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Assessment of spatially explicit annual water-balance model for Sutlej River Basin in eastern Himalayas and Tungabhadra River Basin in peninsular India

Manish Kumar Goyal and Manas Khan

ABSTRACT

In this paper, Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) water yield model, based on the Budyko framework which is relatively simple and requires less data, has been applied in Sutlej River Basin, located in the eastern Himalayas and in Tungabhadra River Basin, located in peninsular India. The effect of extrapolation of the lumped Zhang model to distributed model (InVEST) has also been analyzed. We also determined the most suitable method for calculating reference evapotranspiration among three different methods, i.e., modified Hargreaves, normal Hargreaves and Hamon's equation. It was found that modified Hargreaves method is the most suitable one under limited data conditions although in certain stations in Tungabhadra River Basin, this method is not applicable. We also observed that the InVEST model performed well in the Sutlej River Basin although a certain proportion of the basin is snow covered. The results from the study also show that errors in climate inputs will have significant influence on water yield as compared to other parameters, i.e., seasonality constant (Z) and evapotranspiration coefficient (K_C). In the case of the crop dominated Tungabhadra River Basin, both seasonality constant (Z) and evapotranspiration coefficient (K_C) have comparatively greater sensitivity as compared to the Sutlej River Basin.

Key words | ecosystem, evapotranspiration, water yield, Zhang model

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INTRODUCTION

Hydrological ecosystem services (ES) often include drinking water supply, power production, industrial use, irrigation, and many more. These hydrological ES are dependent on different watershed characteristics such as land use and land cover (LULC), soil type, topography, and climatic conditions. LULC has a dominant influence in producing spatial variability of ES and tradeoffs. With the change in different ES due to climate change, proper analysis and quantification of ES are playing a major role in policy-making of a country. Proper analysis of ES is not easy but rather complicated due to its spatial variability and dependency on so many topographical and climatic factors. The benefits which are derived from ES, should be analyzed and quantified in a spatially explicit manner. Sound quantification techniques also play a crucial role in ES assessment (Burkhard *et al.* 2012). Over the years, efforts have been made to develop different ecosystem assessment tools. In this regard, Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST), developed by Natural Capital Project (www.naturalcapitalproject.org) (Tallis *et al.* 2014) can be used. Although it is a simplified model, it can provide us with satisfactory conclusions regarding different ES.

Sánchez-Canales *et al.* (2012) used the InVEST model in a Mediterranean region basin (the Llobregat basin, Catalonia, Spain) and carried out sensitivity analysis of three main coefficients: Z (seasonal precipitation distribution), prec (annual precipitation), reference evapotranspiration (ET_0) (annual evapotranspiration) using Morris index method and found Z as the least sensitive parameter and precipitation as the most sensitive parameter in humid areas of the study area, but in some watersheds, ET_0 had greater influence than

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precipitation. Terrado *et al.* (2014) used the InVEST model in the heavily humanized Llobregat River Basin (Catalonia, Spain) to assess three ES (i.e., water provisioning, water purification, erosion control) in extreme dry and wet years and found that climatic parameters are very sensitive in semi-arid basins under continuing population pressure. Hoyer & Chang (2014) used this model in Tualatin and Yamhill basins of northwestern Oregon under a series of urbanization and climate change scenarios and found that sensitivity of climatic parameters is higher as compared to other inputs in the water yield model. Most recently, Hamel & Guswa (2014) analyzed the uncertainty of the water yield model in Cape Fear catchment, North Carolina and found precipitation as the most influencing parameter and Z parameter as comparatively more sensitive than K_C within the specified range.

To the authors' best knowledge, no significant work has been done using InVEST in a hilly catchment. In this paper we have used the water yield model of InVEST. We have applied this model in a hilly catchment, Sutlej River Basin (up to Kasol gauge station), with aridity index ranging from 0.139 to 2.39 with a mean of 0.764, situated in the eastern Himalayas and in one peninsular region, Tungabhadra River Basin (up to Haralahalli gauge station), with aridity index ranging from 0.22 to 1.98 with a mean of 0.949, in Karnataka, India and determined the performance of this model in these regions. Some parts of the two regions have a humid ($0.75 > PET/P \geq 0.375$) and sub-humid climate ($2 > PET/P \geq 0.75$) and also semi-arid ($5 > PET/P \geq 2$) (Sutlej River Basin (up to Kasol gauge station)), depending upon aridity index (PET/P) as described by Ponce *et al.* (2000). Different equations (modified Hargreaves, normal Hargreaves, Hamon's equation) for calculating ET_0 have been used and potential applicability of these methods discussed for the basins. We have also compared the model outputs with the observed field data and with estimated values of the lumped Zhang model. The sensitivity of different parameters, which are responsible for determining the amount and nature of water yield from the study area, has also been discussed.

