Supplement of

The benefits and trade-offs of multi-variable calibration of WGHM in the Ganges and Brahmaputra basins

Howlader Mohammad Mehedi Hasan et al.

Correspondence to: Howlader Mohammad Mehedi Hasan (mehedi.hasan@gfz-potsdam.de)

S1. The study basins

Ganges basin: The Bhagirathi and Alaknanda rivers merge and take the name Ganges at Devprayag in the Uttarakhand State of India. The headwaters of the Bhagirathi River reside in the Gangotri glacier at an elevation of about 7000 m above sea level (a.s.l.); the Alaknanda river originates from the foot of the Satopanth and Bhagirath Kharak glaciers at an elevation of around 3900 m a.s.l. A few tributaries of the Ganges River originate in Nepal and join the main Ganges River at different locations in India. The Ganges then flows through India and Bangladesh and confluences with the Brahmaputra River. The total length of the river from Devprayag to the sea is 2525 km. The total area of the river basin is nearly 1.09 million km^2 accounting 26% of the total area of India, 32% of Bangladesh and 100% of Nepal and is home of around 448 million inhabitants (India-WRIS, 2014b; FAO, 2011). Except for the high-altitude Himalayan region, the minimum temperature in the coldest month (January) never goes below 8°C; the mean temperature in the winter months lies between 15°-21°C and in summer between 23°-31°C. The precipitation is governed by the south-west monsoon and nearly 80% of annual precipitation concentrates during the distinct monsoon season in July-September. The mean annual precipitation varies from 760 mm in the western front of the basin to 2290 mm in the lower Gangetic region; more than 84% of the basin receives an annual precipitation of over 1000 mm. Agricultures dominate the land use in the basin, accounting 68% of the total area. There are 75 dams and reservoirs in the Ganges basins. The mean discharge of Ganges measured at the Hardinge Bridge station is 11300 m3/s (Masood et al., 2015).

Brahmaputra basin: The Brahmaputra River originates from a glacier in the Kailas range in Tibet (China) at an elevation of 5300 m a.s.l. and traverses a distance of 2900 km (Immerzeel, 2008) through Tibet (China), India and Bangladesh before it confluences with the Ganges at Goalanda (Bangladesh), 160 km upstream of the river mouth of the combined Ganges-Brahmaputra-Meghna river system at Bay of Bengal (FAO, 2011). Although the main

Brahmaputra does not enter into Bhutan, nearly 96% of the entire country fall inside the Brahmaputra River Basin (India-WRIS, 2014a). The total area of the Brahmaputra basin is about 543400 km² with approximately 130 million inhabitants living in the basin (Ray et al., 2015; FAO, 2011). About 44% of the Brahmaputra basin resides in Tibetan plateau (TP) with elevation above 3500 m a.s.l., the Himalaya belt (HB) covers 29% of the basin with elevations between 100-3500m a.s.l., and the rest (27%) lies in the Floodplains (FP) with elevation less than 100 m a.s.l. (Immerzeel, 2008). The average temperature and precipitation vary within these three zones – Tibetan plateau, Himalayan belt, and floodplains. In TP, the basin average temperatures range from -10°C in winter to 7°C in summer; in the HB the winter temperature is around 2°C and summer temperature is 15°C on average. The FP zone is the warmest with mean temperatures ranging 17°C in winter and 27°C in summer. The India-WRIS (2014a) report indicates a slightly higher basin-wide average temperature, ranging from 22°C to 28°C during the winter months (November to April) and from 30°C to 38°C during the summer months (May to October). The TP zone of the basin receives a mean annual precipitation of 734 mm/yr; the average precipitation in the HB zone is 1349 mm/yr; and in the FP zone is 2354 mm/yr (Immerzeel, 2008). 60-70% of the precipitation is driven by the monsoon and occurs in the months from June to September. The mean streamflow at Bahadurabad gauging station is nearly 20,000 m3/s and can surpass 140,000 m3/s during monsoon (Ray et al., 2015; Papa et al., 2010; FAO, 2011). The total number of dams, both for hydropower and irrigation purposes, in this basin is six.

S2. Elementary Effect Test (EET) method of Morris (1991)

S2.1 Background

Morris's method of sensitivity analysis, also known as the Elementary Effect Test (EET) method, involves calculating local derivatives of a response variable y (where $y=f(\theta)$; $\theta \in R^m$; m being the number of input parameters) with respect to each parameter θ_i, referred to as the Elementary Effect (EE) of θ_i, at multiple random reference points $\theta_{\mathrm{ref},j}$ (where $j \in \{1,2,\ldots,r\}$; r being the total number of elementary effects for a single parameter) in the parameter space Ω (where $\Omega \subseteq R^m$). The elementary effect of the i^{th} parameter is computed as follows:

$$EE_{(i,j)} = \frac{f(\theta_{(per,i,j)}) - f(\theta_{(ref,j)})}{\Delta_{(i,j)}} \tag{I}$$

where, $\theta_{(ref,j)} = (\theta_{(1,j)}, \theta_{(2,j)}, \ldots, \theta_{(i,j)}, \ldots, \theta_{(m,j)})$ is the j^{th} reference parameter set and $\theta_{(per,i,j)} = (\theta_{(1,j)}, \theta_{(2,j)}, \ldots, \theta_{(i,j)} + \Delta_{(i,j)}, \ldots, \theta_{(m,j)})$ is the perturbed parameter set where the i^{th} parameter has been perturbed by $\Delta_{(i,j)}$.

The average of the elementary effects is expressed as the sensitivity index (SI) of the i^{th} parameter as follows,

$$SI_i = C_i \times \frac{1}{r}\sum_{j=1}^{r} EE_{(i,j)} \tag{II}$$

C_i is a scaling constant used for intercomparison of the indices (*SI*) among parameters and enables ranking of these indices. Typically, the parameter range ($RANGE_i = MAX_i – MIN_i$) is used as the scaling constant. The method of Morris also produces an unbiased estimator of the variance S^2 that reflects the combined effect of nonlinearity of the model response and interactions among input parameters (Morris, 1991).

$$S_i^2 = VAR(EE_{(i,j)}) \quad \text{(III)}$$

The unbiased standard error of the mean, i.e., the standard error of the sensitivity index, can be estimated as follows.

$$SEM_i = \frac{S_i}{\sqrt{r}} \quad \text{(IV)}$$

Campolongo et al. (2011) proposed a slight modification of (II) to use absolute elementary effect, which is necessary for non-monotonic models, e.g.,

$$SI_i^* = C_i \times \frac{1}{r}\sum_{j=1}^{r}\left|EE_{(i,j)}\right| \quad \text{(V)}$$

In the current study, we followed the sampling design proposed by Campolongo et al. (2011). However, the modification described in (V) was not applied in this study for two reasons: (1) our model response was not a scalar value but rather a time-series, and (2) the measure of change in the target response variable was computed as the Root Mean Squared Deviation (RMSD) of model responses between perturbed and reference parameter sets, only after both runs had finished. Because the model response consists of a monthly time-series, the RMSD was computed as follows:

$$RMSD = f(\theta_{per}) - f(\theta_{ref}) = \sqrt{\frac{1}{N}\sum_{k=1}^{N}\left(S_{(per,k)} - S_{(ref,k)}\right)^2} \quad \text{(VI)}$$

where $S_{(per, k)}$ and $S_{(ref, k)}$ refer to simulated model responses at the k^{th} point in time (i.e., month) with the perturbed parameter set (θ_{per}) and the reference parameter set (θ_{ref}) and N is the number of time points in the response time-series.

