Hydrol. Earth Syst. Sci. Discuss., 12, 9741–9763, 2015
www.hydrol-earth-syst-sci-discuss.net/12/9741/2015/
doi:10.5194/hessd-12-9741-2015

Hydrology and Earth System Sciences
Discussions
Open Access

Reviving the "Ganges Water Machine": where and how much?

L. Muthuwatta[1], U. A. Amarasinghe[1], A. Sood[1], and S. Lagudu[2]

[1]International Water Management Institute (IWMI), Colombo, Sri Lanka
[2]Council for Scientific and Industrial Research - National Geophysical Research Institute (CSIR-NGRI), Hyderabad, India

Received: 21 July 2015 – Accepted: 31 August 2015 – Published: 25 September 2015

Correspondence to: L. Muthuwatta (l.mutuwatte@cgiar.org)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Surface runoff generated in the monsoon months in the upstream parts of the Ganges River Basin contributes substantially to downstream floods, while water shortages in the dry months affect agricultural production in the basin. This paper examines the parts (sub-basins) of the Ganges that have the potential for augmenting subsurface storage (SSS), increase the availability of water for agriculture and other uses, and mitigate the floods in the downstream areas. The Soil and Water Assessment Tool (SWAT) is used to estimate sub-basin-wise water availability. The water availability estimated is then compared with the sub-basin-wise un-met water demand for agriculture. Hydrological analyses revealed that five sub-basins produced more than 10 billion cubic meters ($\mathrm{B\,m^3}$) of annual surface runoff consistently during the simulation period. In these sub-basins, less than 50 % of the annual surface runoff is sufficient to irrigate all irrigable land in both the *Rabi* (November to March) and summer (April to May) seasons. Further, for most of the sub-basins, there is sufficient water to meet the un-met water demand, provided that it is possible to capture the surface runoff during the wet season. It is estimated that the average flow to Bihar State from the upstream of the Ganges, a downstream basin location, is $277 \pm 121\,\mathrm{B\,m^3}$, which is more than double the rainfall in the state alone. Strong relationships between outflows from the upstream sub-basins and the inflows to Bihar State suggested that flood inundation in the state could be reduced by capturing a portion of the upstream flows during the peak runoff periods.

1 Introduction

Matching water demand with supply in river basins with monsoonal climate is a major challenge. The monsoon-driven seasonal hydrology in India is often associated with floods and droughts, which affects the most vulnerable people of society (women and children, the poor and other disadvantaged social groups), and causes damage to

HESSD
12, 9741–9763, 2015

crops and infrastructure. In these basins, upstream storage is generally the preferred solution to buffer the variability of flow and reduce floods downstream (Khan et al., 2014). Traditionally, dams are the major surface water storage structures. However, the construction of large dams requires huge investments, displaces people, submerges forests, and some of the water released is lost to non-beneficial evaporation (Pavelic et al., 2012). In contrast, underground aquifers are efficient water reservoirs with minimum evaporative losses, no displacement of people or submergence of land (Bouwer, 2000; Dillon, 2005; Ghayoumian et al., 2007).

For centuries, the utilization of water resources in the Ganges River Basin has been severely hampered by substantial seasonal variation in river flows. In the basin, the main source of water is the (southwest) monsoon rainfall, and also the snowmelt and ice melt in the Himalaya during the summer season (Sharma and de Condappa, 2013) which is about 1170 billion cubic meters ($\mathrm{B\,m^3}$). Of this, around 500 $\mathrm{Bm^3}$ becomes stream flow with the rest directly recharging groundwater or returned to the atmosphere through evapotranspiration (Jeuland et al., 2013). The monsoon (between June and September) contributes to about 80 % of total annual rainfall, and about 80 % of the annual river flow (Revelle and Lakshminarayana, 1975). The rainfall during the rest of the year is low and the river flows, generated mainly through recharged groundwater and snowmelt, are barely sufficient to satisfy the water needs of all the sectors (Huda and Shamsul, 2001). For instance, the estimated average annual flow (1990 to 2008) at the Harding Bridge in Bangladesh (just below the Indian border) was about 340 $\mathrm{B\,m^3}$ and ranged from 197 to 486 $\mathrm{B\,m^3}$, whereas flow in the dry season (October to May), at the same location, varied from 43 to 63 $\mathrm{B\,m^3}$.

Extensive flooding in the Ganges River Basin, especially in the downstream areas, occurs annually (Mishra, 1997). The major causes of floods in the downstream areas are the shallow groundwater table and high monsoonal rainfall in these areas, and the large surface runoff generated in the upstream sub-basins. Previous studies (Revelle and Lakshminarayana, 1975; Sadoff et al., 2013) indicated that, due to the limitation of the construction of large surface reservoirs, recharging groundwater beyond the nat-

HESSD
12, 9741–9763, 2015

ural level is the best way to control floods downstream. Subsurface storage (SSS) also allows meeting water requirements during the dry months. Popular belief is that having large dams is the only option to meet the basin's water storage needs (Onta, 2001). ~~However~~, contrary to that, the Ganges strategic basin assessment conducted by the World Bank (2012) found that the sustainable use of the basin's vast groundwater aquifers can store far greater volumes of water compared to the potential of man-made storage in the basin, which is about 130–145 B m^3 (Sadoff et al., 2013). For instance, the estimated storage available in the shallow alluvial aquifers of eastern Uttar Pradesh and Bihar, which could be utilized in the dry season and naturally recharged in the wet season, is 30–50 B m^3 (SMEC, 2009)