STUDY AREA AND DATA

The whole study includes two sub-areas which are discussed below.

Sutlej River Catchment

Sutlej River Catchment (up to Kasol gauge station) as shown in Figure 1, has an approximate area of 51,071.39 km^2. The

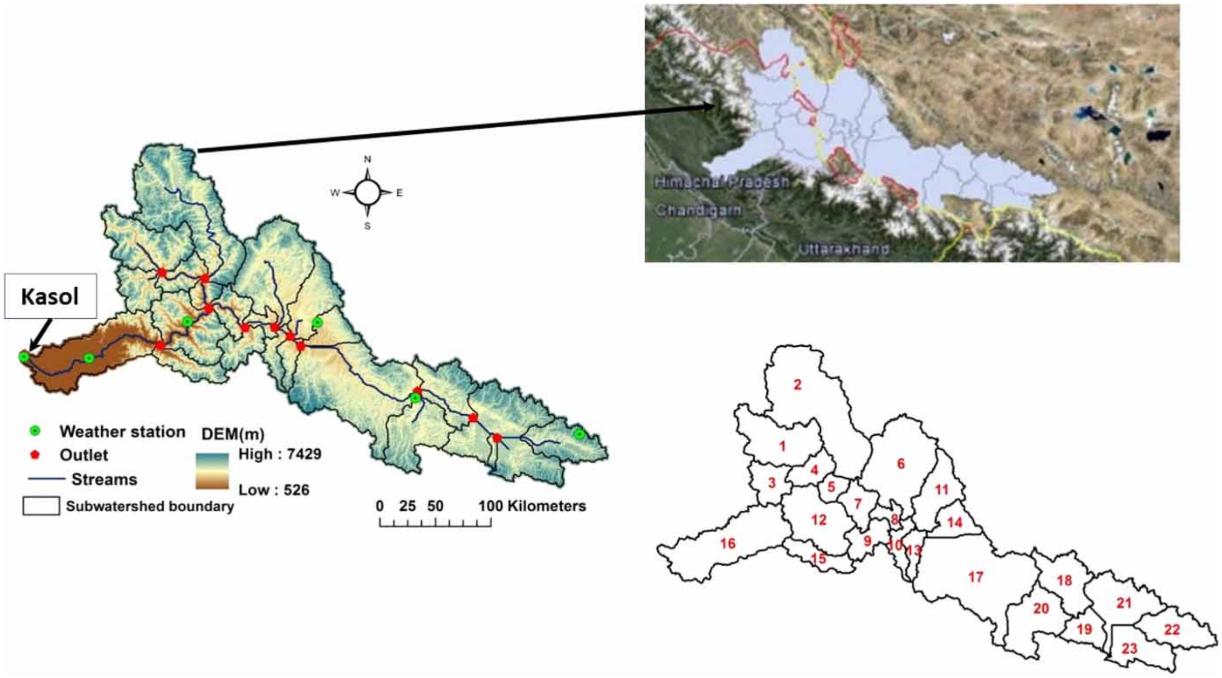

Figure 1 | Study area of Sutlej River Catchment (up to Kasol gauge station) (sub-watersheds are marked by numbers).

whole basin has been delineated into 23 sub-basins (Table 1). It is situated between ~76.82 ° E to ~82 ° E and 33.2 ° N to 30.57 ° N co-ordinates. The rivers in the watershed are mostly fed by snowmelt and rainfall during summer when the temperature remains comparatively high. Most of the study area, especially the middle and upper portion fall in the greater Himalayan range. Due to high altitude and variability in precipitation, very diverse climatic conditions are observed throughout the study area. The lower part of the basin has a tropical and warm temperate climate whereas the middle and upper portion has a very cold climate. Annual average precipitation varies in the range of ~299 mm to ~1,273 mm with mean of ~548 mm in the period 1989 to 2005. The whole basin is dominated by barren (~39%), shrubs (~26%), snow and glacier (~24%), water (~3.7%), and forest (~3.3%) (Singh *et al.* 2015).