The total number of model runs required by the EET methods is $r \times (m + 1)$.

S2.2 Workflow

Below, we present the workflow of the EET sensitivity analysis, adapted from the workflow presented in Pianosi et al. (2015). In the following algorithms, vectors and matrices are shown in boldface, indices are presented in parentheses, and procedures are described with parentheses in regular font.

Algorithm 1: Workflow of EET Sensitivity Analysis

Step 1: Create the EET design matrix ***X*** following the radial-design of Campolongo et al. (2011), as in **Algorithm 2**. The size of ***X*** is n × m; n := $r \times (m + 1)$ is the number of sample, m is the number of parameters, and r is the number of EEs to be computed.

Step 2: Run the simulation model with each parameter set represented by each row of ***X*** and compute $\mathbf{Y} = RMSD(S_1, S_2)$ as in Equation (VI)

Input: ***X*** := the sampling matrix
Output: ***Y*** := *f(**X**)*, the model response which is the *RMSD* between two runs
Set $n \leftarrow$ no. of rows in ***X***
Create a matrix ***Y*** with size $n \times 1$
Set $i \leftarrow 0$
For $i \leftarrow 0$ to (n - 1) do
$\theta \leftarrow X(i, :)$

S_1 ← WGHM (θ), given WGHM is a predefined procedure that describes the WaterGAP GHM

If i is divisible by (m + 1) then

$S_2 \leftarrow S_1$

$Y(i) \leftarrow 0$

Else do

$Y(i)$ ← RMSD (S_1, S_2), given RMSD procedure computes the root mean squared deviation between two simulated time-series

End if

End for

<u>Alternative approach (for scalar model response):</u>

Input: ***X*** := the sampling matrix

Output: ***Y*** := *f(**X**)*, the scalar model response

Set n ← no. of rows in ***X***

Create a matrix ***Y*** with size $n \times 1$

Set $i \leftarrow 0$

For i ← 0 to (n-1) do

$\theta \leftarrow X(i, :)$

$Y(i) \leftarrow f(\theta)$, given f(.) is the procedure defining the model

End for

Step 3: Compute EET Indices

Input: ***X*** := the sampling matrix, ***Y*** := *f(**X**)*, ***RNG*** := a vector of size m with parameter ranges

Output: ***mi*** := a vector of the mean sensitivity indices of m parameters, **sigma** := a vector of standard deviations of sensitivity indices for all parameters

Set r ← no. of elementary effects, m ← no. of parameters, n ← r * (m + 1)

Set ***mi*** ← a vector of m zeros, **sigma** ← a vector of m zeros, **EE** ← an r-by-m matrix of zeros

Set $i \leftarrow 0$, $k \leftarrow 0$

While $i < n$ do

Set $j \leftarrow 0$

For j ← 0 to *(m-1)* do

$\Delta\theta \leftarrow \mathbf{X}(i, j) - \mathbf{X}((i + j + 1), j)$

$\Delta Y \leftarrow \mathbf{Y}(i) - \mathbf{Y}(i + j + 1)$

$\mathbf{EE}(k, j) \leftarrow |\Delta Y / \Delta\theta| * RNG(j)$

End for

$k \leftarrow (k + 1)$

$i \leftarrow i + (m + 1)$

End while

For j ← 0 to *(m-1)* do

mi (j) ← *mean*(EE(:,j)), given the procedure *mean* (...) computes the mean
sigma(j) ← *std*(EE(:,j)), given the procedure *std(...)* computes standard deviation

End for

Step 4: Select influential parameters according to **Algorithm 3**

Algorithm 2: Generation of EET Sampling Matrix following the radial design of Campolongo et al. (2011)

Input: *r* := number of elementary effects per parameter, *m* := number of parameters, **etc** := parameter PDFs and additional information

Output: **X** := an *n*-by-*m* sampling matrix where $n = r * (m + 1)$

Step 1: Generate reference and auxiliary samples using Latin Hypercube Sampling (LHS) strategies. The procedure *lhcube(...)* produces an *n*-by-*m* sample matrix, where *n* is the number of samples and *m* is the number of parameters, respecting probability distribution functions (PDF) of each parameter. The lhcube(…) procedure requires three arguments: (i) *n*, (ii) *m*, and (iii) ***etc*** := parameter PDFs and additional information. See the SAFE toolbox of Pianosi et al. (2015) for detailed implementation of *lhcube(...)* procedure and its usage for drawing samples from parameter PDFs.

Set n ← *r* * 2
AB ← *lhcube*(*n*, *m*, **etc**)
Set ***A*** ← the first half of ***AB*** as the reference or baseline points
Set ***B*** ← the last half of ***AB*** as the auxiliary points. The auxiliary points is used to deviate parameter values from baseline one at a time

Step 2: Create the sampling matrix ***X*** using the *r*-by-*m* baseline matrix ***A*** and *r*-by-*m* auxiliary matrix ***B***. Each parameter value in a baseline sample is replaced one at a time by the respective parameter value in an auxiliary sample to produce *m* perturbed samples for each reference sample. Finally, stack all perturbed samples along with the reference of the baseline sample to form the final sampling matrix ***X***.

Set n ← $r * (m + 1)$, ***X*** ← an *n*-by-*m* matrix with zero values
Set i ← 0
For k ← 0 to (r – 1) do
Set ***a*** ← ***A***(k, :), ***b*** ← ***B***(k, :)
Set ***c*** ← *m*-by-*m* matrix by replicating the ***a*** vector *m* times
For j ← 0 to (m – 1) do **c** (j, j) ← **b**(j) End
X(i, :) ← **a** i.e., copy all elements of ***a*** into the i^{th} row of **X**
For *j* ← 0 to (*m* – 1) do ***X***((*i*+*j*+1), :) ← ***c***(*j*, :) End
i ← *i* + (*m* + 1)
End for

S2.3 Parameter Selection

In the multi-variable, multi-signature setting of sensitivity analysis, our goal was to select parameters that exerted sufficient influence on any of the target response variables across all chosen signatures. Therefore, we individually selected influential parameters for each variable and for each signature, and then we aggregated these selections across all cases. Additionally, during the selection process, we considered the uncertainty associated with sensitivity indices and implemented a Monte Carlo simulation procedure to repeatedly run the selection process, thereby producing a robust solution for parameter selection.

For practical reasons and to limit the number of selected parameters, we employed a selection strategy that ensured a minimum share of all effects produced by all parameters for a response variable and its associated signature were accounted for by the selected parameters. In this study, we chose a threshold of at least 50% of the combined total effect to define the minimum share. The selection algorithm is presented in Algorithms 3 and 4.

