

1 Reviving the ‘Ganges Water Machine’: Where and how much?

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7 Abstract

8 Surface runoff generated in the monsoon months in the upstream parts of the Ganges River Basin (GRB)
9 contributes substantially to downstream floods, while water shortages in the dry months affect
10 agricultural production in the basin. This paper examines the potential for subsurface storage (SSS) in the
11 Ganges Basin to mitigate floods in the downstream areas and increase the availability of water during
12 drier months. The Soil and Water Assessment Tool (SWAT) is used to estimate “sub-basin” water
13 availability. The water availability estimated is then compared with the sub-basin-wise un-met water
14 demand for agriculture. Hydrological analysis reveals that there is sufficient water to meet the un-met
15 water demand in the sub-basin provided that it is possible to capture the surface runoff in sub-surface
16 storage during the wet season. To examine the impacts of groundwater recharge and pumping on flood
17 inundation and flows in the dry season, two groundwater recharge scenarios are tested in the Ramganga
18 sub-basin. Increasing groundwater recharge by 35% and 65% of the current level would increase the net
19 groundwater recharge by 1.25 Bm³ and 1.44 Bm³ respectively, which is 12% and 14% increase compared
20 to the baseline scenario. Some of the groundwater recharge is returned to stream as base flow and has
21 the potential to increase dry-season river flows. Augmenting SSS reduces the peak flow and flood-
22 inundated areas in Ramganga (by up to 8% for 65% scenario compared to baseline), indicating the
23 effectiveness of SSS on reducing inundated areas under floods in the sub-basin. However, this may not be
24 sufficient to effectively control the flood in the downstream areas of GRB, such as in the state of Bihar,
25 prone to floods, that receives total of 277Bm³ from upstream sub-basins.

26 Key words: Ganges, Hydrological modeling, SWAT, Subsurface storage, Surface runoff, Floods.

27

28 Introduction

29 Matching water demand with supply in river basins with monsoonal climate is a major challenge. The
30 monsoon-driven seasonal hydrology in India is often associated with floods and droughts, which affects
31 the most vulnerable people of society (women and children, the poor and other disadvantaged social
32 groups), and causes damage to crops and infrastructure. In these basins, upstream storage is generally
33 the preferred solution to buffer the variability of flow and reduce floods downstream (Khan et al., 2014).
34 Traditionally, dams are the major surface water storage structures. However, the construction of large
35 dams requires huge investments, displaces people, submerges forests, and some of the water is lost to
36 non-beneficial evaporation (Pavelic et al., 2012). In contrast, underground aquifers are efficient water
37 reservoirs with minimum evaporative losses, no displacement of people or submergence of land (Bouwer
38 2000; Dillon 2005; Ghayoumian et al., 2007).

39 For centuries, the utilization of water resources in the Ganges River Basin has been severely hampered by
40 substantial seasonal variation in river flows. In the basin, the main source of water is the (southwest)
41 monsoon rainfall, and also the snowmelt and ice melt in the Himalaya during the summer season (Sharma
42 and de Condappa, 2013). Out of the 1,170 billion cubic meters (Bm^3) of water entering the basin, around
43 500 Bm^3 becomes river flow while the remainder is returned to the atmosphere through
44 evapotranspiration (SAWI, 2013). The monsoon (between June and September) contributes to about 80%
45 of total annual rainfall, and about 80% of the annual river flow (Revelle and Lakshminarayana, 1975). The
46 rainfall during the rest of the year is low and the river flows, generated mainly through recharged
47 groundwater and snowmelt, are barely sufficient to satisfy the water needs of all the sectors (Huda and
48 Shamsul, 2001). For instance, the estimated average annual flow (1990 to 2008) at the Harding Bridge in
49 Bangladesh (just **downstream** of the Indian border) was about 340 Bm^3 and ranged from 197 Bm^3 to 486
50 Bm^3 , whereas flow in the dry season (October to May), at the same location, varied from 43 Bm^3 to 63
51 Bm^3 .

52 Extensive flooding in the Ganges River Basin, especially in the downstream areas, occurs annually (Mishra
53 1997). The major causes of floods in the downstream areas are the shallow groundwater table and high
54 monsoonal rainfall in these areas, and the large surface runoff generated in the upstream sub-basins.
55 Previous studies (Revelle and Lakshminarayana, 1975; Sadoff et al., 2013) indicated that, due to the
56 limitation of the construction of large surface reservoirs, recharging groundwater beyond the natural level
57 is the best way to control floods downstream. Subsurface storage (SSS) also allows meeting water

58 requirements during the dry months. Popular belief is that having large dams is the only option to meet
59 the basin's water storage needs (Onta, 2001). However, contrary to that, the Ganges strategic basin
60 assessment conducted by the World Bank (2012) found that the sustainable use of the basin's vast
61 groundwater aquifers can store far greater volumes of water compared to the potential of man-made
62 storage in the basin, which is about 130-145 Bm³ (Sadoff et al., 2013). For instance, the mean annual
63 replenishable groundwater in the Ganges basin is about 202.5 Bm³ (Ministry of water resources, 2014).
64 Another study found that the estimated storage available in the shallow alluvial aquifers of eastern Uttar
65 Pradesh and Bihar, which could be utilized in the dry season and naturally recharged in the wet season, is
66 30-50 Bm³ (SMEC, 2009).

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

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

78 Amarasinghe et al. (in press) examined the first condition above and estimated un-met demand
79 throughout the basin under two scenarios of irrigation expansion. The main objective of this paper is to
80 examine the second condition above, i.e., assess the potential availability of runoff and the impact of
81 managed groundwater recharge on the river flow. A hydrological model – Soil and Water Assessment Tool
82 (SWAT) was used to conduct a hydrological analysis of the sub-basins of the Ganges River Basin. This study
83 does not cover the analysis to determine whether there is sufficient aquifer storage available to hold the
84 excess runoff, as this requires detailed groundwater aquifer modeling in sub-basins of GRB. In fact, a
85 comprehensive assessment of the groundwater system in the Ganges is beyond the scope of this work.
86 To the best of the authors' knowledge, no such work has been done for whole of GRB although this can
87 be done by using the Gravity Recovery and Climate Experiment (GRACE) satellite (Swenson and Wahar,
88 2006; Morrow et al, 2012, Rodell et al., 2009). Rodell et al., 2009 used GRACE satellite data to estimate

89 the mean rate of groundwater depletion over the Indian states of Rajasthan, Panjab and Haryana as 17.7
90 ± 4.5 km³/year. Chinnasamy (forthcoming) estimated that groundwater depletion rate over Ramganga
91 sub-basin located in the Northwestern part of the GRB as 1.6 km³/year, and concluded that, the depleted
92 aquifer volume can be used to store upto 76% of the rainfall in the sub-basin. Khan et al. (2014) showed
93 that the subsurface storage create in Uttar Pradesh by pumping groundwater during dry period can
94 accommodate up to 37% of the yearly average monsoon flow.