Tungabhadra River Catchment

The other study sub-area is Tungabhadra Catchment (up to Haralahalli gauge station) which is a peninsular region, as shown in Figure 2. It is part of the Krishna River Basin. The study area falls approximately in between ~75°8 E to ~76°16 E and ~13°50 N to ~14°53 N. The whole area is about 7,566.63 km^2 and is delineated into 16 sub-basins (Table 2). The Tungabhadra River is formed by the confluence of its two main tributaries, Tunga and Bhadra. Tunga and Bhadra rivers originate at Varaha Parvatha in the Western Ghats in Karnataka in India. Finally, the two rivers meet at Koodli near Holehonnu to form the Tungabhadra River. The average annual precipitation is between ~827 mm and ~2,220 mm with a mean of ~1,424 mm for the period from 1986 to 2005. 75% to 80% of the total rainfall comes from the south-west monsoon during

Table 1 | Details of study area of Sutlej River Catchment (up to Kasol gauge station)

Sub-basin	Area (km^2)	Latitude	Longitude	Elevation (m)	Minimum elevation (m)	Maximum elevation (m)
1	2,977.86	32.274	78.057	4,967.59	3,438	6,649
2	6,491.71	32.788	78.444	5,099.54	3,127	6,658
3	1,237.83	31.955	77.971	4,849	3,440	6,378
4	976.42	32.081	78.375	4,623.36	3,127	6,540
5	573.53	31.914	78.614	4,416	2,555	6,694
6	4,433.27	32.148	79.251	4,827.86	3,666	6,144
7	1,046.73	31.766	78.858	4,538.93	2,555	6,712
8	472.11	31.707	79.140	4,345.86	3,181	5,477
9	1,047.32	31.464	78.959	4,814.96	3,181	6,064
10	702.46	31.353	79.297	4,802.16	3,666	6,152
11	1,999.4	31.616	79.666	4,625.64	3,666	6,260
12	2,981.52	31.644	78.463	4,407.96	1,885	6,542
13	632.44	31.366	79.429	4,668.08	3,666	6,174
14	1,075.48	31.652	79.821	4,454.74	3,869	5,947
15	1,075.88	31.301	78.472	4,587.54	1,838	6,417
16	4,476.19	31.41	77.529	2,420.43	526	5,783
17	6,847.95	31.177	80.057	4,754.76	3,869	6,973
18	2,102.85	30.906	80.905	4,946.82	4,299	6,158
19	1,063.35	30.713	81.114	4,745.24	4,589	5,931
20	2,575.66	30.469	80.669	4,840.04	4,299	6,107
21	2,628.90	30.924	81.538	5,116.58	4,589	6,685
22	1,901.42	30.72	81.928	5,164.32	4,593	6,048
23	1,751.12	30.562	81.681	5,051.48	4,593	6,857