Algorithm 3: Parameter selection for Multi-variable Multi-signature SA

Input: mi := mean indices for each variable and for each signature, sigma := the standard deviation of the sensitivity indices, r := no. of elementary effects considered to compute the mean index, th := selection threshold, n := number of Monte Carlo runs

Output: S := a vector of true/false indicating which parameters should be selected

```
Set S ← a vector of Booleans initialized to false
For each response variable do
        For each signature do
                mi ← get mean sensitivity indices for the target variable and signature
                sigma ← get standard deviation of the indices

                Set sem ← a vector of m zeros
                For j ← 0 to (m – 1) do sem(k) ← sigma(k) / sqrt(r) End

                s ← ParameterSelection(mi, sem, th, n), the procedure
                        ParameterSelection(…) finds top influential parameter.
                        The procedure details are provided in Algorithm 4.

                For j ← 0 to (m – 1) do
                        If s(j) = true then S(j) ← true
                End for
        End for
End for
```

Algorithm 4: ***S*** = *ParameterSelection* (***mi***, ***sem***, *th*, *n*); a procedure to find top influential parameters that cover at least a given share of the combined total effect, accounting for the uncertainty in the sensitivity indices

Input: ***mi*** := mean sensitivity indices, ***sem*** := standard errors of the mean indices, th := selection threshold of cumulative effect, n := no. of Monte-Carlo runs

Output: ***S*** := a vector of *m* true/false values representing whether each parameter should be selected

Step 1: Generate *n* set of sensitivity indices by Monte Carlo simulation

Set m ← size of ***mi***
Set **MM** ← an *n*-by-*m* matrix of zeros
For j ← 0 to (m – 1) do
    low ← ***mi***(*j*) – ***sem*** (*j*)
    high ← **mi**(*j*) + ***sem*** (*j*)
    MM(:, *j*) = *uniform*(*low*, *high*, *n*) i.e., fill each column of ***MM*** with random *n* values uniformly distributed between the 'low' and the 'high'. The procedure *uniform(...)* produces random values from a uniform distribution.
End for

Step 2: For each set of sensitivity indices, sort the parameters by their effects on a response variable and compute share of each parameters effect to the sum of all effects. Compute cumulative effect of the sorted parameter list and finally select parameters sequentially until the cumulative effect reaches or exceeds the specific threshold

Set ***S*** ← a Boolean vector of size *m*, initialized to *false*
Set ***a*** ← a vector of *m* zeros, ***e1*** ← a vector of *m* zeros, ***e2*** ← a vector of *m* zeros
For i ← 0 to (n – 1) do
    a ← MM(i, :)
    e1 ← ***a****(:)*/*sum*(***a***) i.e., the relative effect for each parameter
    jj ← indices of sorted ***e1*** in descending order
    e2(jj) ← *cumsum*(***e1***(***jj***)) i.e., given the cumsum(…) procedure computes the cumulative sum of a vector, produce the cumulative sums with the sorted ***e1*** values and store them in proper order in ***e2***.

    Set ***temp*** ← ***e2***(***jj***), *k* ← 0
    While *k* < m do
        i_sel ← ***jj***(*k*)
        S(*i_sel*) ← true   i.e., select high influential parameters until cumulative effect reaches or exceeds the threshold
        If ***temp***(*k*) >= *th* then
            break
        End if
        k ← *k* + 1
    End while
End for

S3. Correlation between parameters and model output variables

In order to understand the relationships between the parameters and the response variables, we analysed the correlations of their long-term means with the parameter values of 1,000 reference samples from the sensitivity analysis (Sect. 3.3). In general, most of the parameters show high correlations with all four response variables although they may have low relative influences according to the sensitivity analysis (non-influential parameters in Table S1 in grey). Negative and positive correlations align with our expectation. For example, in the case of the soil water capacity multiplier SL-MSM, higher values of the parameter lead increased evapotranspiration, resulting in reduced streamflow. and the higher soil water storage leads to a larger seasonal TWSA amplitude. Also, the SWSA amplitude decreases as SL-MSM increased because of the low streamflow. Although in most cases, the correlation between the variables and parameters is consistent in both basins in terms of direction and magnitude, differences in correlations are observed for certain parameters and output variables, indicating differences in the hydrological process in the two basins.

Table S1: Correlation between parameters and change in model response due to change in parameter values (N = 1000). For streamflow and evapotranspiration, mean values between 1990 and 2019 are considered and mean seasonal amplitudes in the same simulation period for TWSA and SWSA. Quantities are suppressed in grey colour if the parameter was not selected for calibration and highlighted in bold face if the correlations are in opposite directions in two basins

	Ganges				Brahmaputra			
Parameter	Q mean	TWSA mean amplitude	ET mean	SWSA mean amplitude	Q mean	TWSA mean amplitude	ET mean	SWSA mean amplitude
EP-PTh	-0.99	**-0.98**	0.99	-0.95	-0.98	**0.38**	0.98	-0.96
EP-PTa	-0.97	-0.92	0.97	-0.91	-0.95	-0.93	0.95	-0.93
CA-MC	-0.87	**0.60**	0.87	-0.87	-0.74	**-0.71**	0.74	-0.77
CA-LAIM	-0.83	**0.48**	0.83	-0.83	-0.70	**-0.69**	0.70	-0.72
SN-FT	0.78	-0.78	-0.82	-0.03	0.75	-0.56	-0.75	0.64
SN-MT	0.97	-0.66	-0.97	0.94	0.88	0.83	-0.88	0.90
SN-DM	-0.88	-0.01	0.87	-0.88	-0.84	-0.83	0.84	-0.87
SN-TG	0.98	**-0.53**	-0.98	0.87	0.92	**0.77**	-0.92	0.85
SL-RC	-0.85	0.78	0.86	-0.68	-0.80	0.40	0.80	-0.40
SL-MSM	-0.97	0.98	0.97	-0.96	-0.94	0.93	0.94	-0.96
SL-MEP	-0.89	-0.83	0.89	-0.89	-0.77	-0.76	0.77	-0.79
SW-RRM	**-0.90**	0.98	**0.83**	0.98	**0.91**	0.99	**-0.37**	0.99
SW-LD	**-0.78**	0.90	0.83	0.92	**0.93**	0.96	0.45	0.96
SW-WD	0.83	0.95	-0.88	0.95	0.93	0.93	-0.91	0.93
SW-DC	0.94	0.56	-0.93	0.49	0.87	0.65	-0.88	0.66
SW-ERM	-0.95	**0.83**	0.95	0.95	-0.94	**-0.91**	0.94	-0.61
GW-RFM	-0.53	0.82	0.36	-0.78	-0.76	0.85	0.75	-0.93
GW-MM	**-0.58**	0.93	0.33	-0.93	**0.26**	0.97	0.63	-0.89
GW-CP	-0.76	-0.76	0.83	0.73	-0.61	-0.56	0.70	0.81
GW-DC	**0.82**	0.82	-0.87	0.93	**-0.60**	0.61	-0.83	0.95
NA-SM	-1.00	**0.96**	-0.91	**0.93**	-1.00	**-0.97**	-0.71	-0.97
NA-GM	-0.99	0.82	**-0.93**	0.71	-0.99	0.99	**0.81**	0.77

Table S2: The effects of WGHM parameters on four response variables and their signatures in the Ganges basin, presented as relative percentages of the 'total effect' (i.e., sum of effects of all parameters). The 'Total Effect' is given in units [m^3s^{-1}] for streamflow and [mm] for other variables. The effects of the selected parameters are shown in boldfaces.