95 Recharging of surface runoff to the groundwater aquifer during the monsoon season may have minimal
96 effect to the downstream flow during the monsoon season. In fact, increased groundwater recharge may
97 increase the contribution of groundwater to the river flow. However, the excess pumping of water from
98 the aquifer can affect the dry season flows. Sadoff et al (2013) mentioned that using aquifer is a national-
99 level alternative for upstream water storage and has a potential to argument dry season flows (although
100 it requires other factors such as appropriate energy-pricing and policy environment in conjuntion with a
101 well-managed surface water system). Additionally, pumping groundwater during dry season will reduced

102 pumping water from the river directly. For instance surface water based irrigation projects in State of
103 Uttar Pradesh (UP) annually with about 28 Bm³ of river flow, and at least 50% of that during the dry
104 season. If this volume is not diverted, dry season flow the Ganges at the Bihar boundary would
105 increase by 25% (Khan et al, 2014). In order to to investigate the effect of excess groundwater recharge
106 and abstraction on downstream low flows requires conjunctive modeling that couples both groundwater
107 and surface water models. In this study SWAT (which has a simplified groundwater model linked to surface
108 water model) is used to demonstrate this in the Ramganga sub-basin located in the northwestern part of
109 the GRB. Although this study is a theoretical exercise, it provides a scientific justification for a well-
110 designed managed aquifer recharge program to enhance the sub-surface storage in GRB.

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111 Methodology

112 *The Model*

113 Many models have been developed (e.g., Eastham et al., 2010; Gosain et al., 2011; World Bank, 2012) to
114 study water issues in the Ganges River Basin (Johnston and Smakhtin, 2014). However, they are not
115 available to the public. To overcome this restriction and provide the research community with a working
116 hydrological model for the Ganges River Basin, the International Water Management Institute (IWMI) has
117 developed a publicly available hydrological model for the basin (Muthuwatta et al., 2014) using the Soil
118 and Water Assessment Tool (SWAT) (Arnold et al., 1998). The model set up files can be downloaded from

119 the website http://waterdata.iwmi.org/model_inventory.php, and used in further applications and
120 scenario analyses in a variety of projects.

121 SWAT is a widely used, semi-distributed conceptual hydrological model developed by the Agricultural
122 Research Service of the United States Department of Agriculture (USDA) over the last 30 years, and is
123 available free of charge as a public domain model (Arnold et al.,1998; Gassman et al., 2007; Sood et al.,
124 2013). The model has been previously being used for number of studies for different watershed scales
125 (e.g. Muttiah and Wurbs, 2002; Ringler et al, 2010; Singh & Gosain, 2011, Sood et al, 2013). The
126 hydrological ability of the model to capture real world situations is extensively discussed in these articles.

127 Broadly, the SWAT input data can be grouped into five categories: topography or terrain, land use, soil,
128 land use management and climate (Neitsch et al., 2002). SWAT possesses adequate representation of
129 processes governing hydrology and is particularly suitable for application in large river basins. In SWAT, a
130 river basin is subdivided into a number of catchments, so that each catchment has at least one
131 representative stream. Based on unique combinations of soil, land use and slope, the catchments were
132 further divided into hydrological response units (HRUs), which are the fundamental units of calculation.

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133 Subdividing the watershed into areas having unique land use, soil and slope combinations enables the
134 model to reflect differences in evapotranspiration and other hydrologic conditions. HRUs allow for a
135 modeling efficiency whereby hydrological similarity of responses can be leveraged.

136 SWAT simulates the local water balance of the catchment through four storage volumes - snow, soil
137 profile, shallow aquifer and deep aquifer – based on the soil water balance (Equation 1):

$$138 \quad SW_t = SW_0 + \sum_{t=1}^t (R_t - SR_t - ET_t - P_t - G_t) \quad (1)$$

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140 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 ,
141 and G_t are the daily amounts (in mm) of rainfall, runoff, evapotranspiration, percolation and groundwater
142 flow, respectively, at time t . SW_0 is the initial soil water content. The simulated processes include surface
143 runoff, infiltration, evaporation, transpiration, lateral flow, and percolation to shallow and deep aquifers.

144 ***The Data and Model Setup***

145 The model used in this study was set up using the datasets shown in Table 1. The Ganges River Basin was
146 delineated using 3,000 ha as the minimum area threshold and has resulted in 1,684 catchments (Figure
147 1). The area threshold selected by trial and error in an attempt to match the SWAT sub-basins as
148 closely as possible to capture the all tributaries of the GRB.

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149 The model was initially developed to study river flow entering Bangladesh. Therefore, the spatial domain
 150 of the SWAT model developed for the Ganges does not entirely cover the areas that belong to West Bengal
 151 and Bangladesh. However, this does not affect the current study, as its focus is to assess water availability
 152 in the upstream sub-basins of the Ganges River Basin.

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154 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

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156 Figure 1 shows the 22 major sub-basins delineated for SWAT (Table 3) in the GRB and the area covering
 157 Nepal. The 19 main sub-basins in the Indian part selected in this paper are those considered by the Central
 158 Water Commission (CWC) of India, which is the main government agency responsible for water resources
 159 development and management in the Ganges River Basin. Since the focus of this study is to estimate water
 160 availability in the sub-basins within India, Nepal is considered as one region. Hereafter, in this paper, ‘sub-
 161 basins’ are referred to as the 22 major areas shown in Figure 1, while the smaller spatial units inside those
 162 22 sub-basins and Nepal are termed ‘catchments’.