From a purely biophysical perspective, four conditions are necessary to develop sustainable SSS solutions (that involve groundwater recharge beyond the natural levels) to tackle water scarcity and flood damage in the basin:

- Existence of adequate un-met demand (e.g., for agriculture and other uses) to deplete the water pumped from the aquifers in a basin/sub-basin.
- Existence of adequate flows for capture during the monsoon season.
- Existence of extra space underground which can be created by pumping and depleting groundwater before the onset of the monsoon.
- Ability to actually capture the excess monsoon surface runoff to recharge that additional space created – naturally (through surface water and groundwater interactions) or artificially (through managed aquifer recharge (MAR)).

Amarasinghe et al. (2015) examined the first condition above and estimated un-met demand throughout the basin under two scenarios of irrigation expansion. The main objective of this paper is to examine the second condition above, i.e., assess the potential availability of runoff, by conducting a hydrological analysis of the sub-basins of the Ganges River Basin.

HESSD
12, 9741–9763, 2015

2 Methodology

2.1 The model

Many models have been developed (e.g., Eastham et al., 2010; Gosain et al., 2011; World Bank, 2012) to study water issues in the Ganges River Basin (Johnston and Smakhtin, 2014). However, they are not available to the public. To overcome this restriction and provide the research community with a working hydrological model for the Ganges River Basin, the International Water Management Institute (IWMI) has developed a publicly available hydrological model for the basin (Muthuwatta et al., 2014) using the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998). The model set up files can be downloaded from the website http://waterdata.iwmi.org/model_inventory.php, and used in further applications and scenario analyses in a variety of projects.

SWAT is a widely used, semi-distributed conceptual hydrological model developed by the Agricultural Research Service of the United States Department of Agriculture (USDA) over the last 30 years, and is available free of charge as a public domain model (Arnold et al., 1998; Gassman et al., 2007; Sood et al., 2013). Broadly, the SWAT input data can be grouped into five categories: topography or terrain, land use, soil, land use management and climate (Neitsch et al., 2002). SWAT possesses adequate representation of processes governing hydrology and is particularly suitable for application in large river basins. In SWAT, a river basin is subdivided into a number of catchments, so that each catchment has at least one representative stream. Based on unique combinations of soil, land use and slope, the catchments were further divided into hydrological response units (HRUs), which are the fundamental units of calculation. Subdividing the watershed into areas having unique land use, soil and slope combinations enables the model to reflect differences in evapotranspiration and other hydrologic conditions. Runoff is predicted separately for each HRU and routed to obtain the total runoff for the catchment.

SWAT simulates the local water balance of the catchment through four storage volumes – snow, soil profile, shallow aquifer and deep aquifer – based on the soil water

HESSD
12, 9741–9763, 2015

balance (Eq. 1):

$$\mathrm{SW}_t = \mathrm{SW}_0 + \sum_{t=1}^{t} (R_t - \mathrm{SR}_t - \mathrm{ET}_t - P_t - G_t) \tag{1}$$

Where: SW_t is the soil water content minus the wilting-point water content at time t, and R_t, SR_t, ET_t, P_t, and G_t are the daily amounts (in mm) of rainfall, runoff, evapotranspiration, percolation and groundwater flow, respectively, at time t. SW_0 is the initial soil water content. The simulated processes include surface runoff, infiltration, evaporation, transpiration, lateral flow, and percolation to shallow and deep aquifers.

2.2 The data and model setup

The model used in this study was set up using the datasets shown in Table 1. The Ganges River Basin was delineated using 3000 ha as the minimum area threshold and has resulted in 1684 catchments (Fig. 1). The model was initially developed to study streamflow entering Bangladesh. Therefore, the spatial domain of the SWAT model developed for the Ganges does not entirely cover the areas that belong to West Bengal and Bangladesh. However, this does not affect the current study, as its focus is to assess water availability in the upstream sub-basins of the Ganges River Basin.

Figure 1 shows the catchments delineated for SWAT, 22 major sub-basins (Table 2) in the Ganges River Basin and the area covering Nepal. The 19 main sub-basins in the Indian part selected in this paper are those considered by the Central Water Commission (CWC) of India, which is the main government agency responsible for water resources development and management in the Ganges River Basin. Since the focus of this study is to estimate water availability in the sub-basins within India, Nepal is considered as one region. Hereafter, in this paper, “sub-basins” are referred to as the 22 major areas shown in Fig. 1, while the smaller spatial units inside those 22 sub-basins and Nepal are termed “catchments”. For details of the model setup, including calibration and validation, please refer to Muthuwatta et al. (2014).

