 1460 mm in 1980. Annual potential evaporation is less variable, ranging from a minimum of 1500 mm in 1978, to a maximum 1630 mm in 1972, with a mean annual value of 1.558 m. Annual rainfall in the Basin has declined from 1980 to 2000.

The spatial variation in climate from northwest to southeast across the Basin generally reflects the change in altitude and the increasing influence of the monsoon closer to the Bay of Bengal. Annual potential evaporation is lowest in the mountainous catchments of Chisapani, Devghat, Kampu Ghat, and Everest in the north (Figure 2 and Table 2). In the remaining catchments at lower altitude potential evapotranspiration is relatively uniform, ranging from 1440 to 1770 mm/yr. Annual precipitation is generally greater in the high altitude catchments, with Devghat and Kampu Ghat catchments receiving the most annual rainfall (2590 and 2520 mm respectively). In these catchments, annual precipitation exceeds potential evaporation. In the lower altitude catchments, mean annual rainfall ranges from 790 mm to 1860 mm, and annual potential evaporation exceeds rainfall in all but the Paksey catchment.

All catchments are subject to the influence of the summer monsoon, receiving the majority of their precipitation (67-92%) between June and September. Potential evaporation also exhibits clear seasonality in all catchments, with maximum evaporation occurring in May, prior to the onset of the monsoon. Exceptions are the Chisapani and Everest catchments with maximum evaporation in June, and Paksey with a maximum in May. The strongly seasonal climate found in all catchments across the basin results in marked seasonal variation in flows from all catchments.

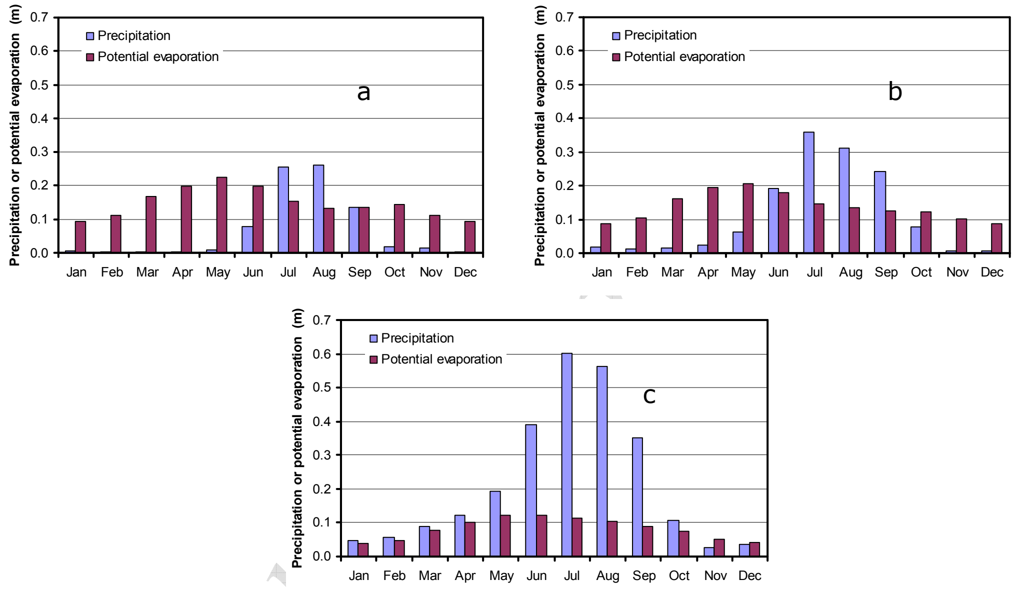

Figure 2. Monthly average precipitation and potential evaporation in the Ganges Basin. a). Chambal (the driest catchment) in the west of the Basin; b). Lower Ganges in the east-central part of the Basin, and c). Devghat (the wettest catchment) in the central north.

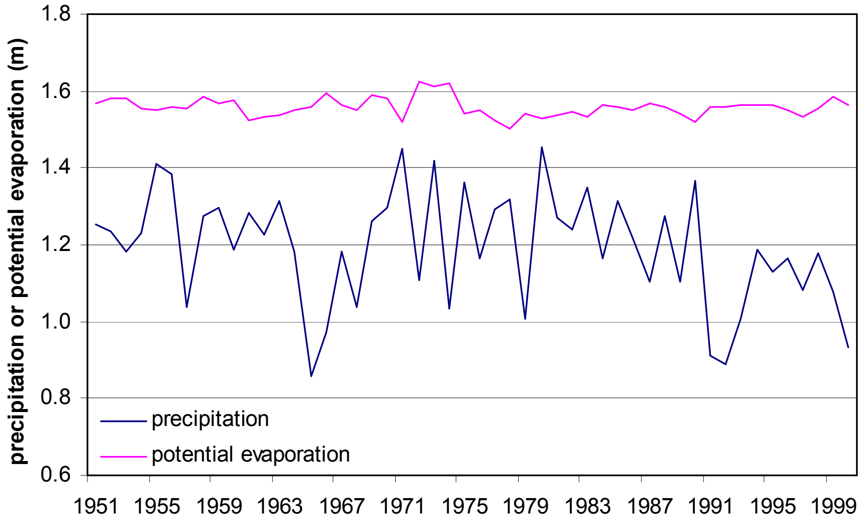

Figure 3. Annual precipitation and potential evaporation in the Ganges Basin from 1951-2000.

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

Catchment	Precipitation (mm)	Evaporation (mm)
Chisapani nr Dondajri *	1849	921
Ghaghara	1228	1592
Chambal	793	1763
Upper Yamuna	892	1453
Yamuna	940	1769
Ganges source	939	1437
Middle Ganges	965	1760
Son	1115	1700
Devghat *	2586	984
Lower Ganges	1328	1649
Kampu Ghat nr Udaypur *	2520	1055
Everest	1162	784
Farakka	1410	1595
Paksey	1860	1528

* Denotes modified precipitation.

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 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. We estimate total catchment evapotranspiration 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. We further partition the rainfed component of evapotranspiration between land uses/vegetation types (agriculture, forest/woodland, grassland, other) based on the ratio of their areas and using crop factors to scale their evapotranspiration relative to other land uses.

Runoff flows into the tributaries and thence into the Ganges River, with downstream flow calculated by simple water balance. We assumed that the base flow in a catchment came from a notional groundwater store whose discharge was equal to the base flow and was constant throughout the year. Deep drainage to the groundwater store is estimated as a proportion of the surface water store.

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 both 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 supply if the volume stored in the reservoir at the beginning of the season is insufficient to meet crop water requirements. If reservoir storage becomes insufficient to meet crop demand during the 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 *Basin Water-use Accounting Concepts and Modelling* (Kirby et al. this series). 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 mcm = 1 bcm (billion cubic metres) = 1000 m over 1 km^2 = 1 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, a dataset called 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. (2007).