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163 The model was initially calibrated and validated for the monthly discharge data collated at the ~~Harding~~
 164 ~~Bridge~~. The calibration period was selected from 1981 to 1990 and the validation period was selected as
 165 1991–2000. The performance indicators, (Nash-Sutcliffe efficiency) NS and coefficient of determination
 166 (R^2) are 0.69 and 0.73, respectively, for the calibration period and indicate reasonable agreement between
 167 observed and simulated river flow time series. For the validation period, NS and R^2 are 0.75 and 0.81.
 168 Additionally the model simulations were compared with the observed flow data at another seven
 169 locations, for which the observed data were available. Table 2 presents the model performance indicators

170 for these seven locations. The performance indicators show reasonable values. Further, simulated water
 171 balance components seem to be comparable to the results of the other similar studies (e.g. Gosain and
 172 Sirinivasan, 2011). For more details on the model setup, including calibration and validation, please refer
 173 to Muthuwatta et al., 2014.

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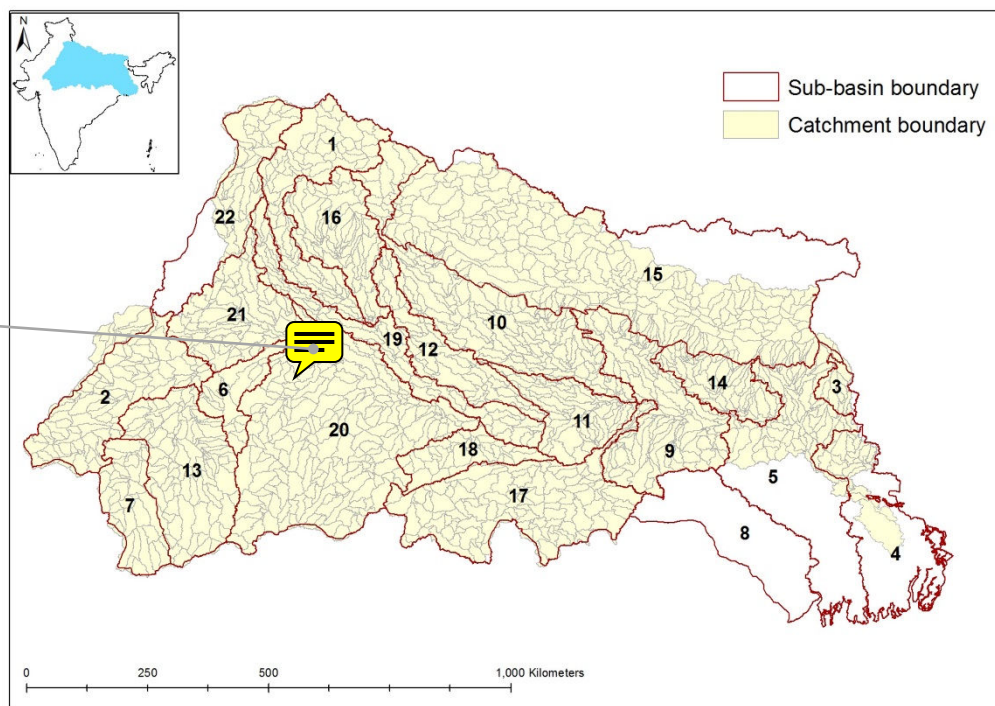
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Table 2: Model performance indicators for seven locations in GRB.

River	Latitude	Longitude	Period	R2	NS
Baghmati	27.15	85.49	1981–2006	0.83	0.82
Karnali	28.96	81.12	1981–2006	0.79	0.61
Seti	29.30	80.78	1986–2006	0.76	0.54
Arun	26.93	87.15	1986–2006	0.63	0.64
Kali Gandaki	27.88	83.80	1996–2006	0.75	0.62
Kali Gandaki	28.00	83.61	1987–1995	0.58	0.58
Kali Gandaki	27.75	82.35	1984–2006	0.76	0.66

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Figure 1: Sub-basins and catchments of the Ganges River Basin (Name of the sub-basins are given in Table 3).

180 *Simulating Sub-basin Runoff*

181 Annual time series of catchment-scale surface runoff from 1991 to 2010 were constructed by aggregating
182 daily surface runoff simulated by SWAT. Next, using geographic information system (GIS) techniques,
183 annual runoff time series were estimated for all sub-basins within the modeled area of the GRB. The study
184 uses the hydrographs of the simulated runoff (SR) to estimate the 75% dependable runoff (SR₇₅). SR₇₅ is
185 an estimate of the runoff that can be expected in the basin, on average, every three out of 4 years, and is
186 considered to be a reliable estimate of water availability for augmenting groundwater storage (Wang et
187 al, 2014).

188 *Simulating Groundwater recharge scenarios in Ramganga*

189 To examine the effect of groundwater recharge on the hydrology such as monthly river flow, Ramganga
190 sub-basin located in the northwestern part of the basin was selected. Ramganga sub-basin was selected
191 because it is the first major upstream basin with typical water resources management challenge of
192 managing seasonal water variability and meeting water demand. Area of the Ramganga sub-basin is about
193 32,000 km² and it belongs to two administrative districts: Uttaranchal and Uttara Pradesh. The important
194 tributaries that flows into Ramganga River are Kho, Gangan, Kosi, and Gorra. The surface water
195 potential in the basin is about 18.6 Bm³. The basin has about 20 million population. The groundwater
196 recharge was controlled in the SWAT model by changing the curve number (CN). CN helps in determining
197 the surface runoff in hydrological models. Reducing CN in the SWAT increases groundwater recharge.

198 *Linking River Flow to Flood-inundated Areas*

199 The effect of surface runoff on flood-inundated area was investigated by relating annual values of
200 maximum flood inundated areas with the river flow. The mapping of maximum flood inundated extent
201 was conducted using MODIS-TERRA satellite datasets that uses 8-day surface reflectance bands to
202 calculate land and water indices (Amarnath et al, 2012).