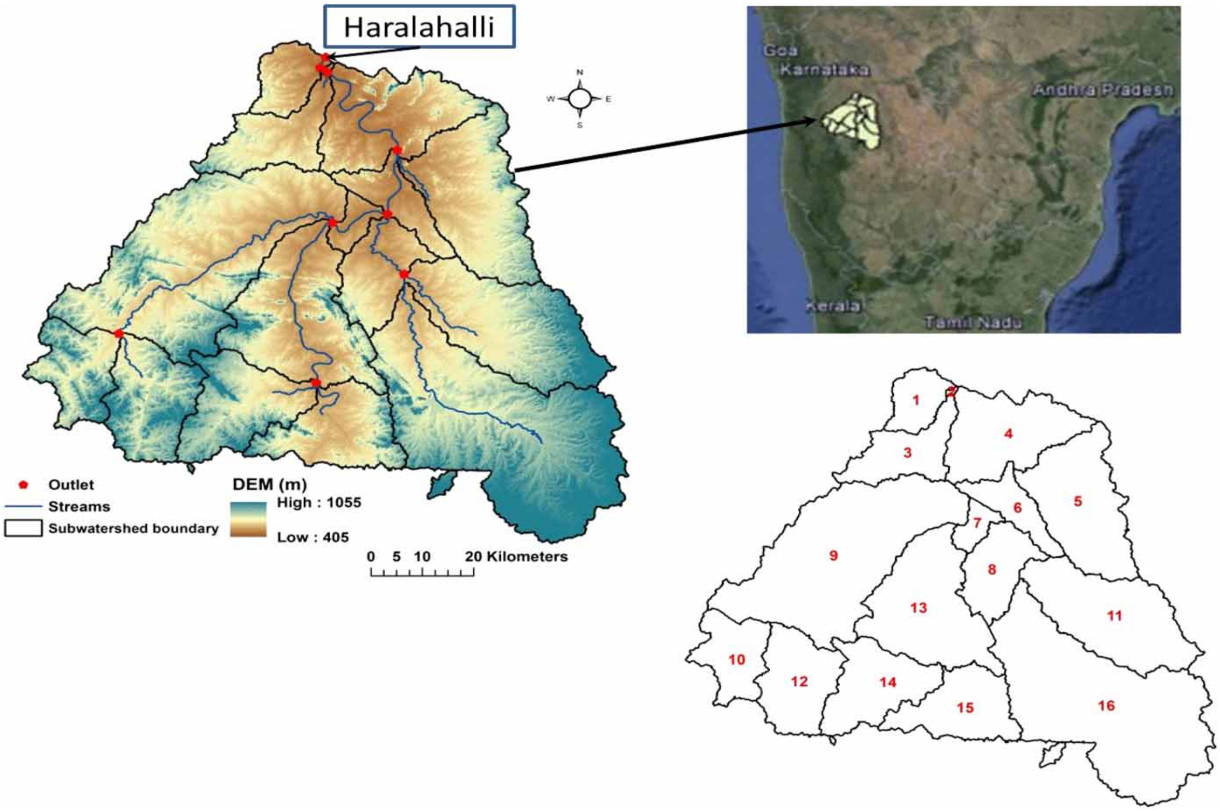

Figure 2 | Study area of Tungabhadra Basin (up to Haralahalli gauge station).

Table 2 | Details of study area of Tungabhadra River Basin (up to Haralahalli gauge station)

Sub-basin	Area (km^2)	Latitude	Longitude	Elevation (m)	Minimum elevation (m)	Maximum elevation (m)
1	165.3	14.783	75.613	481.70	431	615
2	3.5	14.802	75.678	440.68	435	464
3	283.68	14.651	75.565	507.46	435	695
4	511.67	14.699	75.823	477.23	435	786
5	611.61	14.556	75.946	513.05	436	722
6	181.99	14.574	75.805	472.46	436	675
7	77.63	14.501	75.742	460.5	441	500
8	278.26	14.397	75.797	488.94	441	691
9	1,233.57	14.223	75.461	524.97	443	868
10	276.42	14.167	75.235	569.91	497	756
11	663.32	14.283	76.027	551.24	463	917
12	381.89	14.004	75.391	577.63	497	897
13	690.89	14.326	75.647	509.72	443	807
14	397.7	14.118	75.554	564.2	459	938
15	373.65	14.081	75.698	522.73	459	773
16	1,435.56	14.055	76.012	584.79	463	1,055

the period mid-June to mid-October. The mean maximum monthly temperature varies from ~26.3 °C to ~35.5 °C and the mean minimum monthly temperature varies from ~13.8 °C to ~22.3 °C for the time period of 1986–2005.

Data

The precipitation and temperature data are taken from the Indian Meteorological Department (IMD). Annual precipitation and annual ET_0 raster are generated using inverse-distance weighting method for each basin for each corresponding time period. Spatial variation of precipitation and ET_0 are shown in Figures 3 and 4, respectively, for both study sub-areas. Plant available water content (PAWC) has been calculated for the two regions using soil-plant-air-water (SPAW) software (Bernardo *et al.* 1988) depending upon the soil properties. A detailed description of different LULC classes is provided in Table 3.

METHODOLOGY

InVEST model

The InVEST model (Tallis *et al.* 2014) is designed to provide information about how changes in ecosystems are likely to change the flows of benefits to people. This model runs on a gridded format where input parameters are given in raster format which, in turn, help us to understand heterogeneity of key driving factors in water yield, such as soil type, precipitation, vegetation type, etc. In this study we have used the water yield model.

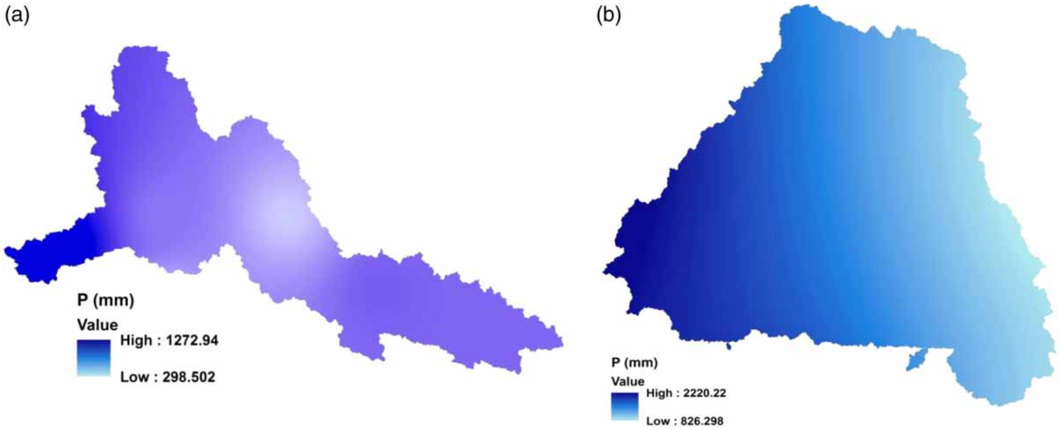

Figure 3 | Spatial variation of average annual precipitation of (a) Sutlej River Basin (up to Kasol gauge station) (1989–2005) and (b) Tungabhadra River Catchment (up to Haralahalli gauge station) (1986–2005).