4.2 Flows

Reach flows were taken from a dataset called dss522.1, 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).

4.4 Data limitations – climate data

For three catchments of the Ganges 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 Chisapani, Devghat, and Kampu Ghat nr Udaypur catchments. We assumed the anomalies observed in these catchments were caused by underestimation of precipitation through inadequate measurement at high altitude. We are unable to evaluate whether precipitation data used for other ungauged catchments may also underestimate annual precipitation. Since discharge exceeds inputs by precipitation into these catchments, we could not apply our normal methodology 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 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 9 of the 14 catchments of the Ganges basin, including Ghagara, Chambal, Upper Yamuna, Yamuna, Ganges Source, Middle Ganges, Lower Ganges, Son, and Everest catchments. Where data were unavailable, we selected model coefficients that give parity in calculated and observed flow in downstream catchments, using rainfall-runoff coefficients similar to nearby catchments with similar climatic and physiographic characteristics where possible.

5 Components and results in detail

5.1 Flow

5.1.1 High altitude catchments

Flow from high altitude catchments of the Basin (Chisapani, Devghat, Kampu Ghat, and Everest) show annual flow peaks in summer months, which largely coincide with monsoonal rainfall (Figure 4).

Flows during winter are low and generally unresponsive to peaks and troughs in precipitation, which is received in part as snowfall. Low temperatures cause snow and ice to accumulate, and land-use data show that these cover 3 to 7% of these catchments. Flows generated by melting of ice and snow contribute to base flows, which reach maxima during summer months to augment runoff generated by monsoonal rainfall (Figure 5). According to Seidel and Martinec (2001) snowfall contributions to runoff are significant in altitudes of 3000-4000 m.a.s.l for the Ganges Basin.

Figures 6 to 8 show flows from the high-altitude catchments of the basin, all of which display strongly seasonal flows. All these catchments are headwater catchments, so discharge results solely from locally-generated runoff. The catchments represent 14% of the total area of the Basin, yet they collectively generate 31% of the total runoff.

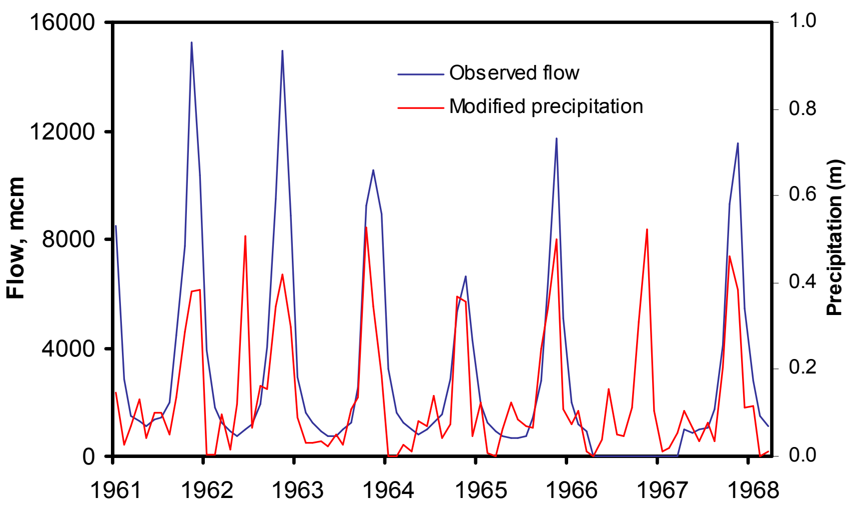

Figure 4. Modified precipitation and observed flow in the Chisapani nr Dondajri catchment.

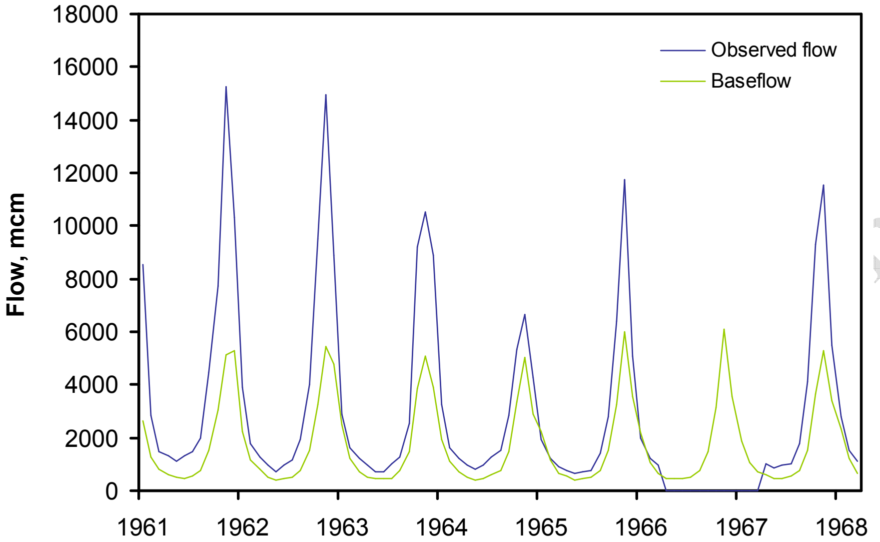

Figure 5. *Observed flow and baseflow from the Chisapani nr Dondajri catchment.*

The total area of irrigated crops is relatively small in these upstream catchments ranging from 73 km^2 in Chisapani to 248 km^2 in Devghat, or less than 1.1% of the catchment area. Surface water diversions for irrigation are less than 0.3% of the locally-generated runoff, so irrigation has a negligible impact on discharge.