HESSD
12, 9741–9763, 2015

2.3 Simulating sub-basin runoff

Annual time series of catchment-scale surface runoff from 1991 to 2010 were constructed by aggregating daily surface runoff simulated by SWAT. Next, using geographic information system (GIS) techniques, annual runoff time series were estimated for all sub-basins within the modeled area of the Ganges River Basin. The study uses the hydrographs of the simulated runoff (SR) to estimate the 75 % dependable runoff (SR_{75}). SR_{75} is an estimate of the runoff that can be expected in the basin, on average, every three out of 4 years, and is considered to be a reliable estimate of water availability for augmenting groundwater storage.

3 Results

3.1 Surface runoff of the sub-basins

The spatial and temporal distribution of the annual surface runoff is analyzed to determine the water availability in different sub-basins. Streamflow includes surface runoff and baseflow from groundwater, which can be captured by diversion or from dams. Surface runoff is part of the precipitation that is left after evapotranspiration and infiltration, which can be captured for MAR before it reaches the stream. Therefore, only the surface runoff portion was considered for augmenting SSS. Figure 2 shows the simulated catchment-scale mean annual surface runoff.

The surface runoff of catchments ranges from less than 0.1 Bm^3 to more than 2.0 Bm^3. The statistics of the estimated surface runoff for the sub-basins is given in Table 3.

The estimates of mean annual surface runoff at sub-basin-scale ranges from 2.24 Bm^3 in Chambal Lower (6) to 63.17 Bm^3 in Nepal (15). Additionally, the high standard deviations in Table 3 indicate significant temporal variation within sub-basins. Further analysis shows that surface runoff in the wet months (June to October) is more than 80 % of the annual surface runoff in most sub-basins (Table 3, last two columns). This intra- and inter-annual variability of the flows clearly indicates the need for storages to capture the excess surface runoff during the monsoon season, which could be a SSS. For this analysis, SR_{75} was used to identify the sub-basins that are consistently producing higher volumes of surface runoff. Figure 3 shows the spatial distribution of SR_{75} of sub-basins.

Ghaghara (10) sub-basin and Nepal have, by far, the largest SR_{75}. The Kali Sindh (13), Ramganga (16), Son (17) and Yamuna Lower (20) sub-basins have more than 10 Bm^3 of SR_{75}. The Gandak (9) also produces higher surface runoff, but the sub-basin is located in the downstream area of the Ganges River Basin. Because of the high monsoon runoff, the upstream sub-basins contribute substantially to flooding in the downstream areas of the Ganges River Basin.

3.2 Un-met water demand for agriculture

8-1

Amarasinghe et al. (2015) estimated the un-met agricultural water demand. Two scenarios were considered in the analysis (Table 4).

– Scenario 1 assumed that all irrigable land will be irrigated in the *Rabi* (November to March) and summer (April–May) seasons.

– Scenario 2 considered all cropland to be irrigated in the *Rabi* and summer seasons.

As of now, all the sub-basins in the Ganges River Basin have substantial un-met water demand for agriculture in the dry season. Therefore, capturing a substantial portion of the surface runoff during the monsoon months can help close the gap between current supply of water and demand in the dry months. Therefore, there is potential for increasing agricultural productivity in these sub-basins with more irrigation in the dry months. Table 4 presents the sub-basin-wise un-met demand (Amarasinghe et al., 2015) and the percentage of dependable runoff required to close the un-met demand.

HESSD
12, 9741–9763, 2015

In the sub-basins, the total un-met demands are 55.03 and 108.4 B m^3 under scenarios 1 and 2, respectively. The values presented in Table 4 show that, for some sub-basins, annual un-met demand exceeds the annual water availability. In these sub-basins, only a part of the un-met demand can be satisfied by additional underground storage. In some other sub-basins, the un-met demand is less than 30 % of the SR_{75} of surface runoff. These sub-basins have the potential to meet all the un-met demand with SSS. For instance, in the Ramganga sub-basin, the SR_{75} of surface runoff is about 10.1 B m^3, and approximately 83 % of this runoff is occurring during the wet season. To meet the maximum un-met agricultural water demand in the Ramganga sub-basin only requires capturing 33 % of the monsoon surface runoff.

3.3 Impact of sub-surface storage on flood control

Floods are a recurrent phenomenon in some parts of the Ganges, such as the State of Bihar, which is located in the middle part of the basin (Fig. 4). More than 20 million people have been affected by floods in 1987, 2004 and 2007. The spatiotemporal flood inundation extent across Bihar, revealed from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data, showed that the flood inundated area can be more than 14 000 km^2 during the peak flood period (Amarnath et al., 2012). Flow coming from upstream of the Ganges plays a substantial role in floods in the state. The mean annual streamflow from the upstream sub-basins from 2001 to 2010 was estimated and is presented in Fig. 4.

The highest flow of 142.7 B m^3 is coming from upstream of the Gomati confluence to Muzaffarnagar (19), as it gets a large contribution from the Yamuna Lower (20). The second highest flow (78.2 B m^3) to Bihar is coming from the Ghaghara sub-basin (10) and it receives outflows from the western part of Nepal. The mean annual flow to Bihar from the various sub-basins in the Indian part of the Ganges River Basin is about 277 ± 121 B m^3, and the mean annual rainfall in Bihar is about 123 ± 32 B m^3. This

HESSD
12, 9741–9763, 2015

indicates that the water volumes received from upstream flows are more than twofold the amount of rainfall in Bihar.