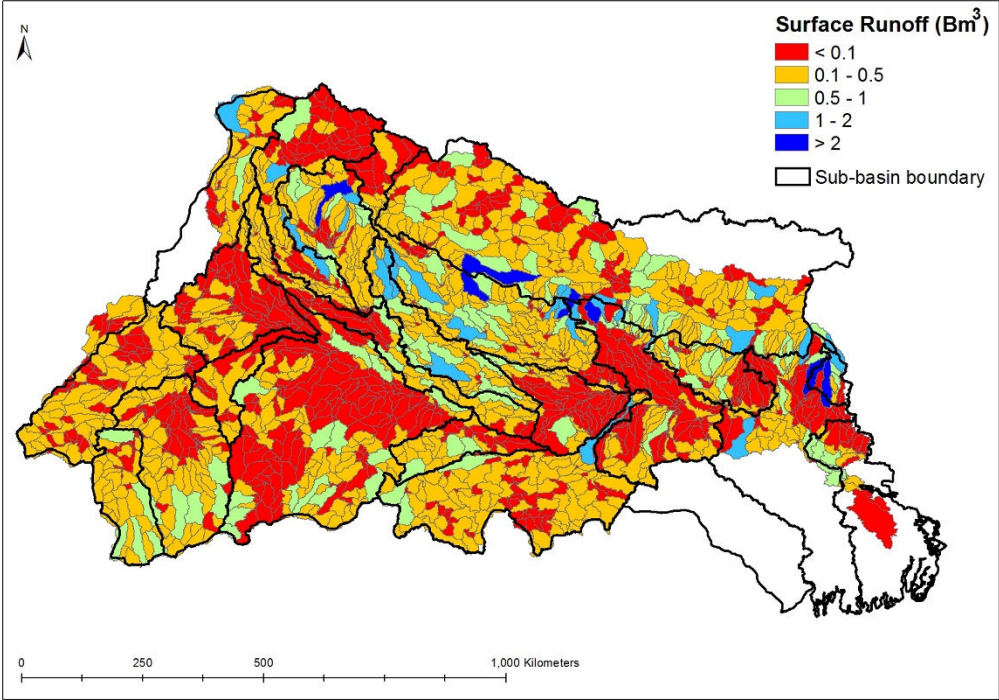
204 **Results**

205 *Surface Runoff of the Sub-basins*

206 The spatial and temporal distribution of the annual surface runoff is analyzed to determine the water
207 availability in different sub-basins. River flow includes surface runoff and baseflow from groundwater,
208 which can be captured by diversion or from dams. Surface runoff is part of the precipitation that is left



209 after evapotranspiration and infiltration, which can be captured for MAR **before it reaches the stream**.
210 Therefore, only the surface runoff portion was considered for augmenting SSS. Figure 2 shows the
211 simulated catchment-scale mean annual surface runoff.



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Figure 2: Mean annual surface runoff of the 1,684 sub-basins (1991-2010).

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215 The **surface runoff** of catchments ranges from less than 0.1 Bm³ to more than 2.0 Bm³. The statistics of
216 the estimated surface runoff for the sub-basins is given in Table 3.

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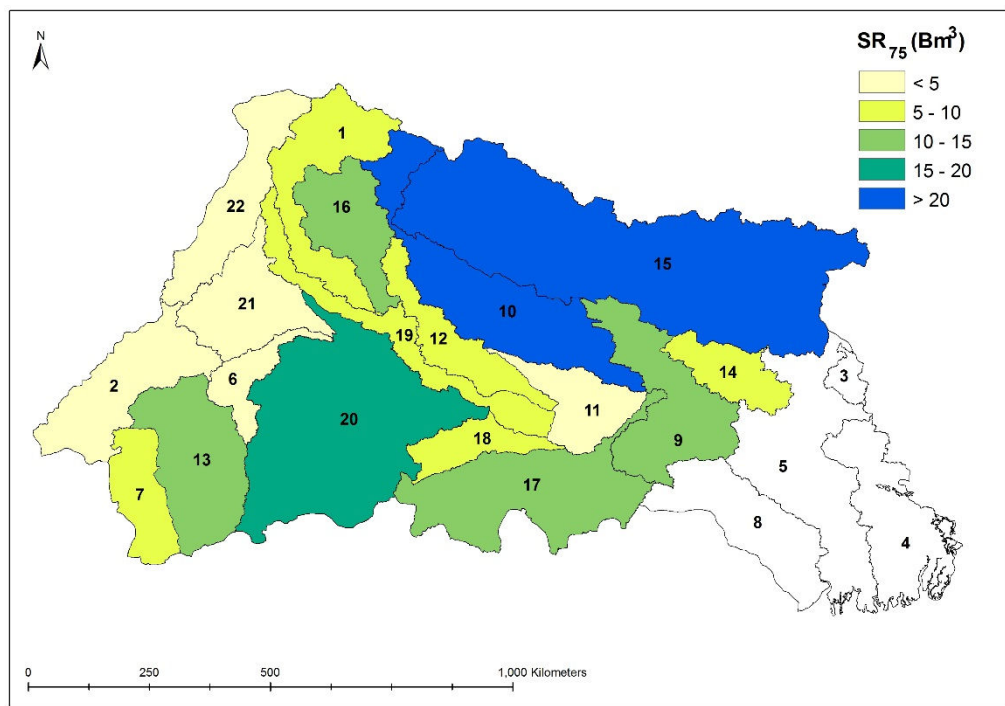
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Table 3: Surface runoff of the sub-basins.

Number	Sub-basin	Runoff (Bm ³)			Share of runoff as a percentage of total	
		Mean	Standard Deviation	SR ₇₅	Wet months (June-October)	Dry months (November-May)
1	Above Ramganga confluence	10.02	5.04	5.48	81.2	18.8
2	Banas	9.89	7.11	3.51	93.8	6.2
3,4	Bangladesh	-	-	-	-	-
5	Bhagirathi and others	-	-	-	-	-
6	Chambal Lower	2.24	1.37	1.23	94.8	5.2
7	Chambal Upper	8.73	3.01	6.60	90.2	9.8
8	Damodar	-	-	-	-	-
9	Gandak and others	16.03	6.57	11.79	86.0	14.0
10	Ghaghara	35.56	17.55	23.34	84.0	16.0
11	Ghaghara confluence to Gomti confluence	4.72	2.07	3.32	88.3	11.7
12	Gomti	13.64	7.34	9.75	90.8	9.2
13	Kali Sindh and others up to the confluence with Parbati	15.48	6.64	10.51	80.9	19.1
14	Kosi	9.44	3.95	6.81	72.8	27.2
15	Nepal	63.17	11.59	54.44	88.0	12.0
16	Ramganga	15.56	7.79	10.11	82.6	17.4
17	Son	19.50	7.88	14.08	85.1	14.9
18	Tons	6.75	2.47	5.17	88.5	11.5
19	Upstream of Gomti confluence with Muzaffarnagar	9.38	4.77	5.70	87.8	12.2
20	Yamuna Lower	22.42	10.78	15.21	93.8	6.2
21	Yamuna Middle	4.81	3.70	2.14	78.7	21.3
22	Yamuna Upper	7.19	3.92	4.49	82.7	17.3