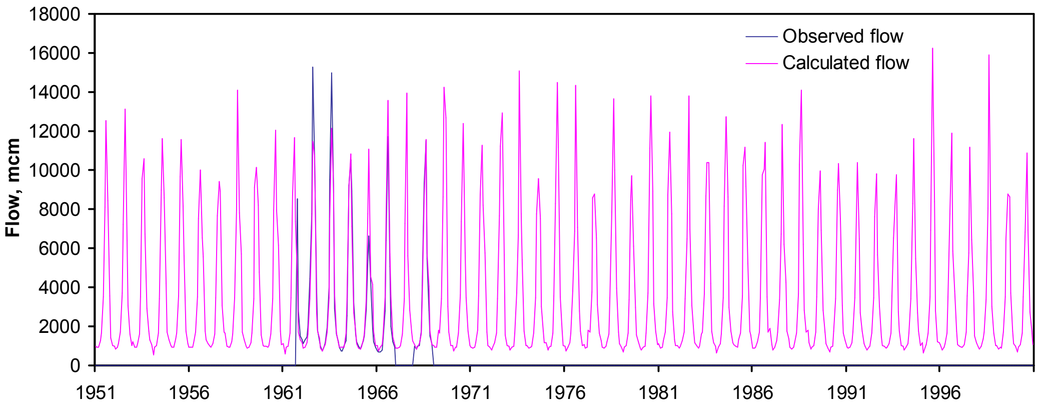

Figure 6. *Observed and modelled flow at Chisapani nr Dondajri.*

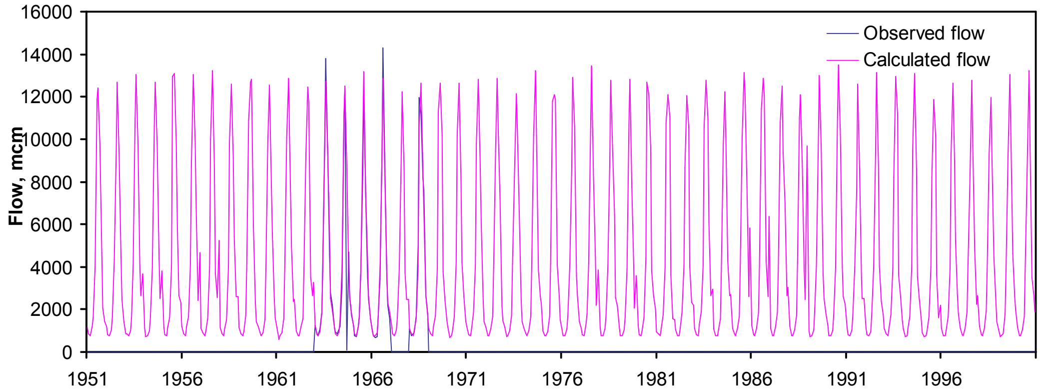

Figure 7. Observed and modelled flow at Devghat.

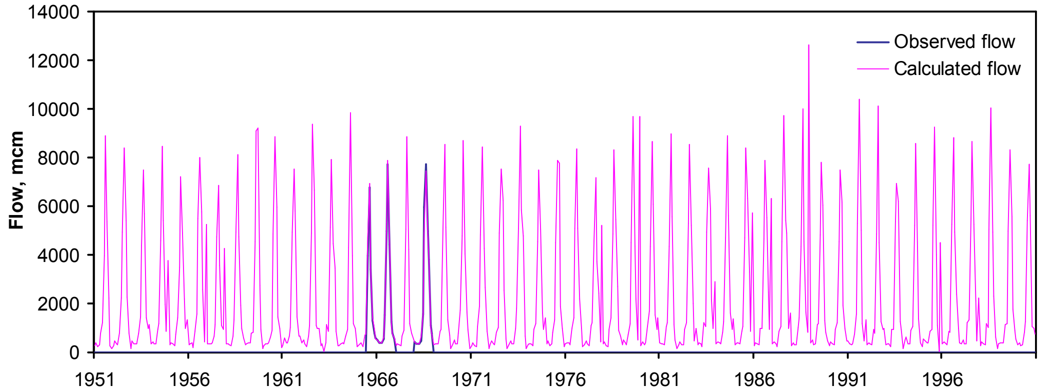

Figure 8. Observed and modelled flow at Kampu Ghat nr Udaypur.

5.2 High altitude and foothills catchments

Parts of the Ganges Source, Upper Yamuna, and Ghaghara catchments are mountainous, high-altitude areas, but the catchments also include flatter, lower-altitude regions. Snow and ice comprise 2.4; 0.5, and 0.04% of the Ganges Source (2004 km^2), Ghaghara (570 km^2), and Upper Yamuna (11 km^2) catchments respectively. Figures 9 to 11 show modelled flows from the Ganges Source, Ghaghara, and Upper Yamuna catchments. There is strongly seasonal flow in all these catchments, with peak flows in summer, and low or negligible flows throughout the dry season.

Areas of irrigated cropping are larger here than in the high altitude catchments with 20,687, 29,786, and 6,471 km^2 under irrigation in the Ganges Source; Ghaghara, and Upper Yamuna catchments, respectively. Surface water is used to irrigate 59% or more of the irrigated area. Thus irrigated crops use larger proportions of runoff generated in these catchments than in the high-altitude catchments. Surface water diversions for irrigation are equivalent to 13%, 19%, and 21% of the runoff generated in the Ghaghara, Ganges

Source, and Upper Yamuna catchments, respectively. Although runoff is generated during each month of the year, irrigation diversions periodically reduce flows from the Ganges Source to zero (Figure 9), but have a larger impact in Upper Yamuna where flows are routinely zero or nearly so in the dry season (Figure 10). Runoff from the Ghaghara catchment is supplemented by inflows from upstream (Chisapani), so discharge is largely continuous throughout the year (Figure 11).

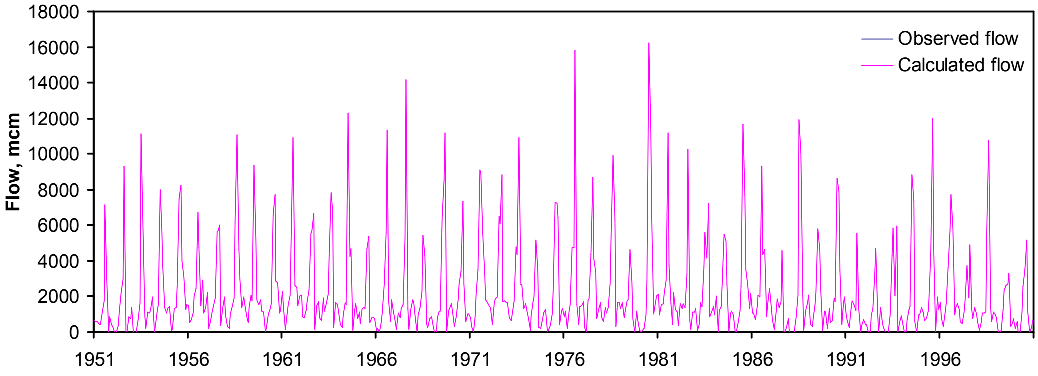

Figure 9. Modelled flow from the Ganges Source catchment.

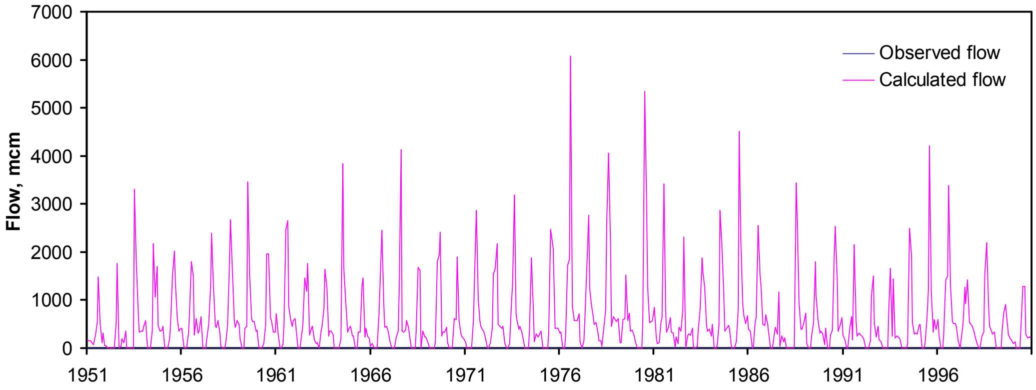

Figure 10. Modelled flow from the Upper Yamuna catchment.