	Parameter Effect (% of Total Effect)															
	Monthly time series				Annual time-series				Monthly means				Seasonal amplitude			
Parameters	Q	TWSA	ET	SWSA	Q	TWSA	ET	SWSA	Q	TWSA	ET	SWSA	Q	TWSA	ET	SWSA
EP-PTh	7.4	2.7	**24.7**	3.8	**11.7**	1.3	**19.8**	3.7	7.8	6.9	**25.6**	3.9	**8.8**	7.5	**41.0**	4.5
EP-PTa	0.8	0.8	3.8	0.8	1.3	0.7	2.2	1.5	0.8	1.3	3.5	0.6	1.1	1.9	6.3	0.9
CA-MC	1.4	0.9	3.1	1.1	2.3	0.9	3.9	1.1	1.5	1.0	3.0	1.1	1.4	0.7	1.7	1.2
CA-LAIM	1.5	1.0	3.2	1.2	2.4	1.0	4.0	1.3	1.5	1.0	3.1	1.1	1.5	0.8	1.7	1.3
SN-FT	0.5	1.5	0.6	0.5	0.5	1.8	0.5	0.6	0.4	0.4	0.4	0.4	0.5	0.6	0.6	0.3
SN-MT	1.9	3.0	2.4	1.8	1.8	3.7	2.8	1.4	1.9	1.4	2.3	1.8	2.2	1.4	2.7	1.8
SN-DM	0.6	1.6	0.8	0.6	0.6	2.0	0.8	0.7	0.5	0.4	0.6	0.5	0.7	0.5	0.9	0.6
SN-TG	2.9	3.2	5.1	2.0	3.7	3.8	6.3	1.7	2.9	1.4	5.1	2.0	2.8	1.5	5.5	1.4
SL-RC	6.4	4.7	14.1	5.1	11.0	5.1	**18.9**	6.2	6.7	4.0	14.4	4.8	5.1	4.9	8.2	4.1
SL-MSM	**13.3**	**7.5**	**29.4**	**11.9**	**16.9**	3.5	**28.4**	5.8	**13.5**	**19.4**	**29.4**	**12.9**	**15.9**	**22.9**	**18.1**	**14.3**
SL-MEP	2.5	1.8	8.3	1.8	4.0	1.6	6.8	2.0	2.6	2.9	8.0	1.8	2.8	2.9	10.5	2.1
SW-RRM	**12.0**	3.8	0.0	**12.8**	0.3	0.8	0.0	**6.8**	**11.0**	**10.8**	0.0	**14.1**	**9.3**	**15.3**	0.0	**18.3**
SW-LD	1.1	0.7	0.1	2.3	0.3	0.5	0.1	4.6	1.0	1.3	0.1	1.8	1.8	1.1	0.1	1.5
SW-WD	**8.8**	3.9	0.4	**13.0**	1.3	1.7	0.6	**14.8**	**8.5**	**10.2**	0.4	**13.3**	**11.3**	**10.0**	0.2	**11.9**
SW-DC	5.3	2.4	1.3	7.8	1.3	1.0	1.6	**8.8**	4.9	6.1	1.3	8.0	5.5	5.0	0.7	5.7
SW-ERM	0.3	0.2	0.6	0.6	0.5	0.2	0.9	1.6	0.3	0.3	0.7	0.4	0.2	0.2	0.3	0.4
GW-RFM	3.4	3.1	0.2	4.7	0.6	3.0	0.1	2.0	3.4	4.4	0.2	5.2	4.5	3.9	0.2	5.0
GW-MM	**7.9**	**10.6**	0.2	**9.3**	1.9	**11.3**	0.2	4.4	**7.9**	**10.2**	0.2	**10.3**	**11.8**	**8.5**	0.2	**11.6**
GW-CP	0.2	0.7	0.5	0.2	0.2	0.9	0.4	0.3	0.1	0.3	0.4	0.1	0.2	0.2	0.6	0.2
GW-DC	3.9	3.3	0.2	6.6	1.7	2.9	0.2	5.0	4.0	5.4	0.2	7.3	5.1	3.2	0.1	6.6
NA-SM	**12.3**	2.9	0.6	**8.5**	**24.4**	2.5	0.8	**16.8**	**13.1**	4.9	0.6	6.4	4.9	3.9	0.3	4.0
NA-GM	5.4	**39.7**	0.4	3.9	11.4	**49.5**	0.6	**9.0**	5.7	6.0	0.4	2.5	2.9	3.0	0.2	2.1
Sum	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table S3: The effects of WGHM parameters on four response variables and their signatures in the Brahmaputra basin, presented as relative percentages of the 'total effect' (i.e., sum of effects of all parameters). The 'Total Effect' is given in units [m3s-1] for streamflow and [mm] for other variables. The effects of the selected parameters are shown in boldfaces.

	Parameter Effect (% of Total Effect)															
	Monthly time series				Annual time-series				Monthly means				Seasonal amplitude			
Parameters	Q	TWSA	ET	SWSA	Q	TWSA	ET	SWSA	Q	TWSA	ET	SWSA	Q	TWSA	ET	SWSA
EP-PTh	**15.8**	3.5	**31.3**	**6.5**	**28.9**	4.1	**32.5**	**10.0**	**17.0**	3.3	**32.7**	6.1	**14.1**	3.5	**36.9**	6.1
EP-PTa	0.5	0.6	1.8	0.7	0.7	0.5	0.9	0.9	0.5	0.7	1.4	0.7	0.4	1.0	3.3	0.9
CA-MC	1.6	1.0	2.8	1.3	2.7	1.0	3.0	1.8	1.6	1.0	2.8	1.2	1.2	1.1	2.6	1.2
CA-LAIM	1.7	1.0	3.0	1.4	2.8	1.1	3.2	2.0	1.6	1.1	2.9	1.3	1.2	1.1	2.7	1.3
SN-FT	1.3	4.4	2.5	2.1	1.9	**7.4**	2.1	3.9	1.2	0.8	2.1	1.5	1.2	1.2	2.5	1.5
SN-MT	5.0	**8.8**	10.4	**7.4**	8.5	**14.5**	9.5	**10.1**	5.1	3.5	10.1	6.9	4.5	3.7	11.1	6.5
SN-DM	1.3	4.6	2.8	2.1	2.1	**7.8**	2.3	3.7	1.2	0.9	2.4	1.6	1.1	1.3	3.1	1.4
SN-TG	**6.9**	**10.5**	**14.7**	5.6	**12.6**	**17.8**	**14.4**	**9.7**	**7.2**	2.6	**14.8**	4.3	6.0	3.1	**17.0**	4.6
SL-RC	**6.6**	2.9	10.4	3.4	10.8	2.7	12.2	5.3	6.7	3.2	10.6	2.9	3.7	2.9	5.3	2.1
SL-MSM	**9.7**	**10.3**	**13.0**	4.9	**11.7**	6.1	**13.2**	3.3	**9.7**	**15.1**	**12.8**	5.3	**12.1**	**15.2**	9.3	6.3
SL-MEP	2.7	1.7	5.6	1.3	4.6	1.1	5.2	1.7	2.8	2.4	5.8	1.3	2.3	1.4	4.5	1.4
SW-RRM	**11.0**	**8.0**	0.0	**17.4**	0.3	2.1	0.0	7.6	**8.7**	**12.3**	0.0	**19.8**	**8.5**	**17.0**	0.0	**24.9**
SW-LD	1.0	1.7	0.0	3.8	0.2	2.7	0.0	**9.6**	0.9	1.1	0.0	1.8	1.0	1.2	0.0	1.7
SW-WD	5.0	4.8	0.3	**10.4**	0.8	2.2	0.3	**7.8**	4.9	7.1	0.3	**11.4**	7.0	6.9	0.2	**9.1**
SW-DC	3.9	4.0	0.4	**8.5**	1.0	2.6	0.5	**9.3**	3.7	5.5	0.4	**8.8**	3.9	4.9	0.1	**6.7**
SW-ERM	0.1	0.2	0.2	0.4	0.3	0.3	0.3	1.1	0.1	0.1	0.3	0.2	0.1	0.2	0.1	0.1
GW-RFM	5.0	5.1	0.4	**6.5**	0.7	2.1	0.3	1.7	5.3	7.8	0.4	**7.6**	6.8	7.6	0.6	**7.6**
GW-MM	**10.9**	**11.2**	0.0	**6.5**	1.5	5.6	0.0	1.3	**11.3**	**16.8**	0.0	**7.5**	**15.0**	**17.6**	0.0	**6.7**
GW-CP	0.2	0.8	0.3	0.3	0.2	1.2	0.2	0.3	0.1	0.3	0.2	0.3	0.1	0.2	0.5	0.3
GW-DC	**6.8**	**8.8**	0.0	6.3	1.9	**7.5**	0.0	2.6	**7.3**	**11.2**	0.0	**7.4**	**8.2**	**5.8**	0.0	**7.3**
NA-SM	2.3	1.3	0.0	2.7	4.3	1.6	0.0	5.7	2.4	1.2	0.0	1.9	1.1	1.4	0.0	1.9
NA-GM	0.7	5.0	0.0	0.5	1.4	**8.1**	0.0	0.6	0.7	1.7	0.0	0.5	0.3	1.7	0.0	0.4
Sum	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table S4: Correlation between parameter values and the calibration objectives in all compromise solutions of all calibration experiments