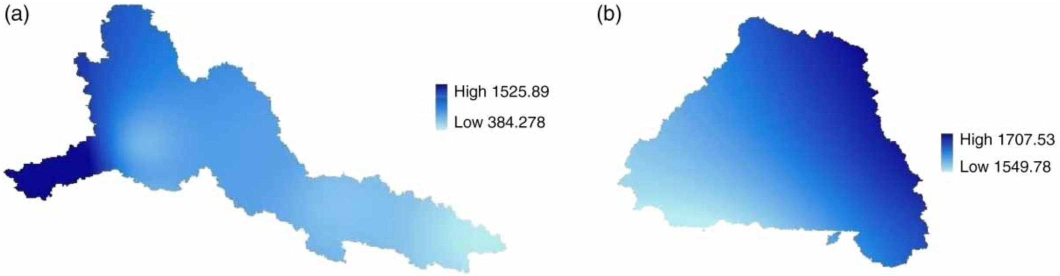

Figure 4 | Spatial variation of average annual ET_0 of (a) Sutlej River Basin (up to Kasol gauge station) (1989–2005) and (b) Tungabhadra River Basin (up to Haralahalli gauge station) (1986–2005).

Table 3 | Different study areas with their corresponding LULC classes with % area, root depth, and K_C value (LULC <2% is not shown)

Study area	LULC class	% area	K_C	Root depth
Sutlej River Basin (up to Kasol gauge station)	Barren	38.84	0.2	N.A.
	Shrubs	26.1	0.6	1,500
	Snow and glacier	24.18	2	N.A.
	Water	3.63	1	N.A.
	Urban	3.55	0.4	N.A.
	Forest	2.09	1	2,500
Tungabhadra River Basin (up to Haralahalli gauge station)	Crop land	62.55	0.75	1,500
	Forest	15.76	1	5,000
	Fallow	8.4	0.2	500
	Scrub	7.16	0.6	2,000
	Urban	2.84	0.5	N.A.
	Water bodies	2.27	1	N.A.

N.A., not applicable.

Background theory

The water yield model is based on an empirical function which is known as the Budyko curve (Budyko 1974). The model runs on a gridded map. In this model, water yield Y(x) is determined for each pixel (x) on the landscape as follows:

$$Y(x) = \left(1 - \frac{AET(x)}{P(x)}\right) \times P(x) \tag{1}$$

where $AET(x) =$ actual evapotranspiration on pixel x; $P(x) =$ annual precipitation on pixel x.

The InVEST model uses an expression of the Budyko curve by Fu (1981) and Zhang *et al.* (2004):

$$\frac{AET(x)}{P(x)} = 1 + \frac{PET(x)}{P(x)} - \left[1 + \left(\frac{PET(x)}{P(x)}\right)^{\omega}\right]^{\left(\frac{1}{\omega}\right)} \tag{2}$$

where $PET(x) =$ potential evapotranspiration on each pixel (mm); $\omega(x) =$ a non-physical parameter that characterizes the natural climatic soil properties.

Again, $PET(x)$ is calculated by the following expression:

$$PET(x) = Kc(x) \times ETo(x) \tag{3}$$

where $ET_0(x)$ is the reference evapotranspiration from pixel x calculated based on evapotranspiration of grass of alfalfa grown at that location. $K_C(x)$ is the vegetation evapotranspiration coefficient which varies with changes in characteristics of LULC found on each pixel (Allen *et al.* 1998). The values of ET_0 are adjusted by K_C for each pixel over the LULC map. $\omega(x)$ is an empirical parameter. In the InVEST model, expression given by Donohue *et al.* (2012) has been used to define $\omega(x)$, which is as follows:

$$\omega(x) = z.\frac{AWC(x)}{P(x)} + 1.25 \tag{4}$$

From the above expression, we can see that the minimum value of $\omega(x)$ is 1.25 for bare soil where root depth is zero (Donohue *et al.* 2012). Here, Z is known as seasonality factor whose value varies from 1 to 30. It depicts the nature of local precipitation and other hydrogeological parameters. $AWC(x)$ is the volumetric plant available water content expressed in depth (mm) which can be calculated by the following expression for each pixel x:

$$AWC(x) = Min.\,(\text{Restricting layer depth, root depth}) \times PAWC \tag{5}$$

Root restricting layer depth is generally defined as soil depth up to which soil can allow the penetration of roots and root depth is defined as the depth where 95% of the root biomass occurs. PAWC is generally taken as the difference between field capacity and wilting point.