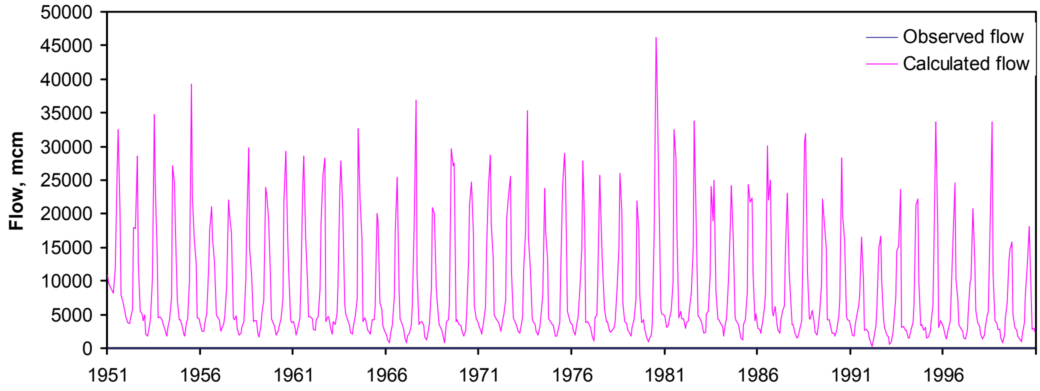

Figure 11. Modelled flow from the Ghaghara catchment.

Both locally-derived runoff and inflows from upstream make important contributions to discharge from the Ghaghara catchment (Figure 12). Local runoff contributes 59% to the mean annual discharge from the catchment. The Upper Yamuna and Ganges Source catchments are headwater catchments and therefore receive no inflows from catchments further upstream.

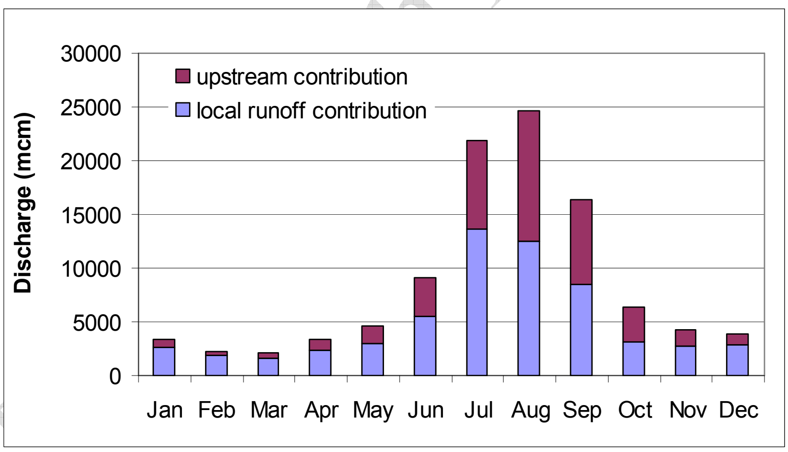

Figure 12. Contribution of upstream inflows and locally generated runoff to flows from the Ghaghara catchment.

5.2.1 Low altitude catchments

As for other Ganges Basin catchments, flows from the low-altitude catchments are strongly seasonal with maximum flows in summer, and low or zero flows during the dry season. The impact on discharge of diversions for irrigation is important for these catchments, since the area irrigated from surface water ranges from 5,601 km^2 in the Son catchment to 43,133 km^2 in Yamuna, or 7 to 26% of the total areas of these catchments, respectively. In the low-altitude catchments upstream of Farakka, mean annual diversions range from 49% of the mean annual runoff in the Middle Ganges catchment to 68% in the Chambal catchment. Although runoff is generated throughout the year, diversions reduce discharge to zero or close to zero for one month or more each year (Figures 13 to 17).

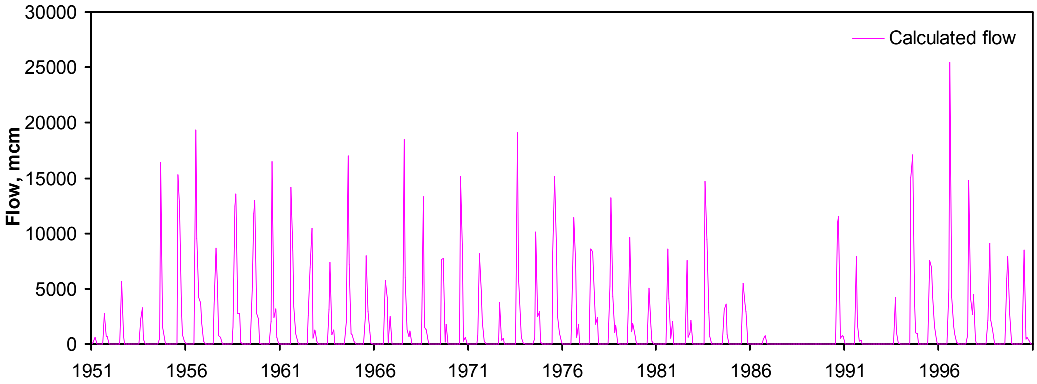

Figure 13. Modelled flow from the Chambal catchment.

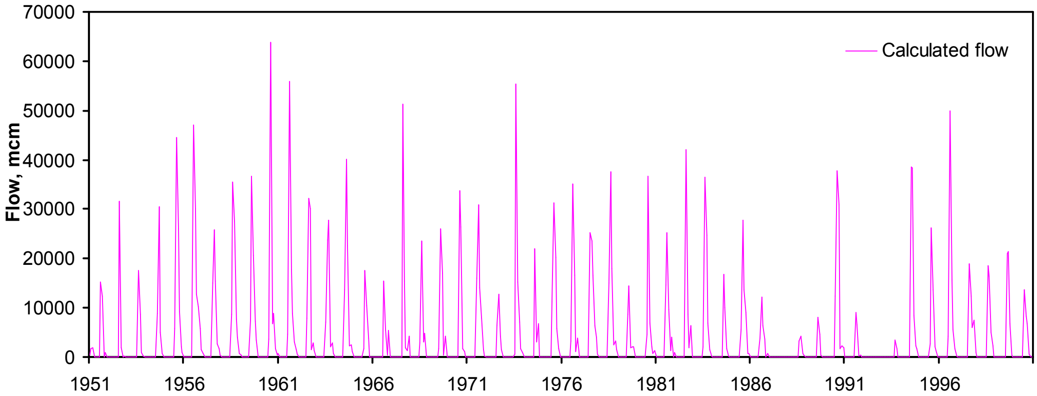

Figure 14. Modelled flow from the Yamuna catchment.