	Pearson Correlation Coefficient (r)							
	Ganges				Brahmaputra			
Parameters	NSE_{Q}	NSE_{TWSA}	NSE_{ET}	NSE_{SWSA}	NSE_{Q}	NSE_{TWSA}	NSE_{ET}	NSE_{SWSA}
P-PM	-0.94	0.33	0.42	-0.58	-0.69	0.19	0.02	0.29
EP-PTh	0.17	-0.61	-0.73	0.10	0.21	0.20	0.44	0.08
SN-FT					0.50	0.09	-0.20	0.04
SN-MT					0.18	0.11	0.11	0.03
SN-DM					0.37	0.12	-0.05	0.29
SN-TG					0.54	-0.38	-0.06	0.14
SL-MSM	0.00	0.45	0.89	-0.02	0.06	-0.06	0.44	0.05
SL-RC	0.40	0.27	0.47	0.08	-0.52	-0.38	0.01	-0.09
GW-RFM					-0.44	0.05	-0.06	-0.11
GW-MM	-0.02	0.23	0.28	0.15	0.42	-0.32	0.04	0.35
GW-DC					0.12	-0.21	0.09	-0.08
SW-RRM	-0.50	-0.21	0.00	-0.88	0.33	0.18	0.00	-0.58
SW-LD					0.19	-0.25	0.00	0.09
SW-WD	-0.45	-0.07	0.23	-0.71	0.05	-0.09	-0.16	-0.34
SW-DC	0.46	-0.37	-0.41	0.25	0.48	0.14	-0.05	0.33
NA-GM	0.16	-0.74	-0.28	-0.19	-0.34	-0.35	-0.12	-0.20
NA-SM	0.46	-0.21	-0.10	0.15				

Table S5: Number of the acceptable Pareto solutions considering observation uncertainties in the 4-objective calibration, for the different thresholds M1 to M5 in delineating the set of "acceptable" solutions.

Basin	Total Solutions[a]	M1: MIN_{CS}	M2: MIN_{CS} $-MAD_{OBJOU}$	M3: MIN_{CS} $-STD_{OBJOU}$	M4: $Q_{05, OBJOU}$	M5: MIN_{OBJOU}
Ganges	8705	43	647	483	1419	2506
Brahmaputra	339	38	154	118	221	259

[a] total number of non-dominated Pareto solutions in 8 replications

Table S6: Correlations among the parameters of the acceptable Pareto solutions considering observation uncertainties of the Ganges basin

	Pearson Correlation Coefficient (r)									
	P-PM	EP-PTh	SL-MSM	SL-RC	GW-MM	SW-RRM	SW-WD	SW-DC	NA-GM	NA-SM
P-PM	1	0.06	-0.06	0.35	0.28	-0.3	0.01	-0.2	-0.2	0.02
EP-PTh	0.06	1	0.07	-0.12	-0.1	0.07	-0.04	-0.05	0.04	0.05
SL-MSM	-0.06	0.07	1	-0.24	-0.17	-0.03	0.08	-0.02	0.11	-0.07
SL-RC	0.35	-0.12	-0.24	1	-0.1	-0.08	-0.04	-0.05	-0.04	-0.14
GW-MM	0.28	-0.1	-0.17	-0.1	1	0.18	-0.04	-0.02	-0.2	0.32
SW-RRM	-0.3	0.07	-0.03	-0.08	0.18	1	-0.15	-0.22	-0.07	0.02
SW-WD	0.01	-0.04	0.08	-0.04	-0.04	-0.15	1	-0.1	-0.12	-0.03
SW-DC	-0.2	-0.05	-0.02	-0.05	-0.02	-0.22	-0.1	1	-0.01	0.1
NA-GM	-0.2	0.04	0.11	-0.04	-0.2	-0.07	-0.12	-0.01	1	-0.22
NA-SM	0.02	0.05	-0.07	-0.14	0.32	0.02	-0.03	0.1	-0.22	1

Table S7: Correlations among the parameters of the acceptable Pareto solutions considering observation uncertainties of the Brahmaputra basin

	Pearson Correlation Coefficient (r)															
	P-PM	EP-PTh	SN-FT	SN-MT	SN-DM	SN-TG	SL-MSM	SL-RC	GW-RFM	GW-MM	GW-DC	SW-RRM	SW-LD	SW-WD	SW-DC	NA-GM
P-PM	1	-0.02	-0.01	-0.26	-0.25	-0.28	0.01	-0.12	0.28	-0.29	-0.34	-0.03	0.01	0.14	-0.08	-0.03
EP-PTh	-0.02	1	0.23	-0.27	0.15	0.7	0.27	-0.36	-0.44	0.45	0.31	-0.4	0.24	0.03	0.13	-0.33
SN-FT	-0.01	0.23	1	0.02	0.17	-0.03	-0.11	-0.19	-0.1	0.07	-0.01	0	0.12	0.01	-0.13	-0.1
SN-MT	-0.26	-0.27	0.02	1	0.15	-0.45	0	0.09	0.2	-0.23	-0.01	0.26	-0.24	-0.14	-0.23	0.14
SN-DM	-0.25	0.15	0.17	0.15	1	0.39	0.18	0.01	-0.51	0.52	0.55	-0.44	0.38	0	0.12	-0.18
SN-TG	-0.28	0.7	-0.03	-0.45	0.39	1	0.27	-0.05	-0.72	0.78	0.64	-0.63	0.38	0.03	0.26	-0.33
SL-MSM	0.01	0.27	-0.11	0	0.18	0.27	1	-0.11	-0.27	0.2	0.33	-0.24	0.06	-0.16	0.03	-0.06
SL-RC	-0.12	-0.36	-0.19	0.09	0.01	-0.05	-0.11	1	-0.09	0.05	0.11	-0.11	-0.12	0.06	0.15	0.14
GW-RFM	0.28	-0.44	-0.1	0.2	-0.51	-0.72	-0.27	-0.09	1	-0.9	-0.76	0.75	-0.39	0	-0.14	0.36
GW-MM	-0.29	0.45	0.07	-0.23	0.52	0.78	0.2	0.05	-0.9	1	0.79	-0.69	0.33	-0.03	0.11	-0.33
GW-DC	-0.34	0.31	-0.01	-0.01	0.55	0.64	0.33	0.11	-0.76	0.79	1	-0.63	0.23	-0.14	0.14	-0.29
SW-RRM	-0.03	-0.4	0	0.26	-0.44	-0.63	-0.24	-0.11	0.75	-0.69	-0.63	1	-0.4	-0.37	-0.33	0.29
SW-LD	0.01	0.24	0.12	-0.24	0.38	0.38	0.06	-0.12	-0.39	0.33	0.23	-0.4	1	-0.03	0.2	-0.38
SW-WD	0.14	0.03	0.01	-0.14	0	0.03	-0.16	0.06	0	-0.03	-0.14	-0.37	-0.03	1	0.31	-0.01
SW-DC	-0.08	0.13	-0.13	-0.23	0.12	0.26	0.03	0.15	-0.14	0.11	0.14	-0.33	0.2	0.31	1	-0.21
NA-GM	-0.03	-0.33	-0.1	0.14	-0.18	-0.33	-0.06	0.14	0.36	-0.33	-0.29	0.29	-0.38	-0.01	-0.21	1