229 The estimates of mean annual surface runoff at sub-basin-scale range from 2.24 Bm³ in Chambal Lower
 230 (6) to 63.17 Bm³ in Nepal (15). Additionally, the high standard deviations in Table 4 indicate significant
 231 temporal variation within sub-basins. Further analysis shows that surface runoff in the wet months (June
 232 to October) is more than 80% of the annual surface runoff in most sub-basins (Table 4, last two columns).

233 This intra- and inter-annual variability of the flows clearly indicates the need for storages to capture the
 234 excess surface runoff during the monsoon season, which could be a SSS. For this analysis, SR_{75} was used
 235 to identify the sub-basins that are consistently producing higher volumes of surface runoff. Figure 3 shows
 236 the spatial distribution of SR_{75} of sub-basins.



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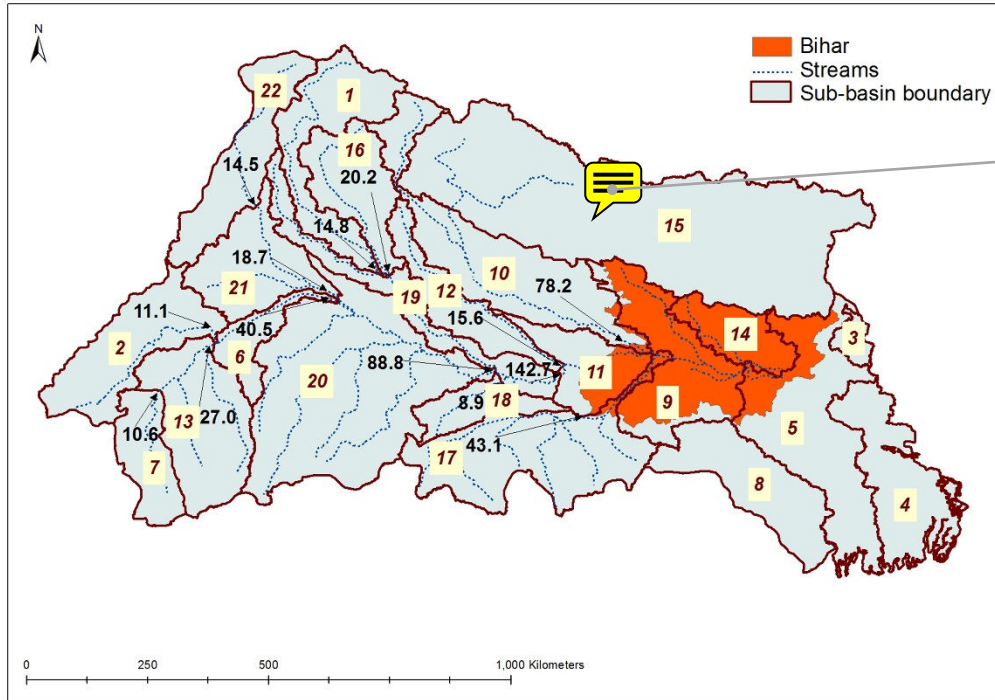
238 **Figure 3: Sub-basin-scale annual dependable runoff (SR_{75}) in the Ganges River Basin (1991-2010).**

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

245 ***Total discharge of the sub-basins.***

246 The mean annual discharge from the upstream sub-basins from 2001 to 2010 was estimated and is
 247 presented in Figure 4.



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249 Figure 4: Mean annual outflow (Bm³) from the sub-basins in the Ganges River Basin (the numbers in
 250 black represent the mean annual outflow, and the numbers in brown on the yellow background
 251 represent numbers of the sub-basins).

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253 The highest flow of 142.7 Bm³ to Bihar in the downstream of the GRB is coming from upstream of the
 254 Gomati confluence to Muzaffarnagar (19), as it gets a large contribution from the Yamuna Lower (20) and
 255 Ramganga (16). The second highest flow (78.2 Bm³) to Bihar is coming from the Ghaghara sub-basin (10)
 256 and it receives outflows from the western part of Nepal. The mean annual flow to Bihar from the various
 257 sub-basins in the Indian part of the Ganges River Basin is about 277±121 Bm³, and the mean annual rainfall
 258 in Bihar is about 123±32 Bm³. This indicates that the water volumes received from upstream flows are
 259 more than twofold the amount of rainfall in Bihar. Flow from Ghaghara and Yamuna Lower sub-basins is
 260 approximately 30% of the total inflow from the upstream Ganges River Basin to Bihar. The contributions
 261 from Son, Kali Sindh and Ramganga are 17%, 10% and 7%, respectively. The estimated discharges at the

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262 sub-basin outlets, as shown in Figure 4 include the contributions from upstream sub-basins and also the
 263 contribution of groundwater to the river flow. Therefore, the values presented in Figure 4 are significantly
 264 higher compared to the surface values presented in Figure 3.

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266 ***Un-met Water Demand for Agriculture***

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

13-1 269 Scenario 1: Provide irrigation to the total irrigable area, i.e., increase irrigated area in the Rabi season from
270 26 million are (Mha) (current irrigated area in this season) to 30 Mha (irrigable area), and in the hot-
271 weather season from 3 Mha (current irrigated area in this season) to 30 Mha (irrigable area), respectively.

272 Scenario 2: Provide irrigation to the total cropped area. At present, not all cropped area is equipped for
273 irrigation. i.e., irrigable area (30 Mha) is less than the cropped area (35 Mha). Therefore, the Scenario B is
274 to increase irrigable area and to increase irrigated area from 26 to 35 Mha in the Rabi season and from 3
275 to 35 Mha in the hot-weather season respectively.