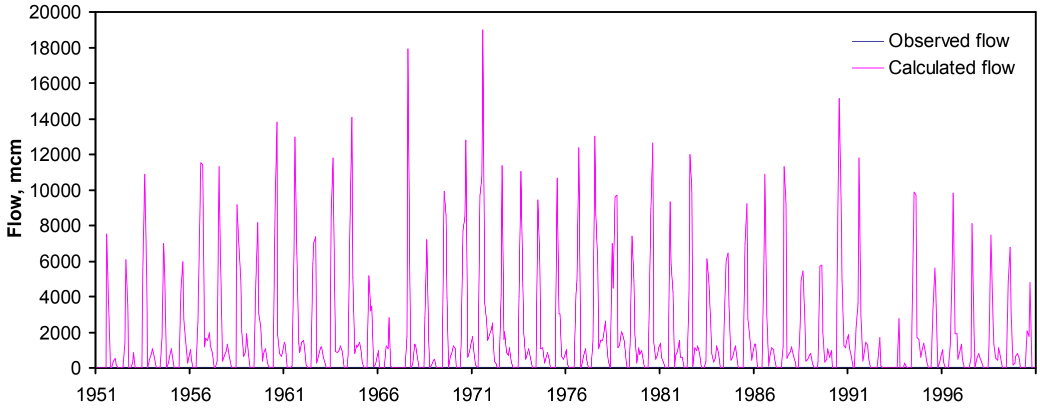

Figure 15. Modelled flow from the Son catchment.

The impact of diversions for irrigated cropping on discharge is less critical for the Middle and Lower Ganges catchments, as locally-generated runoff is augmented by inflows from the catchment upstream (Figures 16 and 17). However, irrigation diversions periodically reduce their discharge to neglible.

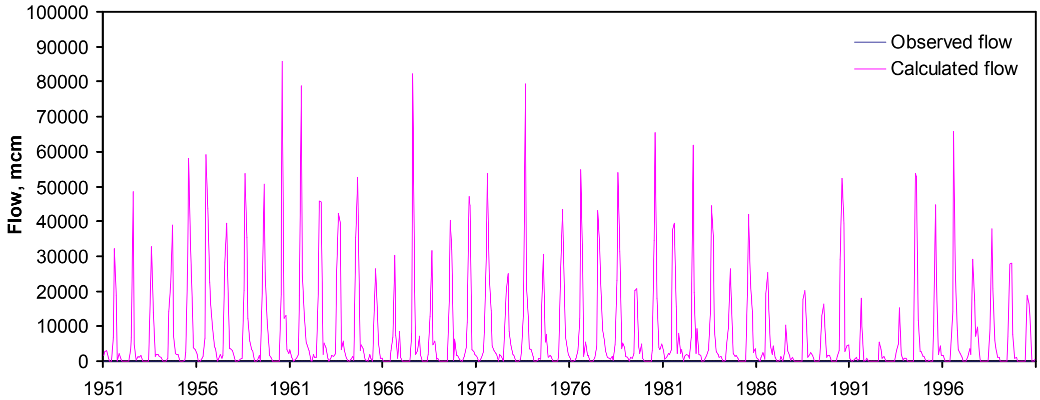

Figure 16. Modelled flow from the Middle Ganges catchment.

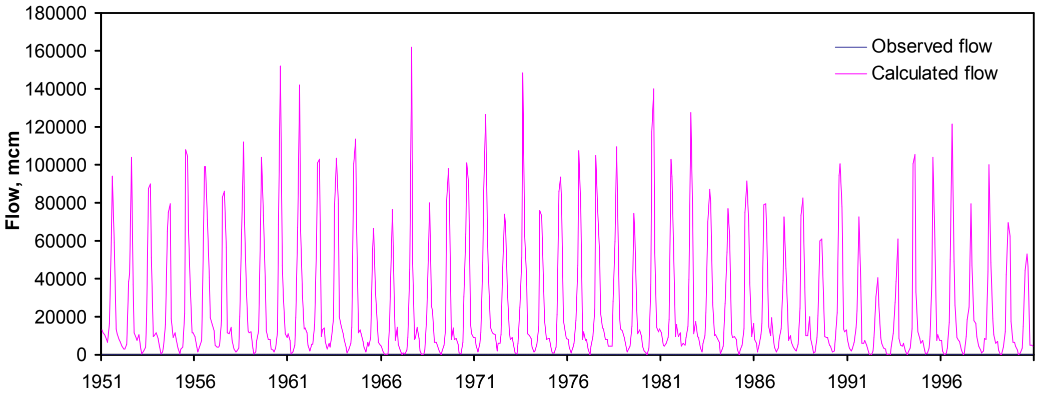

Figure 17. Modelled flow from the Lower Ganges catchment.

Discharge from the Farakka and Paksey catchments show similar seasonal distribution of flows to the upstream catchments (Figures 18 and 19). The match of the modelled discharge to observed discharge for these two catchments gives some confidence in the modelling of the gross volume of inflows from upstream and hence the modelling of gross water use. Irrigated cropping is extensive in both catchments, covering 12,189 and 13,819 km^2 or 30% and 32% percent respectively of the Farakka and Paksey catchments. Much of this is irrigated from surface water sources, with 68% of irrigated land in Paksey and 72% in Farakka irrigated with surface water. Diversions are equivalent to 16% and 12% of annual runoff in the Farakka and Paksey catchments.

The Farakka Barrage was constructed in 1974, and diversions to the Hooghly River began in April 1975. We do not have data for the volumes diverted to the Hooghly River at Farakka. We have assumed that diversions from 1978 were according to the five-year agreement between India and Bangladesh, signed on 5 November, 1977 (Rahaman 2006). Sharing flows at Farakka was based on the availability of 75 percent of the observed flows. Water is generally shared at 60% for Bangladesh and 40% for India. If flow is less than 80% of the 75% availability figure for that month, Bangladesh gets a minimum of 80% of its 60% share. From January 1997, we assumed flow at Farakka was diverted to the Hooghly River according to the Ganges Water Sharing Treaty between India and Bangladesh, signed on 12 December, 1996 (Rahaman 2006). The agreement was that the discharge at Farakka is shared equally between India and Bangladesh if flow is 70,000 cusecs (about 2000 m^3/sec) or less. From 70,000 to 75,000 cusecs (about 2000-2100 m^3/sec) Bangaldesh will get 35,000 cusecs (about 1000 m^3/sec), with India getting the remainder. If the discharge is greater than 75,000 cusecs (about 2100 m^3/sec), India will get 40,000 cusecs (about 1100 m^3/sec) and Bangladesh the remainder. Since we have no data or treaty/agreement to guide us for the pre-1978 diversions, we have assumed no water was diverted between 1975 and 1977.