Table S8. Parameter dispersion (range) in the compromise solutions among replications, presented as the ratio to the a-priori parameter range (Table 2) in the Ganges River Basin.

	The ratio of the parameter range in the compromise solutions to the a-priori range														
	Q	T	E	S	QT	QE	QS	TE	TS	ES	QTE	QTS	QES	TES	QTES
P-PM	14.5	0.5	1.9	21.9	1.7	1.3	1.1	1.9	12.7	2.2	1.8	3.1	1.7	1.3	4.1
EP-PTh	87.1	0.1	2.7	100.0	0.1	1.5	46.4	2.2	0.0[a]	2.1	2.0	2.4	11.1	5.2	16.6
SL-MSM	37.8	14.7	8.9	0.4	1.2	9.1	0.5	4.2	0.1	0.2	13.4	5.2	7.4	0.8	4.3
SL-RC	12.7	0.1	6.7	0.1	1.5	33.7	0.0[a]	0.9	6.9	1.9	2.3	8.4	11.2	5.0	16.5
GW-MM	62.4	22.0	3.8	56.8	11.5	23.4	4.8	11.1	6.6	1.7	20.7	23.6	4.7	7.4	20.2
SW-RRM	15.9	10.4	78.7	0.0[a]	1.2	4.1	3.4	0.0[a]	0.0[a]	0.0[a]	14.6	5.4	6.8	0.1	11.0
SW-WD	27.5	20.3	28.2	0.0[a]	5.7	27.3	0.0[a]	21.9	0.2	0.0[a]	5.6	1.2	0.6	0.1	1.1
SW-DC	100.0	100.0	0.0[a]	100.0	48.2	0.3	0.5	1.8	99.9	0.0[a]	0.9	18.7	21.6	0.1	39.5
NA-GM	33.7	14.5	92.4	2.6	1.0	2.7	13.3	1.4	0.2	0.3	51.6	4.9	78.0	1.1	33.2
NA-SM	27.2	16.1	46.6	9.9	5.8	4.8	1.1	22.6	30.3	11.1	38.5	20.2	12.4	23.4	23.2
Average	41.9	19.9	30.0	36.5	7.8	10.8	8.9	7.6	19.6	2.8	15.1	9.3	15.6	4.5	17.0

[a] very small value close to 0 but not equals 0

Table S9. Parameter dispersion (range) in the compromise solutions among replications, presented as the ratio to the a-priori parameter range (Table 2) in the Brahmaputra River Basin.

	The ratio of the parameter range in the compromise solutions to the a-priori range														
	Q	T	E	S	QT	QE	QS	TE	TS	ES	QTE	QTS	QES	TES	QTES
P-PM	8.0	55.3	78.0	43.5	7.7	2.1	5.8	48.8	44.4	20.5	1.6	6.2	2.9	27.5	2.1
EP-PTh	79.6	72.5	73.2	81.6	91.2	52.2	59.5	63.1	70.4	59.3	26.4	91.5	49.9	68.8	31.2
SN-FT	27.9	70.1	99.5	53.5	30.5	92.4	28.5	98.2	43.5	45.8	34.9	20.0	25.8	81.8	23.3
SN-MT	5.8	80.3	12.7	27.3	9.3	8.6	24.9	19.6	11.7	16.9	8.2	12.8	20.2	13.0	5.6
SN-DM	36.6	74.2	30.4	84.9	84.0	73.8	76.8	44.0	90.1	71.0	97.6	72.3	74.7	60.0	58.0
SN-TG	1.7	100.0	62.2	9.0	22.7	33.6	1.9	32.2	95.8	46.2	21.1	7.0	26.0	43.9	10.5
SL-MSM	59.7	85.5	0.9	41.6	68.7	4.7	42.7	3.4	61.3	34.7	1.8	44.2	1.3	8.2	9.8
SL-RC	4.3	53.3	97.0	57.9	4.8	21.9	11.5	62.6	46.3	100.0	2.2	3.1	4.3	72.5	3.4
GW-RFM	50.6	95.0	98.9	77.5	78.8	28.9	21.8	62.6	79.2	46.2	66.9	13.4	13.1	63.6	11.8
GW-MM	44.4	86.0	96.3	82.7	74.2	22.5	19.3	23.3	78.4	47.8	84.1	5.3	10.0	72.7	39.1
GW-DC	31.2	59.2	77.0	47.5	68.3	31.9	12.4	0.1	48.9	64.9	57.0	28.8	9.5	47.6	35.0
SW-RRM	22.4	79.6	84.5	10.2	72.0	28.4	7.6	39.8	10.9	18.4	68.1	32.0	7.1	11.9	14.7
SW-LD	32.5	85.8	28.9	99.5	98.2	34.5	93.2	94.7	94.1	96.4	69.5	97.1	47.3	96.0	88.9
SW-WD	63.4	98.5	47.5	48.9	32.5	30.7	13.6	59.7	57.1	44.9	54.1	15.9	10.5	50.8	16.9
SW-DC	53.5	99.9	81.2	50.7	26.7	75.2	2.1	100.0	64.8	88.0	13.6	99.9	5.0	47.0	13.3
Average	34.8	79.7	64.5	54.4	51.3	36.1	28.1	50.1	59.8	53.4	40.5	36.6	20.5	51.0	24.2

Table S10: NSE, Correlation (r), and KGE scores of the overall compromise solution of the calibration experiments of the Ganges basin in the calibration period. KGE is computed as $KGE = 1 - \sqrt{(r-1)^2 + (\beta-1)^2 + (\gamma-1)^2}$, following Kling et al. (2012) for streamflow and evapotranspiration. For the variables TWSA and SWSA KGE was adapted from Gupta et al. (2009) by omitting the β-term, $KGE = 1 - \sqrt{(r-1)^2 + (\alpha-1)^2}$. Here, $\alpha = (\sigma_{sim}/\sigma_{obs})$, $\beta = (\mu_{sim}/\mu_{obs})$, $\gamma = (\sigma_{sim}/\mu_{sim})/(\sigma_{obs}/\mu_{obs})$, and r is the Pearson's correlation coefficient.