Determination of *Z* parameter

The 'seasonality factor' Z varies depending upon the local precipitation patterns, such as rainfall intensity and topographical and hydrological characteristics of an area. Three methods have been discussed in the user's guide of InVEST (Tallis *et al.* 2014). The work of Donohue *et al.* (2012) suggested that Z can be linked to the number of rain events per year, N, and can be computed by ($N/5$). The work of Xu *et al.* (2013) gave values of ω globally in their study. So if we know the average values of AWC, P, then we can calculate the value of Z using Equation (4), mentioned above. A third method of determining Z value is by calibrating the model through comparing model outputs with the observed values.

Sensitivity of the model to *Z* and K_C

In our study, we have analyzed the sensitivity of Z and K_C parameter for the two regions. The work of Tallis *et al.* (2014) has shown the uncertainties in choosing Z parameter. As Z is also dependent on AWC, so it also depicts the sensitivity of AWC as well. In this study, the baseline value of Z has been calculated by means of Equation (4). The mean value of ω ($\omega = 2.06$ for Sutlej River Basin and $\omega = 2.02$ for Tungabhadra River Basin) has been estimated as suggested by Xu *et al.* (2013). The mean values of available water content (AWC), calculated by means of Equation (5) and precipitation (P) for the whole basin, have been used in Equation (4) to find out the baseline value for each study area. A baseline value of 13 has been used for Sutlej River Basin (up to Kasol gauge station) and a value of 10 has been used for the Tungabhadra River Basin (up to Haralahalli gauge station). All the Z values are taken at whole watershed level. We have varied the values of Z in between 1 and 30 and observed changes in water yield at watershed level. We have also calculated the value of Z via calibration. Due to lack of exact rain events data we could not use the method specified by Donohue *et al.* (2012).

From the work of McMahon *et al.* (2013), it has been observed that it is quite difficult to estimate the values of K_C for forest exactly, due to variation of K_C depending upon different characteristics of trees in a forest. We have chosen the baseline value of K_C of forest as 1 from the FAO 56 guidelines (Allen *et al.* 1998) and varied the value between 0.7 and 1.1 as it is expected to remain to be so for both the catchments. But the Tungabhadra River Basin (up to Haralahalli gauge station) is mainly crop dominated. Thus we have taken the baseline value of K_C as 0.75 for crop and then varied the value between 0.7 and 0.9 as it is expected to be so in that watershed and determined the changes in water yield with respect to baseline run, which is shown in Table 4. We have also varied the values of precipitation and ET_0 and compared the results with the baseline run for each of the basins. The ranges of sensitivity analysis of different parameters are given in Table 5.

Comparison of lumped Zhang model and distributed InVEST model

In the InVEST model, an expression of the Budyko curve by Fu (1981) and Zhang *et al.* (2004) has been used. Basically the Zhang model is a lumped model and in the InVEST model, this theory has been used at pixel to pixel level. The equation of the lumped Zhang model is as follows:

$$\frac{AET}{P} = 1 + \frac{PET}{P} - \left[1 + \left(\frac{PET}{P}\right)^{\omega}\right]^{\left(\frac{1}{\omega}\right)} \qquad (6)$$

where $AET =$ actual evapotranspiration; $PET =$ potential evapotranspiration; $\omega =$ a non-physical parameter that characterizes the natural climatic soil properties and where mean values of PET, P, ω, averaged at watershed level, are used (Zhang *et al.* 2004). Thus we have tried to find out results of this application by calculating the water yield from the whole watershed by Equations (1) and (2). For calculating the value of ω, we calculated the average values of P, PET, AWC, and baseline value of Z for each study area. AET for vegetated areas have been calculated using Equation (2) and for non-vegetated areas AET has been calculated as $\text{Min}\,(Kc \times ETo,\ P)$. Last, the water yield from both vegetated and non-vegetated areas are area-weighted averaged to get the final water yield output.