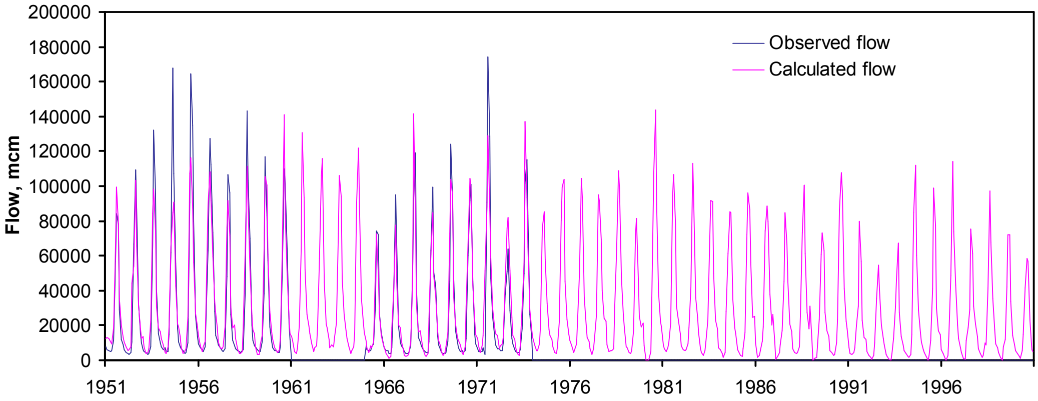

Figure 18. Observed and modelled flow at Farakka.

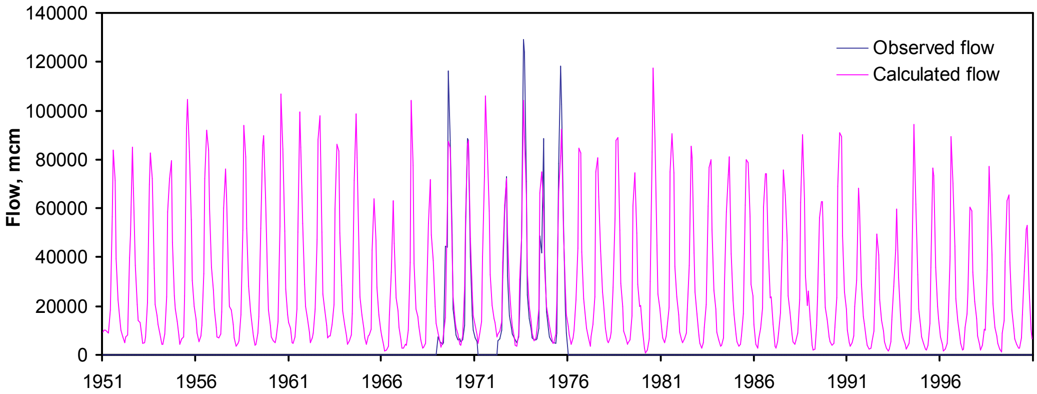

Figure 19. Observed and modelled flow at Paksey.

Figures 18 and 19 show the impact of these assumed diversions at Farakka on modelled discharge from the Farakka and Paksey catchments. We do not have flow data after December 1973 for Farakka, or after December 1975 for Paksey, so these flows are speculative. Flows at both Farakka and Paksey tend to be lower post-1978, compared with pre-1978. Dry season flows are reduced to zero with increasing frequency after 1978, compared with before 1978. Although speculative, these modelled results are broadly in line with the conclusions of Mirza (1997). The reduction in flows after 1978 may result in part from several years of low rainfall from 1980 to 2000 (Figure 3). Annual rainfall was below average for 13 years, or 65% of the time during the period 1981 to 2000. This compared with 12 years below average, or 40% of the time between 1951 and 1980.

Whole basin annual runoff and precipitation show similar trends through time from 1951 to 2000 (Figure 20), with peaks in annual rainfall generally resulting in peaks in runoff. Annual average runoff is 568,160 mcm, but shows large temporal variation ranging from 409,600 mcm in 1992 and 678,160 mcm in 1955. Runoff tends to decline after 1980, in parallel with a decreasing trend in rainfall from 1981 to 2000.

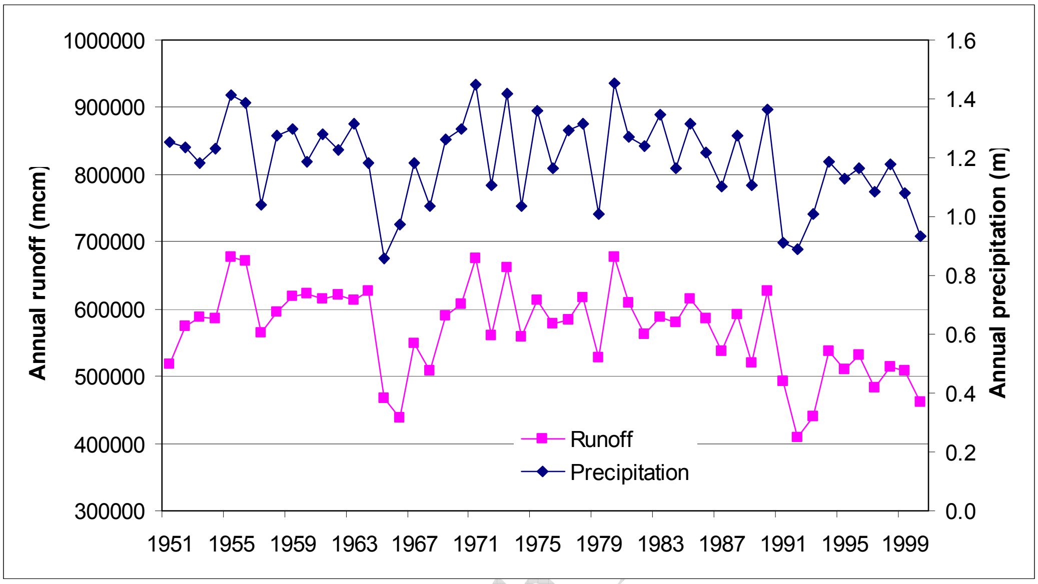

Figure 20. Whole basin annual precipitation and runoff from 1951 to 2000.

5.3 Water use

Figure 21 summarizes the major water uses in the Basin. The mean annual input by precipitation to the Ganges Basin totals about 1,170,000 mcm. 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 429,000 mcm or about 37% of the total precipitation input. Rainfed agriculture is the most extensive land use, covering 52% of the Basin. Its water use is correspondingly high, with a mean annual water use of about 372,000 mcm, or 32% of the water used (Figure 21).

Irrigated agriculture covers 25% of the Basin, with 17% of the total area irrigated from surface water sources, and 8% from groundwater. The estimated mean annual water use by irrigated agriculture is about 210,000 mcm, or 18% of the total water use. The majority of the irrigated water use is from crops irrigated from the surface water resource (70%), with the remaining 30% from groundwater irrigated crops.