As presented in Fig. 3, five sub-basins located in the upstream part of the Ganges River Basin consistently produce higher surface runoff compared to other sub-basins. These sub-basins are Ghaghara (10), Son (17), Yamuna Lower (20), Ramganga (16) and Kali Sindh (13). Figure 5 shows the relationship between the outflows from four upstream sub-basins with inflow to the State of Bihar. Coefficient of determinant (R^2) in each graph indicates that annual outflows from the upstream sub-basins are strongly correlated with the inflows to the State of Bihar. R^2 for Kali Sindh is 0.71 and not presented in Fig. 5.

Flow from Ghaghara and Yamuna Lower sub-basins is approximately 30 % of the total inflow from the upstream Ganges River Basin to Bihar. The contributions from Son, Kali Sindh and Ramganga are 17, 10 and 7 %, respectively. This implies that, by capturing a portion of the upstream flows during peak runoff periods would reduce the flow to Bihar, which creates floods during the wet season.

4 Conclusions

Creating additional SSS beyond the current levels in the Ganges River Basin can simultaneously enhance water supply for beneficial depletion and control downstream floods. Water availability analysis conducted and based on time series of simulated surface runoff using SWAT showed that annual total surface runoff generated in the Ganges River Basin is about 298 ± 99 B m^3, and runoff in the monsoon months contributes to 80 % of this total runoff. The sub-basin-wise mean annual surface runoff ranges from 2.24 to 35.56 B m^3, and the contribution of runoff from Nepal is about 63 B m^3. Several sub-basins in the Ganges River Basin produce sufficiently high dependable annual surface runoff that can be stored underground and used during the dry season. For instance, annual surface runoff in the five sub-basins in the upstream of Ganges River Basin is more than 10 B m^3. Comparison of sub-basin-wise surface runoff with the estimated un-met water demand indicated that capturing only a portion of the wet-season runoff would be sufficient to provide water to irrigate all the irrigable land in the dry months.

Further analysis revealed that the annual surface runoff from the upstream of the Ganges River Basin to the State of Bihar, a flood-prone area located downstream, is twice the amount of rainfall in the same area. Sub-basin-wise streamflow analysis in the Ganges River Basin showed that approximately 60 % of the upstream flow to Bihar comes through the Ghaghara and Yamuna Lower sub-basins. This runoff contributes to the recurrent floods in Bihar. As shown in Fig. 5, there are strong linear correlations between annual outflows from the upstream sub-basins and the inflow to the State of Bihar. This suggests that SSS upstream has the potential to control floods downstream, by capturing a portion of the surface runoff during the wet season in the upstream sub-basins.

This study only discusses the surface water availability for SSS, and further analysis is needed to ascertain the storage capacity of the aquifer and how much additional storage capacity can be created by pumping groundwater during the dry months. Further, a detailed analysis of the soil, topographic and geological characteristics is required to determine the suitable areas for groundwater recharge.

Finally, it is pertinent to understand the interactions between groundwater and surface water in the sub-basin. This requires coupling a groundwater-surface water model to run some scenarios to investigate the effect of pumping and recharging of groundwater on the hydrology of the Ramganga sub-basin.

Acknowledgements. This research study was undertaken as part of the CGIAR Research Program on Water, Land and Ecosystems (WLE) by the International Water Management Institute (IWMI), Colombo, Sri Lanka, and the National Institute of Hydrology (NIH), Roorkee, India. The authors would like to acknowledge the valuable assistance provided by staff members of IWMI's GIS, RS and Data Management (GRandD) unit, especially Salman Siddiqui (Senior Manager, GRandD unit).

References

Amarasinghe, U. A., Muthuwatta, L. P., Lagudu, S., Anand, S., and Jain, S. K.: Reviving the "Ganges Water Machine": Why?, Hydrol. Earth Syst. Sci. Discuss., 12, 8727–8759, doi:10.5194/hessd-12-8727-2015, 2015.

Amarnath, G., Mohamed, A., Pramod, A., and Smakhtin, V.: Detecting spatio-temporal changes in the extent of seasonal and annual flooding in South Asia using multi-resolution satellite data, edited by: Civco, D. L., Ehlers, M., Habib, S., Maltese, A., Messinger, D., Michel, U., Nikolakopoulos, K. G., and Schulz, K., Earth Resources and Environmental Remote Sensing/GIS Applications III: Proceedings of the International Society for Optics and Photonics (SPIE), Vol. 8538, Amsterdam, Netherlands, 1–6 July 2012, Bellingham, WA, USA, International Society for Optics and Photonics (SPIE), 11 pp., 2012.

Arnold, J. G., Srinivasan, R., Muttiah, R. S., and Williams, J. R.: Large area hydrologic modeling and assessment part 1: model development, J. Am. Water Resour. As., 34, 73–89, 1998.

Bouwer, H.: Integrated water management: emerging issues and challenges, Agr. Water Manage., 45, 217–228, 2000.

Dillon, P. J.: Future management of aquifer recharge, Hydrogeol. J., 13, 313–316, 2005.

Eastham, J., Kirby, M., Mainuddin, M., and Thomas, M.: Water Use Accounts in CPWF Basins: Simple Water-Use Accounting of the Ganges Basin, CPWF Working Paper: Basin Focal Paper Series BFP05, CGIAR Challenge Program on Water and Food, Colombo, Sri Lanka, 30 pp., 2010.