Performance of the model

Performance of the model has been assessed by comparing the model outputs with the observed data for both the catchments. We have run the model with the baseline values of Z

Table 4 | Variation of water yield at baseline ($K_{C\ Forest} = 1$ and $K_{C\ Crop} = 0.75$) with changes in K_C values of both forest and crop in Tungabhadra River Basin (up to Haralahalli gauge station)

Study area	Forest K_C	Crop K_C	% Change in crop K_C	% Change of water yield w.r.t baseline
Tungabhadra River Basin (up to Haralahalli gauge station)	1	0.7	−10	2.71
		0.75	0	0
		0.825	10	−3.69
		0.9	20	−6.98
	1.1	0.7	−10	1.53
		0.75	0	−1.18
		0.825	10	−4.87
		0.9	20	−8.15
	0.9	0.7	−10	3.57
		0.75	0	1.33
		0.825	10	−2.83
		0.9	20	−6.12
	0.8	0.7	−10	4.79
		0.75	0	2.77
		0.825	10	−1.6
		0.9	20	−4.89
	0.7	0.7	−10	6.2
		0.75	0	4.17
		0.825	10	−0.2
		0.9	20	−3.49

Table 5 | Range of sensitivity of parameters

Study area	Data	Type	Value (range and mean)	Source	Range of sensitivity analysis
Sutlej River Basin	Precipitation	Raster	(298.5–272.94 mm); 548.4 mm	IMD	±20%
	ET_0	Raster	(384–1,526 mm); 628 mm	IMD	±10%
	DEM	Raster	30 m (526–7,429 m; 4,653.2 m)	ASTER DEM	N.A.
	LULC	Raster	See Table 3	Landsat imagery	N.A.
	Root restricting layer depth	Raster	(0–1,524 mm); 1,040 mm	FAO soil maps	N.A.
	PAWC	Raster	(001–0.272); 0.12144	SPAW	N.A.
	K_C	Per LULC class	See Table 3	Allen *et al.* (1998)	(−30%; +10%)
	Z	Constant	13	Xu *et al.* (2013)	(1–30)
Tungabhadra River Basin	Precipitation	Raster	(826.298–2,220.22 mm); 1,424.57 mm	IMD	±20%
	ET_0	Raster	(1,549.78–1,707.53 mm); 1,635.84 mm	IMD	±10%
	DEM	Raster	30 m	Cartosat-1, Bhuvan, ISRO	N.A.
	LULC	Raster	See Table 3	LISS-III Imagery	N.A.
	Root restricting layer depth	Raster	(0–1,000 mm); 1,000 mm	FAO soil maps	N.A.
	PAWC	Raster	(0.1107–0.1285); 119	Using SPAW	N.A.
	K_C	Per LULC Class	See Table 3	Allen *et al.* (1998)	(−30%; +10%)
	Z	Constant	10	Xu *et al.* (2013)	(1–30)

and also tried to calibrate the model by varying the Z parameter. Uncalibrated model run is necessary to find out the sensitivity of different parameters of the model.

Uncalibrated model run

We tried to find out the appropriateness of the method of determining Z using the value of ω given by Xu *et al.* (2013). We have taken Z value as 13 for the Sutlej River Basin (up to Kasol gauge station) and 10 for the Tungabhadra River Basin (up to Haralahalli gauge station) for the baseline run. The changes in water yield with the changes of K_C, P, ET_0 in both of the catchments and the dependency of the model on these parameters are found from these analyses.

Calibrated model run

The model has been calibrated by eliminating the error that is the difference between observed and calculated water yield by varying the value of Z between 1 and 30 for the catchments. We have observed that the sensitivity of Z parameter to the model is much smaller in the hilly catchment and we could not calibrate the model varying Z values in the case of the Sutlej River Basin (up to Kasol gauge station). In the case of the Tungabhadra River Basin (up to Haralahalli gauge station), we calibrated the model with a Z value of 4.

RESULTS

Sensitivity of the model to climate, Z and K_C

In the case of the Sutlej River Basin (up to Kasol gauge station), precipitation is the most sensitive parameter, 10% increment of which results in 16.52% increase in water yield with respect to baseline run. A 10% increment in ET_0 decreases the baseline water yield by 5.51%. The baseline value of Z is taken as 13 and a change of Z value from 13 to 1 results in 22.8% increase in water yield, and a change of Z value from 13 to 30 results in a 2.4% decrease in water yield. A 30% change in K_C results in 1.28% change in water yield within the specified range of K_C values (0.7 to 1.1 for forest), which shows that Z parameter has more effect on the water yield within its range (1–30) than K_C if we restrict the value of K_C within its probable specified range. Otherwise, K_C is more sensitive than Z parameter if no specified range is given.