	Ganges											
	Q			TWSA			ET			SWSA		
	NSE	r	KGE	NSE	r	KGE	NSE	r	KGE	NSE	r	KGE
Q	0.97	0.98	0.95	-2.16	0.91	0.85	0.31	0.97	0.33	0.45	0.87	0.56
T	0.70	0.97	0.45	0.85	0.93	0.90	0.88	0.94	0.89	0.65	0.82	0.63
E	-15.41	0.97	-2.26	0.27	0.83	0.54	0.96	0.98	0.97	-3.60	0.93	-1.04
S	-0.54	0.92	0.03	0.45	0.84	0.35	0.05	0.92	-0.13	0.92	0.96	0.96
QT	0.95	0.98	0.88	0.84	0.93	0.89	0.87	0.94	0.89	0.63	0.81	0.60
QE	0.96	0.98	0.91	-5.89	0.98	0.75	0.93	0.97	0.94	-0.13	0.61	0.55
QS	0.94	0.97	0.94	-27.02	0.57	0.51	-0.36	0.92	-0.27	0.89	0.94	0.94
TE	0.52	0.97	0.33	0.85	0.92	0.90	0.93	0.97	0.95	0.61	0.79	0.61
TS	-2.44	0.94	-0.56	0.81	0.90	0.88	0.88	0.97	0.87	0.88	0.94	0.91
ES	-6.23	0.95	-1.35	0.66	0.90	0.70	0.94	0.98	0.92	0.89	0.95	0.94
QTE	0.94	0.97	0.85	0.84	0.92	0.89	0.92	0.96	0.95	0.58	0.79	0.53
QTS	0.93	0.98	0.71	0.80	0.90	0.79	0.65	0.96	0.66	0.80	0.89	0.85
QES	0.94	0.98	0.90	-20.40	0.84	0.61	0.88	0.96	0.84	0.77	0.88	0.82
TES	-3.45	0.95	-0.75	0.81	0.91	0.90	0.93	0.97	0.94	0.88	0.94	0.94
QTES	0.91	0.98	0.76	0.81	0.92	0.83	0.88	0.96	0.89	0.77	0.88	0.82

Table S11: NSE, Correlation (r), and KGE scores of the overall compromise solution of the calibration experiments of the Brahmaputra basin in the calibration period

	Brahmaputra											
	Q			TWSA			ET			SWSA		
	NSE	r	KGE	NSE	r	KGE	NSE	r	KGE	NSE	r	KGE
Q	0.95	0.98	0.98	0.76	0.94	0.84	0.93	0.96	0.96	0.79	0.94	0.75
T	0.93	0.97	0.87	0.97	0.99	0.98	0.79	0.98	0.83	0.61	0.96	0.47
E	0.90	0.97	0.80	0.92	0.96	0.87	0.96	0.98	0.94	0.91	0.96	0.93
S	0.24	0.95	0.59	0.70	0.97	0.88	0.75	0.93	0.85	0.95	0.97	0.97
QT	0.95	0.98	0.94	0.96	0.98	0.96	0.74	0.98	0.71	0.84	0.96	0.75
QE	0.95	0.98	0.97	0.81	0.94	0.83	0.96	0.98	0.95	0.85	0.94	0.89
QS	0.95	0.97	0.97	0.70	0.95	0.95	0.60	0.97	0.77	0.94	0.97	0.96
TE	0.90	0.97	0.84	0.97	0.98	0.97	0.96	0.98	0.95	0.79	0.97	0.66
TS	0.87	0.97	0.84	0.96	0.98	0.93	0.94	0.98	0.92	0.94	0.97	0.96
ES	0.22	0.96	0.54	0.81	0.95	0.84	0.96	0.98	0.95	0.94	0.97	0.96
QTE	0.95	0.98	0.90	0.96	0.98	0.98	0.96	0.98	0.94	0.88	0.96	0.83
QTS	0.95	0.97	0.93	0.96	0.98	0.95	0.78	0.98	0.79	0.94	0.97	0.96
QES	0.95	0.98	0.97	0.89	0.96	0.91	0.96	0.98	0.95	0.94	0.97	0.95
TES	0.70	0.97	0.75	0.96	0.98	0.96	0.96	0.98	0.93	0.94	0.97	0.97
QTES	0.94	0.98	0.87	0.96	0.98	0.98	0.96	0.98	0.95	0.94	0.97	0.97

Table S12: Bias Ratio (R. Bias; *β*) and Variance Ratio (R. Var; *γ* for Q and ET, *α* for TWSA and SWSA) scores of the overall compromise solution of the calibration experiments of the Ganges and the Brahmaputra basin in the calibration period. For the definition of *α*, *β*, and *γ*, see the caption of Table S8

	(R. Bias / R. Var)							
	Ganges				Brahmaputra			
	Q	TWSA	ET	SWSA	Q	TWSA	ET	SWSA
Q	1.01/0.96	- /0.88	0.65/1.57	- /1.42	1.00/0.99	- /1.15	0.98/1.00	- /1.24
T	1.51/0.79	- /0.93	0.98/0.90	- /0.68	0.97/1.12	- /0.98	0.84/1.04	- /1.53
E	4.26/0.90	- /1.42	0.99/1.02	- /3.04	0.85/1.12	- /0.87	0.99/1.06	- /1.05
S	1.96/0.88	- /0.37	0.66/2.07	- /0.98	1.37/1.18	- /0.89	0.87/0.96	- /0.98
QT	1.06/0.90	- /0.91	0.95/0.92	- /0.64	0.98/1.05	- /0.97	0.81/1.21	- /1.25
QE	1.04/0.92	- /1.25	0.98/1.04	- /1.23	1.01/0.98	- /1.16	0.99/1.05	- /1.09
QS	1.00/0.95	- /1.25	0.53/2.18	- /0.98	0.99/1.01	- /1.00	0.78/1.04	- /0.97
TE	1.64/0.79	- /0.94	0.98/1.03	- /0.67	1.01/1.16	- /0.97	1.00/1.05	- /1.34
TS	2.55/0.85	- /0.93	0.88/1.04	- /0.94	1.07/1.14	- /0.94	1.03/1.07	- /0.97
ES	3.34/0.79	- /1.28	0.96/1.06	- /1.03	1.46/1.03	- /1.15	0.99/1.05	- /0.97
QTE	1.09/0.88	- /0.93	0.98/1.01	- /0.58	0.96/1.09	- /1.01	0.99/1.06	- /1.17
QTS	1.21/0.81	- /0.82	0.77/1.25	- /0.90	0.97/1.06	- /0.96	0.83/1.13	- /0.97
QES	1.10/0.98	- /1.35	0.92/1.13	- /0.87	0.99/1.01	- /1.08	0.99/1.05	- /0.97
TES	2.74/0.86	- /0.99	0.95/0.99	- /0.98	1.20/1.15	- /0.96	0.99/1.06	- /0.98
QTES	1.22/0.91	- /0.86	0.90/1.04	- /0.87	0.96/1.12	- /1.01	0.99/1.05	- /0.99