Gassman, P. W., Reyes, M. R., Green, C. H., and Arnold, J. G.: The soil water assessment tool: historical development, applications, and future research directions, T. ASABE, 50, 1211–1250, 2007.

Ghayoumian, J., Mohseni Saravi, M., Feiznia, S., Nouri, B., and Malekian, A.: Application of GIS techniques to determine areas most suitable for artificial groundwater recharge in a coastal aquifer in southern Iran, J. Asian Earth Sci., 30, 364–374, 2007.

Gosain, A. K., Aggarwal, P. K., and Rao, S.: Linking water and agriculture in river basins: impacts of climate change, unpublished report, 2011.

Huda, A. and Shamsul, T. M.: Constraints and opportunities for cooperation towards development of water resources in the Ganges basin, in: Sustainable Development of the Ganges–Brahmaputra–Meghna Basins, edited by: Biswas, A. K. and Uitto, J. I., United Nations University Press, Tokyo, Japan, 46–57, 2001.

Jeuland, M., Harshadeep, N., Escurra, J., Blackmore, D., and Sadoff, C.: Implications of climate change for water resources development in the Ganges basin, Water Pol., 15 26–50, 2013.
Johnston, R. and Smakhtin, V.: Hydrological modeling of large river basins: how much is enough?, Water Resour. Manag., 28, 2695–2730, doi:10.1007/s11269-014-0637-8, 2014.
Khan, M. R., Voss, C. I., Yu, W., and Michael, H. A.: Water resources management in the Ganges Basin: a comparison of three strategies for conjunctive use of groundwater and surface water, Water Resour. Manag., 28, 1235–1250, doi:10.1007/s11269-014-0537-y, 2014.
Mishra, D. K.: The Bihar flood story, Econ. Polit. Weekly, 32, 2206–2217, 1997.
Muthuwatta, L. P., Sood, A., and Sharma, B.: Model to assess the impacts of external drivers on the hydrology of the Ganges River Basin, IAHS-AISH P., 364, 76–81, 2014.
Neitsch, S. L., Arnold, J. G., Kiniry, J. R., Williams, J. R., and King, K. W.: Soil and Water Assessment Tool Theoretical Documentation, Version 2000, Grassland, Soil and Water Research Laboratory, Temple, TX, Blackland Research Center, Temple, TX, 2002.
Onta, I. R.: Harnessing the Himalayan waters of Nepal: a case for partnership for the Ganges Basin, edited by: Biswas, A. K. and Uitto, J. I., Sustainable Development of the Ganges-Brahmaputra-Meghna Basins, 100–121 (Tokyo: United Nations University Press), 2012.
Pavelic, P., Srisuk, K., Saraphirom, P., Nadee, S., Pholkern, K., Chusanathas, S., Munyou, S., Tangsutthinon, I., and Smakhtin, V.: Balancing-out floods and droughts: opportunities to utilize floodwater harvesting and groundwater storage for agricultural development in Thailand, J. Hydrol., 470, 55–64, 2012.
Revelle, R. and Lakshminarayana, V.: The Ganges water machine, Science, 188, 611–616, 1975.
Sadoff, C., Harshadeep, N. R., Blackmor, D., Wu, X., O'Donnell, A., Jeuland, M., Lee, S., and Whittington, D.: Ten fundamental questions for water resources development in the Ganges: myths and realities, Water Policy, 15, 147–164, 2013.
Sharma, B. R. and de Condappa, D.: Opportunities for harnessing the increased contribution of glacier and snowmelt flows in the Ganges Basin, Water Policy, 15, 9–25, 2013.
Sood, A., Muthuwatta, L., and McCartney, M.: A SWAT evaluation of the effect of climate change on the hydrology of the Volta River basin, Water Int., 38, 297–311, doi:10.1080/02508060.2013.792404, 2013.
SMEC (Snow Mountain Engineering Corporation International Pty Ltd): Preparation of Ghanga Gomti Basin Plans and Development of Decision Support Systems, Final Report prepared for the State Water Resources Agency, Uttar Pradesh, 2009.

HESSD
12, 9741–9763, 2015

World Bank: Ganges Strategic Basin Assessment: a Discussion of Regional Opportunities and Risks, Draft Final Report, March 2012, World Bank, Washington, 2012.

HESSD
12, 9741–9763, 2015

Table 1. An overview of the main datasets used in this study.

Category	Data	Data source
Topography	Digital elevation model (DEM)	Shuttle Radar Topography Mission (SRTM)
Land use	Land-use map	IWMI database – Satellite-based land-use map
Soils	Digital map of soils and soil properties	FAO soil map of the world (1995)
Climate	Rainfall, temperature, relative humidity, sunshine hours, wind speed	Meteorological organization in Bangladesh, Re-analysis data, India Meteorological Department
Hydrology	River discharge	IWMI Water Data Portal

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

HESSD

12, 9741–9763, 2015

Reviving the "Ganges Water Machine": where and how much?

L. Muthuwatta et al.

Table 2. Names of the sub-basins.