13-2 276 As of now, all the sub-basins in the Ganges River Basin have substantial un-met water demand for
277 agriculture in the dry season. Therefore, capturing a substantial portion of the surface runoff during the
278 monsoon months can help close the gap between current supply of water and demand in the dry months,
279 thus increasing agricultural productivity in these sub-basins. Table 4 presents the sub-basin-wise un-met
280 demand and the percentage of dependable runoff required to close the un-met demand.

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

Sub-basin	Unmet demand (Bm 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

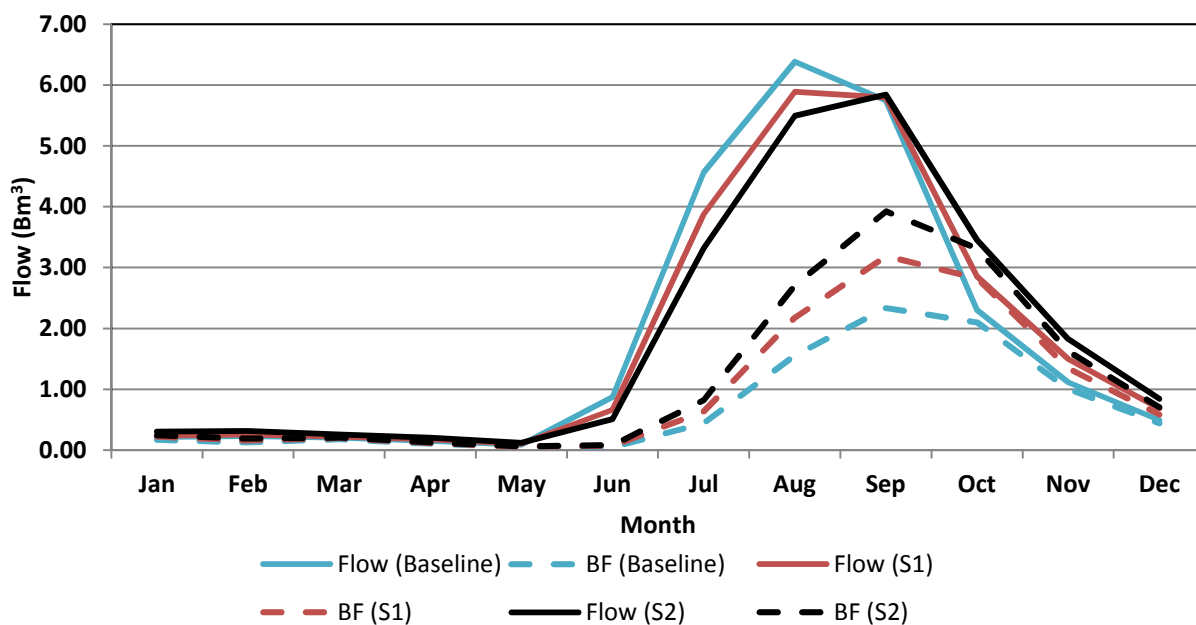
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299 In the sub-basins, the total un-met demands are 55.03 Bm³ and 108.4 Bm³ under scenarios 1 and 2,
300 respectively. The values presented in Table 4 show that, for some sub-basins, annual un-met demand
301 exceeds the annual water availability. In these sub-basins, only a part of the un-met demand can be
302 satisfied by additional underground storage. In some other sub-basins, the un-met demand is less than

303 30% of the SR₇₅ of surface runoff. These sub-basins have the potential to meet all the un-met demand
 304 with SSS. In the Ramganga sub-basin, the SR₇₅ of surface runoff is about 10.1 Bm³, and approximately 83%
 305 of this runoff is occurring during the wet season. To meet the maximum un-met agricultural water demand
 306 in the Ramganga sub-basin only requires capturing 33% of the monsoon surface runoff.

307 ***Effect of enhanced groundwater recharge on the hydrology***

308 Although surface runoff is available to store in sub surface as presented in Table 3 and 4, it is pertinent to
 309 scrutinize the effect of capturing surface runoff on dry season flows, peak flows in the stream and the
 310 downstream water availability. This is demonstrated for the Ramganga sub-basin by simulating
 311 hydrological variables for the baseline scenario and two alternative scenarios. The scenarios assume 35%
 312 and 65% increase of groundwater recharge compared to the baseline. Increase of groundwater recharge
 313 was implemented in the calibrated SWAT model by changing the curve number (CN). Volumes of
 314 groundwater recharge and the changes of base flow under these scenarios were estimated. Figure 5
 315 shows the mean monthly distribution of base flow and the total stream flow at the main outlet of
 316 Ramganga under three scenarios from 1991 to 2010.



317
 318 Figure 5: Mean monthly distribution of river flow and base flow in Ramganga sub-basin under different
 319 scenarios (BF –Base flow, S1 – Scenario 1, S2 – Scenario 2).

320 The results reveal that more than 85% of the recharge in Ramganga occurs between July and October and
321 about 80% of the groundwater contribution (base flow) occurs during the period August to November
322 (Figure 5). The analysis shows reduction of river flow during the high flow months of July, August and,
323 September, as compared to the baseline. Under the baseline scenario, the stream flow volume at the sub-
324 basin outlet during this three-month period is 16.7 Bm³. It reduces to 15.6 Bm³ and 14.7 Bm³ respectively
325 when groundwater recharge increased by 35% and 65% compared to the baseline scenario. The overall
326 reduction of high flows under the two scenarios is 6.8% and 12.2% respectively.

16-1

327 As presented in Figure 5, the high flow occurs during the four-month period from August to
328 November. The baseline scenario indicate about 7.1 Bm³ of base flow during these four months and it
329 increases to 9.5 Bm³ and 11.6 Bm³ when groundwater recharge is increased by 35% and 65% respectively.
330 Further analysis reveals that the annual net groundwater recharge (because some recharged water flows
331 back to the stream) increases by 1.25 Bm³ (35% scenario) and 1.44 Bm³ (65% scenario), which is about
332 14% and 16% increase respectively, as compared to the baseline.