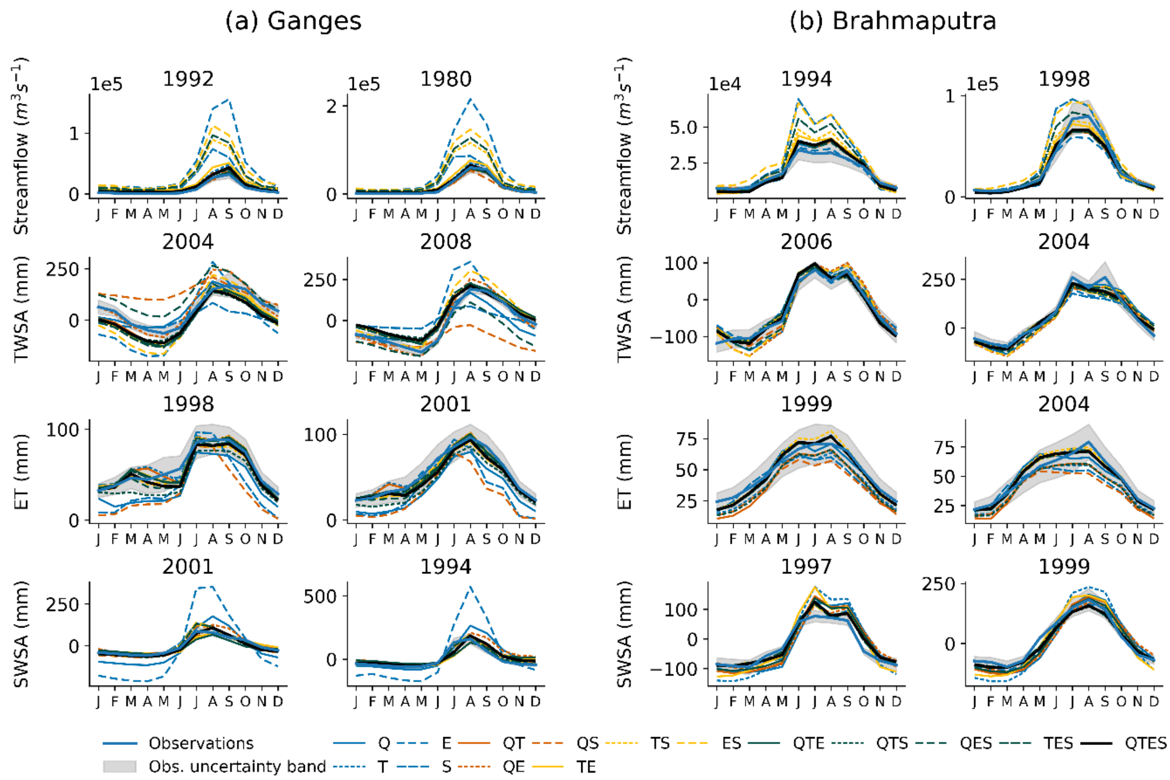

Figure S1. Comparison of simulations of the four response variables - streamflow, TWSA, ET, and SWSA, using the overall compromise solution of the experiments in the Ganges basin (a) and the Brahmaputra basin (b). For each variable, two years have been chosen for that there is no missing value for the entire year and the seasonal amplitude is the lowest (left column of each subplot) and the highest (right column of the subplot).

Table S13: Average Uncertainty Bandwidth (AUBW) of observation and ensemble of the 'acceptable' solutions considering observation uncertainties. AUBW is expressed as % for Q and ET variables and for TWSA and SWSA in mm. AUBW is computed according to Jin et al. (2010) **as $AUBW = \frac{1}{n}\sum_i \frac{Upperlimit_i - Lowerlimit_i}{EnsembleMean_i}$; for observations, the observed value at time-step t is used as the mean. For TWSA and SWSA, AUBW is computed without the denominator term as $AUBW = \frac{1}{n}\sum_i (Upperlimit_i - Lowerlimit_i)$.**

		Average Uncertainty Bandwidth (AUBW)			
		Observations		Candidates for compromise solutions	
Variables	[unit]	Ganges	Brahmaputra	Ganges	Brahmaputra
Q	-	41.7%	41.7%	65.1%	32.8%
TWSA	mm	53.9	56.7	50.7	51.1
ET	-	53.4%	50.5%	32.2%	23.8%
SWSA	mm	29.3	43.3	32.1	35.5

References:

Campolongo, F., Saltelli, A., and Cariboni, J.: From screening to quantitative sensitivity analysis. A unified approach, Comput Phys Commun, 182, 978–988, https://doi.org/https://doi.org/10.1016/j.cpc.2010.12.039, 2011.

FAO: AQUASTAT Transboundary River Basins – Ganges-Brahmaputra-Meghna River Basin, Rome, Italy, 2011.

Gupta, H. V, Kling, H., Yilmaz, K. K., and Martinez, G. F.: Decomposition of the mean squared error and {NSE} performance criteria: Implications for improving hydrological modelling, J Hydrol (Amst), 377, 80–91, http://dx.doi.org/10.1016/j.jhydrol.2009.08.003, 2009.

Immerzeel, W.: Historical trends and future predictions of climate variability in the Brahmaputra basin, International Journal of Climatology, 28, 243–254, https://doi.org/10.1002/joc.1528, 2008.

India-WRIS: Basin Reports - Brahmaputra Basin, New Delhi - 110066, INDIA, 2014a.

India-WRIS: Basin Reports - Ganga Basin, New Delhi - 110066, INDIA, 2014b.

Jin, X., Xu, C.-Y., Zhang, Q., and Singh, V. P.: Parameter and modeling uncertainty simulated by GLUE and a formal Bayesian method for a conceptual hydrological model, J Hydrol (Amst), 383, 147–155, https://doi.org/10.1016/j.jhydrol.2009.12.028, 2010.

Kling, H., Fuchs, M., and Paulin, M.: Runoff conditions in the upper Danube basin under an ensemble of climate change scenarios, J Hydrol (Amst), 424–425, 264–277, https://doi.org/https://doi.org/10.1016/j.jhydrol.2012.01.011, 2012.

Masood, M., Yeh, P. J.-F., Hanasaki, N., and Takeuchi, K.: Model study of the impacts of future climate change on the hydrology of Ganges-Brahmaputra-Meghna basin, Hydrol Earth Syst Sci, 19, 747–770, https://doi.org/10.5194/hess-19-747-2015, 2015.

Morris, M. D.: Factorial Sampling Plans for Preliminary Computational Experiments, Technometrics, 33, 161–174, https://doi.org/10.1080/00401706.1991.10484804, 1991.

Papa, F., Durand, F., Rossow, W. B., Rahman, A., and Bala, S. K.: Satellite altimeter-derived monthly discharge of the Ganga-Brahmaputra River and its seasonal to interannual variations from 1993 to 2008, J Geophys Res Oceans, 115, https://doi.org/10.1029/2009JC006075, 2010.

Pianosi, F., Sarrazin, F., and Wagener, T.: A Matlab toolbox for Global Sensitivity Analysis, Environmental Modelling & Software, 70, 80–85, https://doi.org/10.1016/j.envsoft.2015.04.009, 2015.

Ray, P. A., Yang, Y.-C. E., Wi, S., Khalil, A., Chatikavanij, V., and Brown, C.: Room for improvement: Hydroclimatic challenges to poverty-reducing development of the Brahmaputra River basin, Environ Sci Policy, 54, 64–80, https://doi.org/10.1016/j.envsci.2015.06.015, 2015.