No.	Name	No.	Name
1	Above Ramganga confluence	12	Gomti
2	Banas	13	Kali Sindh and others up to confluence with Parbati
3	Bangladesh	14	Kosi
4	Bangladesh	15	Nepal
5	Bhagirathi and others (Ganga Lower)	16	Ramganga
6	Chambal Lower	17	Son
7	Chambal Upper	18	Tons
8	Damodar	19	Upstream of Gomti confluence to Muzaffarnagar
9	Gandak and others	20	Yamuna Lower
10	Ghaghara	21	Yamuna Middle
11	Ghaghara confluence to Gomti confluence	22	Yamuna Upper

HESSD
12, 9741–9763, 2015

Table 2. Surface runoff of the sub-basins.

Sub-basin	Runoff ($B\,m^3$)			Share of runoff as a percentage of total	
	Mean	Standard Deviation	SR_{75}	Wet months (Jun–Oct)	Dry months (Nov–May)
Above Ramganga confluence	10.02	5.04	5.48	81.2	18.8
Banas	9.89	7.11	3.51	93.8	6.2
Bangladesh	–		–	–	–
Bhagirathi and others	–		–	–	–
Chambal Lower	2.24	1.37	1.23	94.8	5.2
Chambal Upper	8.73	3.01	6.60	90.2	9.8
Damodar	–		–	–	–
Gandak and others	16.03	6.57	11.79	86.0	14.0
Ghaghara	35.56	17.55	23.34	84.0	16.0
Ghaghara confluence to Gomti confluence	4.72	2.07	3.32	88.3	11.7
Gomti	13.64	7.34	9.75	90.8	9.2
Kali Sindh and others up to the confluence with Parbati	15.48	6.64	10.51	80.9	19.1
Kosi	9.44	3.95	6.81	72.8	27.2
Nepal	63.17	11.59	54.44	88.0	12.0
Ramganga	15.56	7.79	10.11	82.6	17.4
Son	19.50	7.88	14.08	85.1	14.9
Tons	6.75	2.47	5.17	88.5	11.5
Upstream of Gomti confluence with Muzaffarnagar	9.38	4.77	5.70	87.8	12.2
Yamuna Lower	22.42	10.78	15.21	93.8	6.2
Yamuna Middle	4.81	3.70	2.14	78.7	21.3
Yamuna Upper	7.19	3.92	4.49	82.7	17.3

HESSD
12, 9741–9763, 2015

Table 4. Sub-basin-wise un-met agricultural water demand and the percentage of surface runoff required to close the un-met demand.

18-1

Sub-basin	Un-met demand ($B m^3$)		Percentage of the SR_{75} required to close the un-met demand	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
Above Ramganga confluence	1.71	2.44	31.2	44.5
Banas	1.21	4.09	34.5	116.6
Bangladesh	–	–	–	–
Bhagirathi and others	4.61	15.12	39.1	128.4
Chambal Lower	0.83	1.39	67.7	113.4
Chambal Upper	2.57	5.15	38.9	78.0
Damodar	–	–	–	–
Gandak and others	5.17	7.17	43.9	60.8
Ghaghara	5.11	7.49	21.9	32.1
Ghaghara confluence to Gomti confluence	3.37	2.89	101.5	87.1
Gomti	2.63	2.83	27.0	29.0
Kali Sindh and others up to confluence with Parbati	3.9	7.14	37.1	67.9
Kosi	1.03	2.39	15.1	35.1
Nepal	–	–	–	–
Ramganga	2.48	3.28	24.5	32.4
Son	1.92	11.82	13.6	83.9
Tons	0.68	2.34	13.2	45.3
Upstream of Gomti confluence to Muzaffarnagar	2.93	3.9	51.4	68.5
Yamuna Lower	7.75	18.67	51.0	122.8
Yamuna Middle	3.41	4.72	159.1	220.2
Yamuna Upper	3.72	5.58	82.8	124.2

HESSD
12, 9741–9763, 2015

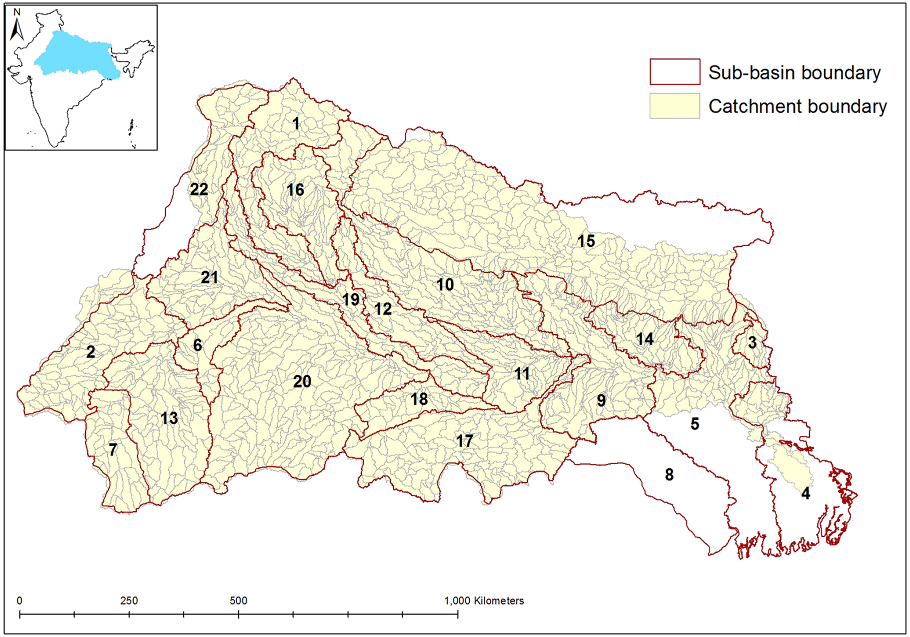


Figure 1. Sub-basins and catchments of the Ganges River Basin.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |
HESSD
12, 9741–9763, 2015