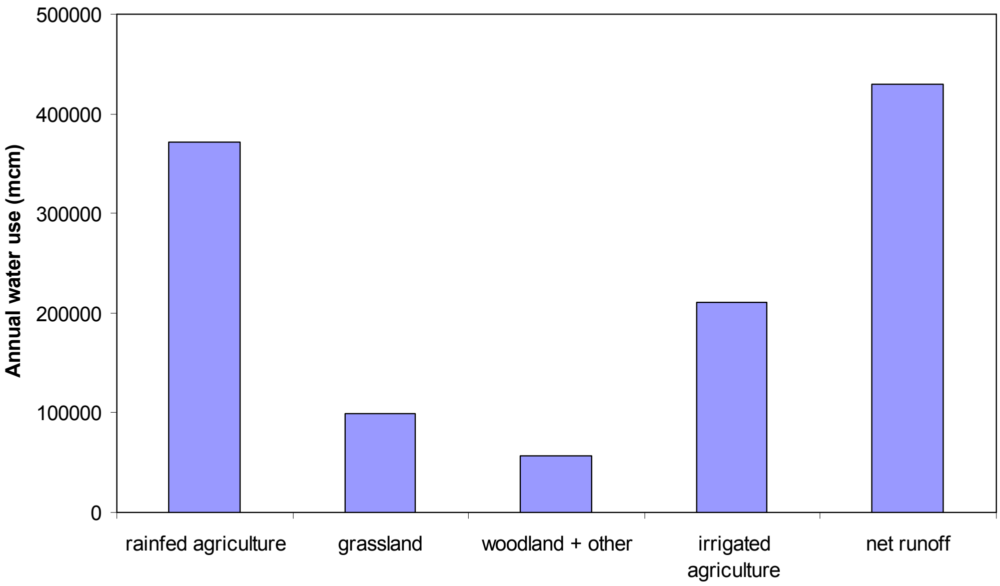

Figure 21. Summary of major water uses in the Ganges Basin.

Grassland covers 14% of the Basin and consumes about 100,000 mcm (8%) of the water used. Land uses included in the 'woodland + other' class are woodlands and forests; urban; bare ground; barren and sparsely vegetated; and snow and ice. This land-use class, covering 8% of the Basin, is largely dominated by woodland, and has the lowest mean annual water use of about 57,000 mcm (5% of the water used).

The distribution of the different water uses across the Basin is shown in Figure 22. 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 21. The figure shows the different behaviour of the runoff-generating northern parts of the Basin rimmed by the Himalayas and the flatter, drier, irrigated southern parts of the Basin. Irrigation is a major water user in most parts of the Basin except the northern mountain rim.

In catchments at lower altitudes, either rainfed or irrigated agriculture is the most important components of vegetation water use. Irrigated water use is most important in the Chambal, Yamuna, Son, and Lower Ganges catchments, and rainfed agriculture in the Upper Yamuna, Ganges Source, Midddle Ganges, Farakka, and Paksey catchments. Water used in irrigation in the lower-altitude catchments ranged from 11% in the Ganges Source catchment to 46% in Upper Yamuna. Water use of rainfed agriculture ranges from 27% in the Son catchment to 28% in the Middle Ganges. Either grassland or woodland are the least important uses of water in the lower-altitude catchments. Water use by grassland ranges from 1% in the

Paksey catchment to 15% in Upper Yamuna. Water use by woodland ranges from 0.1% in the Yamuna catchment to 8% in Ganges Source.

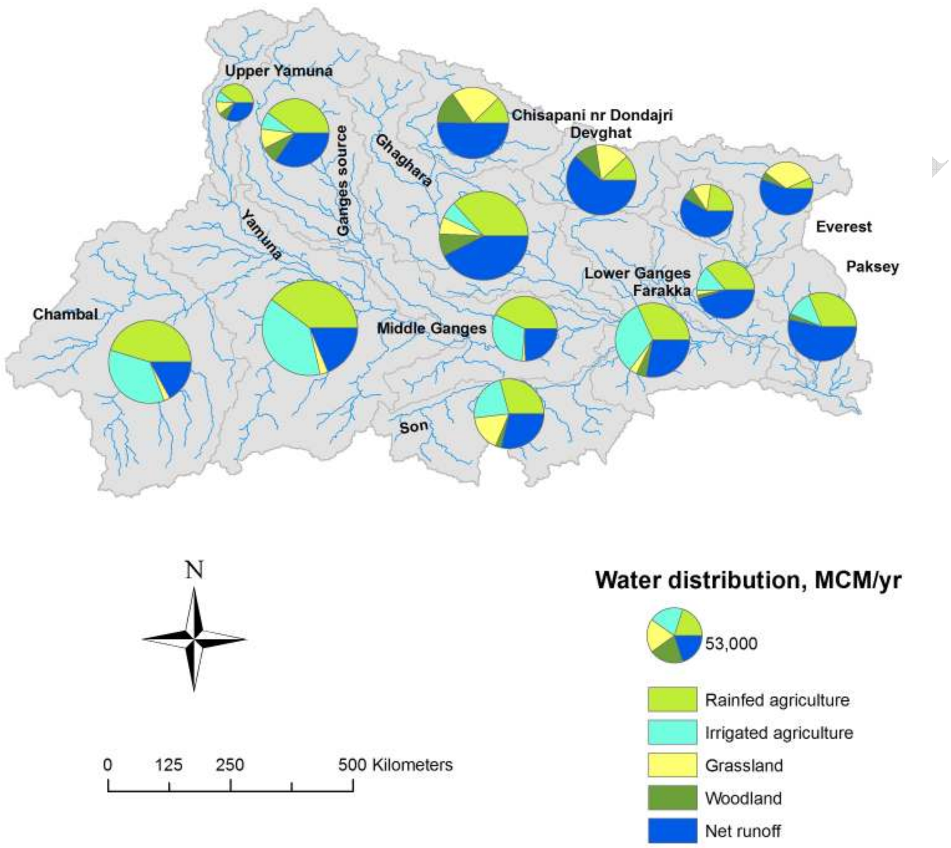

Figure 22. The spatial distribution of major water uses in catchments of the Ganges Basin.

Net runoff is generally lower in the lower-altitude catchments than the high-altitude Chisapani, Devghat, Kampu Ghat, and Everest catchments, ranging from 17% in the Chambal catchment to 62% in Devghat. Of the low-altitude catchments, net runoff is greatest in the wetter Paksey and Farakka catchments. Thus we may consider the low-altitude catchments (with the exception of Paksey and Farakka) as net users of water, and the high-altitude catchments as net contributors of water to the Basin.

The crop coefficients and calendars we have used for estimating the water use of irrigated crops are based on data from Ullah et al. (2001) for the Indus Basin. We assumed crop types, coefficients, and cropping calendars in Ganges catchments were similar to those in the Indus basin catchments with similar climate. 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 derived from local data. Crop coefficients used for partitioning catchment evapotranspiraton 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.