16-2

333 This shows that increasing groundwater recharge by 35% would help to increase SSS, which is sufficient
334 to meet the unmet agricultural water demand under the two scenarios presented in Table 4 by about 50%
335 and 33% respectively. Further, it shows that the overall increase of base flow during the dry months from
336 January to May is about 24% compared to the baseline scenario. From September to December, the river
337 flow receives substantial portion of water from the groundwater discharge due to the increase of recharge

16-3

338 during the high flow months. Therefore as presented in Figure 5, river flow after the rainy season
339 increases. For instance, increase of flow compared to the baseline is 28% and 53% respectively and the
340 increase of base flow is 36% and 65%. Further, during dry months from January to May, the increase of
341 base flow in two scenarios is 18% and 30%.

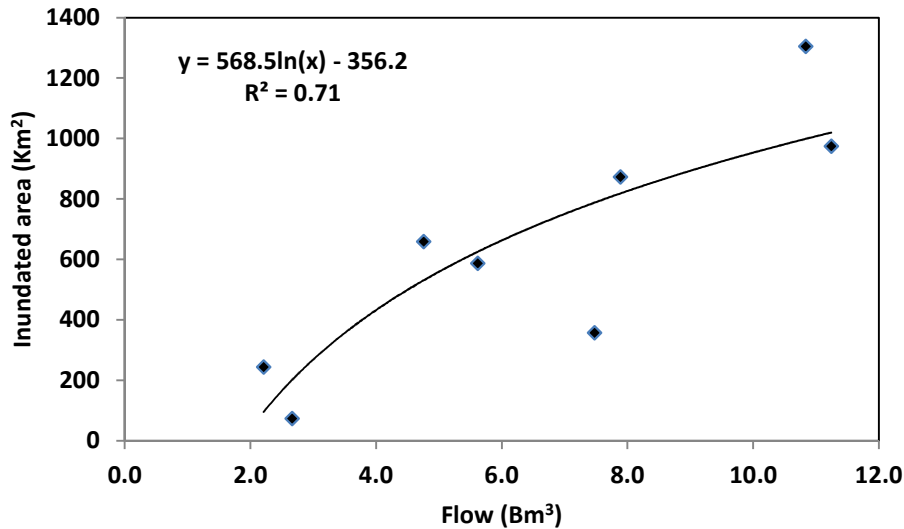
16-6

342 **Effect on floods**

16-4

343 The relationship between the simulated maximum monthly river flow and the maximum flood
344 inundated areas in Ramganga is shown in Figure 6. Horizontal axis represents simulated maximum
345 monthly river flow during a year from 2003 to 2010 at the Ramganga outlet. Vertical axis represents the
346 maximum flood inundation areas estimated based on the satellite images in the corresponding year.

16-5



347

348 Figure 6: Relationship between annual maximum floods inundated area and the maximum monthly river
 349 flow in Ramganga.

17-1

350 The coefficient of determinant (R^2) indicates a strong correlation between area under floods and
 351 the annual runoff and this implies that the annual runoff explain more than 70% of the variation in
 352 maximum flood inundated area. The mathematical relationship between maximum flood inundated area
 353 and the surface runoff is given in Equation 2:

354 Maximum Flood Inundated area = $568.7 \times \ln(\text{Flow}) - 356.2$ (2)

355 The maximum monthly flow in Ramganga of about 6.4 Bm^3 in August (Figure 5) has a
 356 corresponding flood inundated area of about 700 km^2 . Reduction of peak flow to 5.9 Bm^3 (35%
 357 groundwater recharge scenario) would reduce the flood-inundated area by about 6.6%. Similarly, the
 358 reduction of flood-inundated area compared to the baseline scenario is about 8.0% for 65% groundwater
 359 recharge scenario. For this scenario, the reduced outflow from the basin is about 10%. This analysis show
 360 the potential impacts of enhanced sub-surface storage on the flooding in the Ramganga sub-basin located

17-2

17-3

361 in the upstream. This volume of inflow in the Ramganga is negligible compared to the inflow received by
 362 the areas such as Bihar in the downstream. Therefore, to understand the potential impacts of SSS on
 363 flooding in the GRB, it requires further research to investigate the effect of SSS on control of floods in the
 364 downstream areas.

365 Conclusions

18-1 366 Creating additional SSS beyond the current levels in the Ganges River Basin can simultaneously enhance
367 water supply for beneficial depletion and control downstream floods. Water availability analysis

18-2 368 conducted on time series of simulated surface runoff using SWAT hydrological model shows that annual
369 total surface runoff generated in the Ganges River Basin is about $298 \pm 99 \text{ Bm}^3$, and runoff in the monsoon
370 months contributes to 80% of this total runoff. The sub-basin-wise mean annual surface runoff ranges
371 from 2.24 Bm^3 to 35.56 Bm^3 , and the contribution of runoff from Nepal is about 63 Bm^3 . Several sub-
372 basins in the Ganges River Basin produce sufficiently high dependable annual surface runoff that can be
373 stored underground and used during the dry season. For instance, annual surface runoff in each of the
374 five sub-basins in the upstream of Ganges River Basin is more than 10 Bm^3 . Comparison of sub-basin-wise
375 surface runoff with the estimated un-met water demand indicates that capturing only a portion of the
376 wet-season runoff would be sufficient to provide water to irrigate all the irrigable land in the dry months.

18-3 377 Further analysis reveals that the annual surface runoff from the upstream of the Ganges River Basin to
378 the State of Bihar, a flood-prone area located downstream, is twice the amount of rainfall in the same
379 area. Sub-basin-wise river flow analysis in the GRB shows that approximately 30% of the upstream flow
380 to Bihar comes through the Ghaghara and Yamuna Lower sub-basins. This runoff contributes to the
381 recurrent floods in Bihar.

18-4 382 Case study based on Ramganga indicates that increasing 35% and 65% groundwater recharge compared
383 to the baseline scenario may reduce the peak monthly flow by about 6.8% and 12% respectively. Further
18-5 384 the net groundwater recharge increases by 14% and 16% respectively. Further, the results indicate that
385 the dry season flow can increase by 18% to 30% in these two scenarios. Abstracting more water than
386 the net recharge volumes can harm the current water balance and the downstream flows and would need
387 more analysis.