Reviving the "Ganges Water Machine": where and how much?

L. Muthuwatta et al.

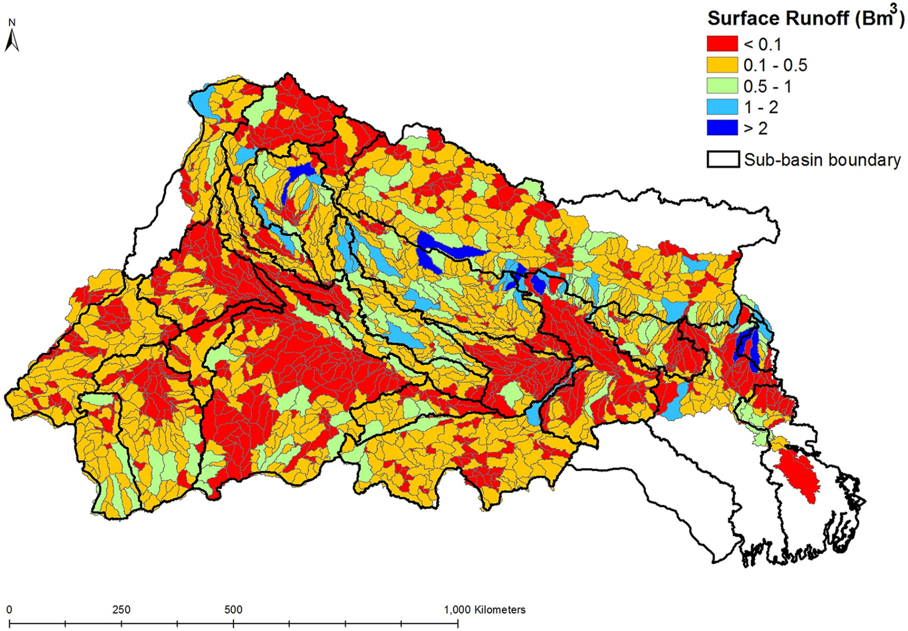


Figure 2. Mean annual surface runoff of the 1684 catchments (1991–2010).

HESSD
12, 9741–9763, 2015

Reviving the "Ganges Water Machine": where and how much?

L. Muthuwatta et al.

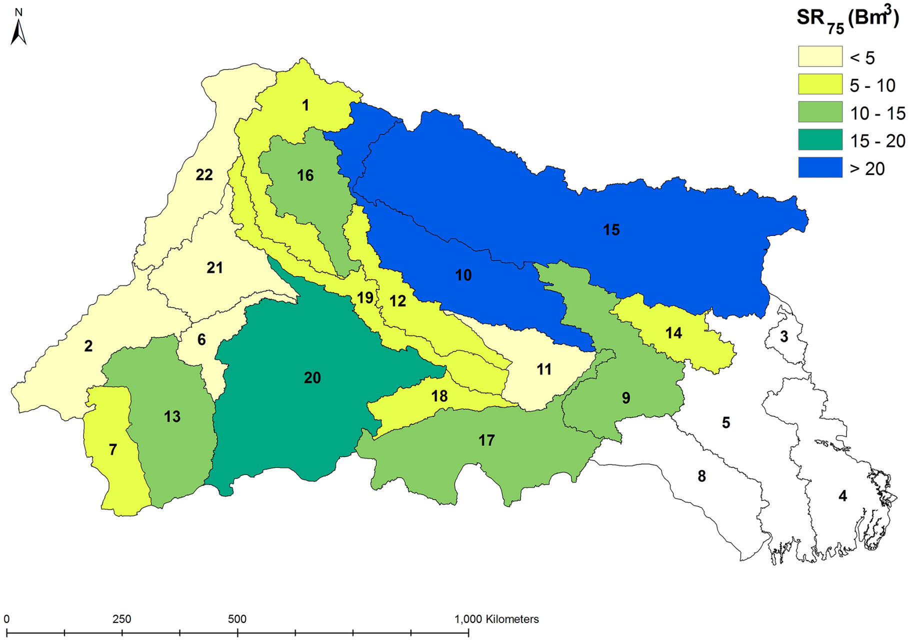


Figure 3. Sub-basin-scale annual dependable runoff (SR_{75}) in the Ganges River Basin (1991–2010).