5.4 Catchment and basin hydrological characteristics

Selected hydrological characteristics will be useful for comparing the Ganges Basin hydrological function and its vulnerability with those of other basins under study in the Challenge program. We briefly outline some of these hydrological characteristics 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 Ganges Basin is 49% (i.e. mean annual runoff is 49% of mean annual precipitation). Similarly, 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 Ganges Basin.

Catchment	Runoff ratio (%)
Chisapani nr Dondajri *	50
Devghat *	62
Kampu Ghat nr Udaypur *	58
Everest	46
Ghaghara	35
Chambal	29
Upper Yamuna	28
Yamuna	33
Ganges source	30
Middle Ganges	31
Son	44
Lower Ganges	37
Farakka	38
Paksey	46
Whole basin	49

* Denotes modified precipitation used in calculating ratios

Catchments in the high-altitude parts of the Basin (Chisapani, Devghat, and Kampu Ghat) generally show the greatest ratios of runoff to precipitation (> 50%). In the lower-altitude catchments of the Basin, the ratio ranges from 29% in Chambal to 46% at Paksey. 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 23). As expected, runoff/area increases with increasing precipitation. As shown above (Figure 20) total annual runoff from the Basin varies with the annual variation in rainfall for 1950-2000. A single function may be used to quantify the relationship between annual runoff for the whole Basin and precipitation (Figure 24). The relationship may be used as a first estimate of the impact of changing rainfall under climate change scenarios. If potential evaporation were to change significantly under climate change, the rainfall-runoff relationship may also be expected to change.

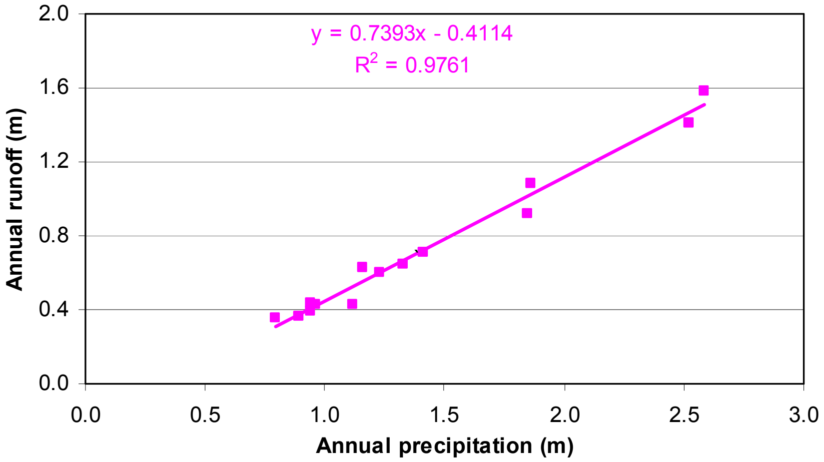

Figure 23. Annual average runoff/area as a function of annual average precipitation (or modified precipitation) for catchments of the Ganges Basin.

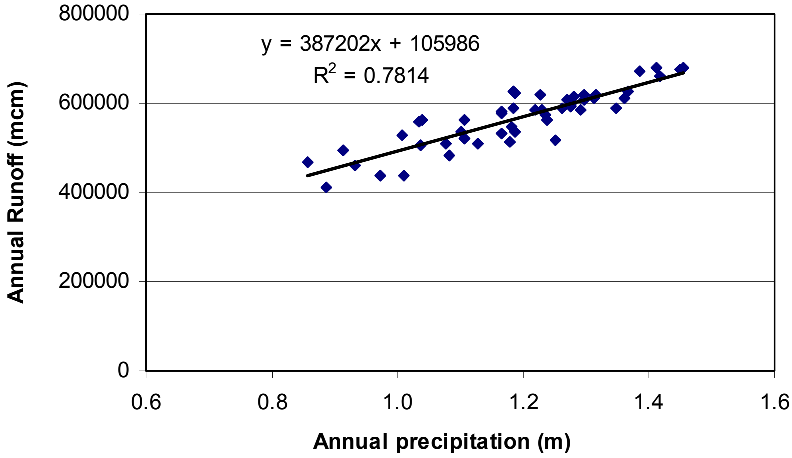

Figure 24. Annual runoff for the whole Ganges Basin as a function of annual precipitation.

6 Example use

To demonstrate the application of the spreadsheet, we ran a scenario on the impact of changed irrigation efficiency on irrigated agriculture in the Ganges 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 the irrigation efficiency increased to 0.6. We also assumed that the area of irrigated land 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 both wet-season and dry-season flows reduce marginally at Farakka (Figure 25). Thus, locally-reduced irrigation demand does not translate to a reduced water use at a basin level, and the small overall reduction in flows results from the increased area of irrigated crop. Molle and Turral (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 water to other uses downstream. The predicted water use by irrigated crops increases from about 106,000 to 117,000 mcm per year.

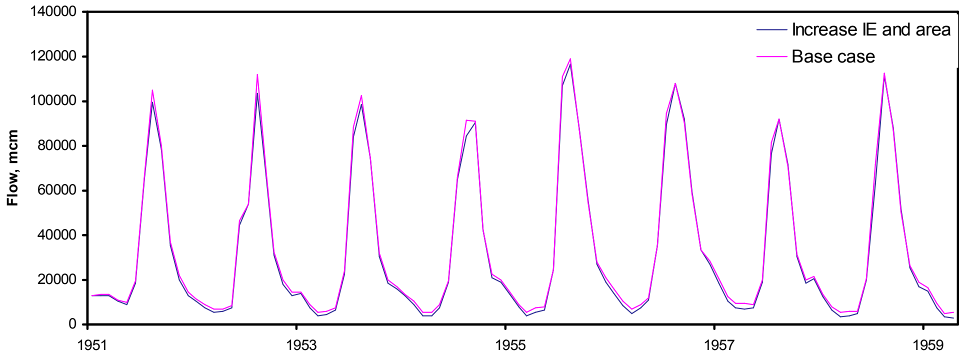

Figure 25. Discharge at Farakka for the base case and for the scenario of increased irrigation efficiency and area of irrigation as described in the text.

7 Conclusions

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

The Ganges basin has high annual average rainfall of more than 1000 mm spatially averaged across the Basin, and 2000 mm or more in the northern Himalayan catchments. The rain falls mainly 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 accounts for more water than any other use, followed by rainfed agriculture. Irrigation is the third major water user, accounting for a little under a quarter of the total water use: one-third of the irrigation water comes from groundwater.

We have undertaken a preliminary scenario that simulates the impact of increasing both irrigation efficiency and the area irrigated on 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 increasing the irrigated area, which leads to an overall net increase in water consumption.

8 Acknowledgements

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