388 More than 70% of the variations of flood-inundated areas in the Ramganga sub-basin can be explained by
389 the maximum monthly river flow values. By increasing groundwater recharge by 35% and 65% during the
390 peak flow month's flood-inundated area can be reduced by about 6.6% and 8% respectively.

391 This study only discusses the surface water availability for SSS, and further analysis is needed to ascertain
392 the storage capacity of the aquifer and how much additional storage capacity may be created by pumping

393 groundwater during the dry months. Further, a detailed analysis of the soil, topographic and geological
394 characteristics is required to determine the suitable areas for groundwater recharge.

395 Finally, to understand the detailed interactions between groundwater and surface water in the sub-basin
396 a coupled groundwater-surface water model is required to run scenarios to investigate the effect of
397 pumping and recharging of groundwater on the hydrology of the basin.

398

399 **Acknowledgements**

400 This research study was undertaken as part of the CGIAR Research Program on Water, Land and
401 Ecosystems (WLE) by the International Water Management Institute (IWMI), Colombo, Sri Lanka, and the
402 National Institute of Hydrology (NIH), Roorkee, India. The authors would like to acknowledge the valuable
403 assistance provided by staff members of IWMI's GIS, RS and Data Management (GRandD) unit, especially
404 Salman Siddiqui (Senior Manager, GRandD unit). Authors thank the two anonymous reviewers and Prof.
405 Nanditha Basu for their useful comments and suggestions during the review process.

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488

489

490

491

- 1-1** Apr 26, 2016, 07:29
What's the difference between gw recharge and net gw recharge? Sentence seems inconsistent (increasing recharge by 35% increases recharge by 12%).
- 4-1** Apr 26, 2016, 07:29
Reduce
- 4-2** Apr 26, 2016, 07:29
How do you know that?
- 4-3** Apr 26, 2016, 07:29
And replaced by gw pumping? It's not clear that Khan et al support the statement that gw pumping will replace sw pumping and that that will increase baseflow.
- 4-4** Apr 26, 2016, 07:29
Investigation of
- 4-5** Apr 26, 2016, 07:29
Increased?
- 5-1** Apr 26, 2016, 07:29
You mean that homogeneity in land use and hydrological response is assumed? I wouldn't say it leverages similarity.
- 5-2** Apr 26, 2016, 07:29
But any threshold size would include all tributaries in the model domain. I still don't understand the rationale for area threshold selection.
- 6-1** Apr 26, 2016, 07:29
Where's Harding bridge? What's the drainage area? Show in figure 1.
- 7-1** Apr 26, 2016, 07:29
Describe in one sentence why some subbasins (eg 8) don't have any swat hrus.
- 7-2** May 7, 2016, 07:40
Isn't the rmse most important since you're estimating volumes ?
- 7-3** Apr 26, 2016, 07:29
Some of these aren't listed in table 3, so we don't know where the are. Please put the gage locations on figure 1.
- 7-4** May 7, 2016, 07:40
Please add a sparse river network so we can see how the subbasins are connected.
- 8-1** Apr 26, 2016, 07:29
Flow
- 8-2** Apr 26, 2016, 07:29
Grammar
- 8-3** Apr 26, 2016, 07:29
Determines

8-4 Apr 26, 2016, 07:29

In just the ramganga? Whole Ganges?

Linear regression? How many years? How did you identify the date that had the peak flood area?

8-5 Apr 26, 2016, 07:29

What was done in amarnath? The flood mapping of ramganga? Clarify.

9-1 May 7, 2016, 07:40

The hydrological terms are a bit mixed up here.

But all ET had to infiltrate first. What's left after infiltration and ET (assuming no saturation overland or subsurface storm flow) is recharge, which becomes GW discharge and surface runoff during baseflow.

Usually surface water runoff is defined as all streamflow, including storm flow and baseflow, which is what is leftover after Et and change in storage ($Q = P - ET \pm \text{change in storage}$). Or by surface runoff do you mean infiltration excess overland flow? I think that's what you mean, but then it's what is left after infiltration, not infiltration and ET.

12-1 May 7, 2016, 07:40

And "surface runoff"?

12-2 May 7, 2016, 07:40

From the ungaged subbasin?

12-3 May 7, 2016, 07:40

Why do some subbasins have no values (eg Nepal).

13-1 May 7, 2016, 07:40

Kharif? Or third summer crop (April-June)? Define the seasons by months.

Why is irrigated area so much smaller in hot than rabi? Without knowing whether this is kharif season or not makes it hard to tell. If it's a third crop, then what is kharif irrigated area? And is it assumed to be maximum and not changed in the scenarios?

13-2 May 7, 2016, 07:40

Same as hot season? But rabi is also a period of low rainfall.

15-1 May 7, 2016, 07:40

But you also have to assume that the unmet demand is going to et, no? Just adjusting the CN would increase flow, but meeting unmet demand would decrease flow. If you're trying to simulate change in streamflow by enhancing recharge but not changing ET, that needs to be stated. But that is not the same as scenario 1 and 2, where unmet demand goes to et.

16-1 May 7, 2016, 07:40

indicates

16-2 May 7, 2016, 07:40

50% of what?

16-3 May 7, 2016, 07:40

Even after pumping of gw to meet unmet demand?

16-4 May 7, 2016, 07:40

Each year

-
- 16-5** May 7, 2016, 07:40
Taken from another reference?
- 16-6** May 7, 2016, 07:40
What's the impact on annual discharge? It should large and equal to unmet demand.
- 17-1** May 7, 2016, 07:40
Maximum monthly
- 17-2** May 7, 2016, 07:40
On monthly maximum? Annual?
- 17-3** May 7, 2016, 07:40
Grammar
- 18-1** May 7, 2016, 07:40
Grammar
- 18-2** May 7, 2016, 07:40
Total surface runoff? Elsewhere in the paper total runoff is surface plus gw.
- 18-3** May 7, 2016, 07:40
Is that a big number or a small number? Compared to what?
- 18-4** May 7, 2016, 07:40
I don't think that's a meaningful comparison. High I flow compared with local rain is true for any large river.
- 18-5** May 7, 2016, 07:40
Before meeting unmet demand through irrigation....
- 18-6** May 7, 2016, 07:40
So, is et from unmet demand simulated by you or not?