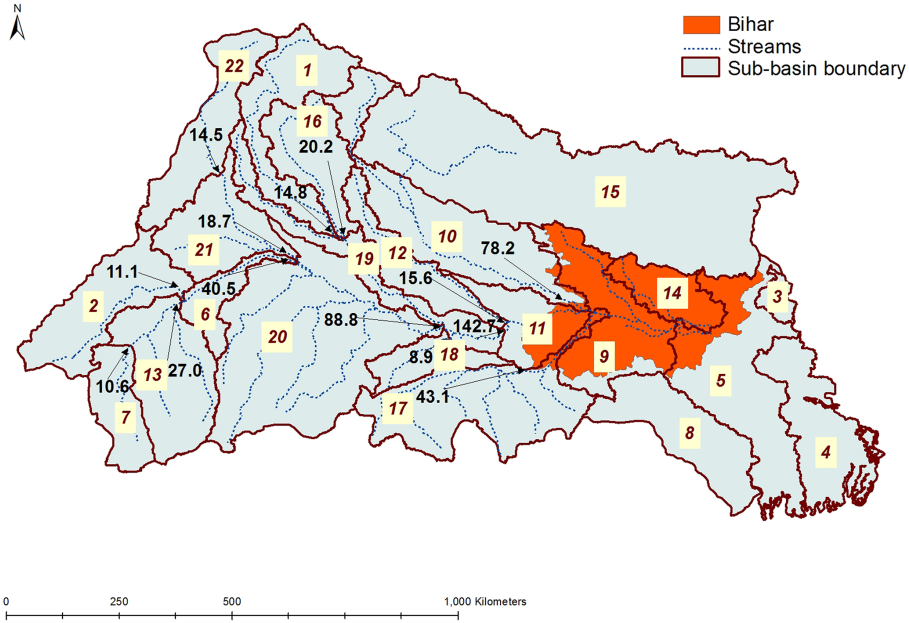


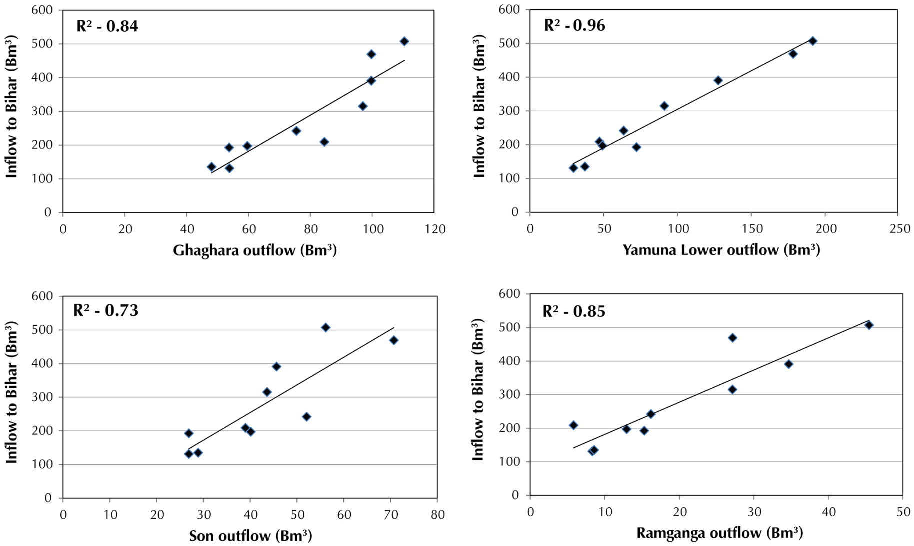
Figure 4. Mean annual outflow ($\mathrm{B\,m^3}$) from the sub-basins in the Ganges River Basin (the numbers in black represent the mean annual outflow, and the numbers in brown on the yellow background represent numbers of the sub-basins).

HESSD
12, 9741–9763, 2015

Reviving the "Ganges Water Machine": where and how much?

L. Muthuwatta et al.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion



23-1

Figure 5. Relationship between outflows from upstream sub-basins and inflow to the State of Bihar.

HESSD
12, 9741–9763, 2015

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◂| |▸
◂ ▸
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Notes

3-1
Oct 12, 2015, 06:55
Downstream of

4-1
Oct 12, 2015, 06:55
But 30-50 is smaller than 130-145. How much greater?

4-2
Oct 12, 2015, 06:55
Into?

5-1
Oct 12, 2015, 06:55
Wonderful! This is a great service!

8-1
Oct 12, 2015, 06:55
These scenarios seem identical. 2 includes non-irrigable crop land? Why include those if they can't be irrigated? Or does irrigable mean currently irrigated in at least on season? Or in irrigated command areas?

10-1
Oct 14, 2015, 06:58
higher volumes of

10-2
Oct 14, 2015, 06:58
Wouldnt a percent contribution be more useful?

10-3
Oct 14, 2015, 06:58
Major assumption. Can the aquifers store it?

11-1
Oct 14, 2015, 06:58
Previous page says 30%

11-2
Oct 14, 2015, 06:58
Why just that subbasin?

17-1
Oct 12, 2015, 06:55
I think it would be useful to have runoff expressed in mm, which normalizes for subbasin area.

17-2
Oct 14, 2015, 06:58
Include the number, then could remove table 2

18-1
Oct 14, 2015, 06:58
Include the number

23-1
Oct 14, 2015, 06:58
Useful?