In the case of Tungabhadra River Basin (up to Haralahalli gauge station), a 10% increase in precipitation results in 19.6% increase in water yield with respect to the baseline. Whereas a 10% increase in ET_0 results in 5.8% decrease in water yield. Thus precipitation and ET_0 are more sensitive in Tungabhadra River Basin than Sutlej River Basin. A change of Z value from baseline value of 10 to 1 results in 50% increase in water yield. We have run the model for different combinations of K_C for both crop and forest and have observed the variation in water yield to remain within 1–8% within the specified range of K_C. Hence Z parameter is comparatively a more sensitive parameter than K_C within the specified range of Kc.

Z parameter has greater sensitivity towards the water yield in the Tungabhadra River Basin (up to Haralahalli gauge station) as compared to Sutlej River Basin (up to Kasol gauge station). It is also clear from Figure 5 that the sensitivity of K_C towards the water yield is more significant in the case of Tungabhadra River Basin (up to Haralahalli gauge station) as compared to the Sutlej River Basin (up to Kasol gauge station).

Comparison of lumped Zhang model and distributed InVEST model

In the case of Sutlej River Basin (up to Kasol gauge station), the value of water yield from the lumped Zhang model underpredicts by 29.066% with respect to the result from the distributed InVEST model. In the case of Tungabhadra River Basin (up to Haralahalli gauge station), the lumped Zhang model underpredicts by 15.4% as compared to the distributed InVEST model.

Performance of the model

Uncalibrated model run

Here the baseline values of Z parameter are determined by Equation (4) using values of ω obtained from the study of Xu *et al.* (2013). In the case of Sutlej River Basin (up to

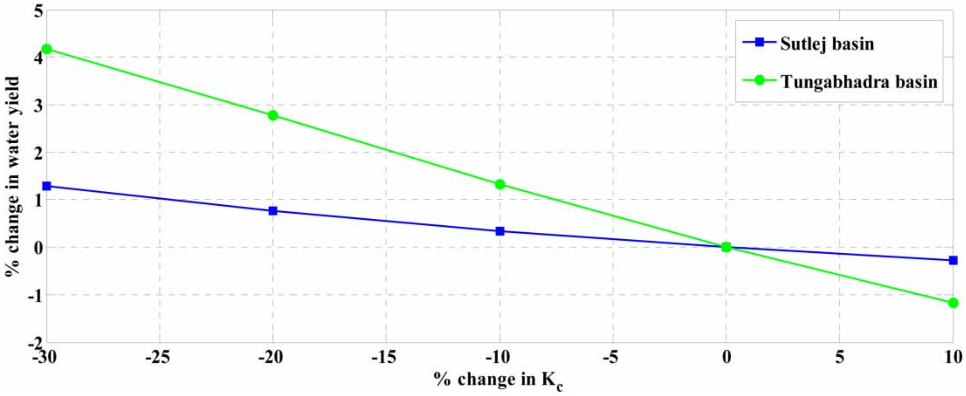

Figure 5 | Variation of % change in water yield with respect to baseline water yield (when $K_C = 1$ for forest and $K_C = 0.75$ for crop (Tungabhadra River Basin)) with changes in K_C value for the two basins. Here % change in K_C value is plotted by the x axis and % change in water yield is plotted by the y axis.

Kasol gauge station), the model overpredicts by 6.7% as compared to observed water yield when the model is run for $Z = 13$ as baseline value.

In the case of Tungabhadra River Basin (up to Haralahalli gauge station), the model underestimates by 28.14% as compared to the observed water yield at Haralahalli gauge station (observed gauge discharge values have been taken from India-WRIS (Water Resources Information System of India)) when the model is run for $Z = 10$ as baseline value.

Calibrated model run

The model is calibrated by varying the Z parameter for each of the two catchments. We observed that for the Sutlej River Basin (up to Kasol gauge station) we could not calibrate the model, i.e., the simulated model output value could not be matched with the observed water yield value by varying the value of Z parameter within its range of 1–30, due to low sensitivity of Z parameter. The baseline and calibrated values of Z of each catchment are given in Table 6.

Limitations of using modified Hargreaves method

Use of the 'modified Hargreaves' equation (Droogers & Allen 2002) for calculating ET_0 under limited data conditions is a very popular one and derives better result than Penman–Monteith when information is uncertain. In our study, we have calculated ET_0 using the normal Hargreaves (Hargreaves *et al.* 1985; Hargreaves 1994), modified Hargreaves, and Hamon (Hamon 1961) equations and have observed that in certain months the modified Hargreaves equation is not applicable in five gauge stations in Tungabhadra River Basin (up to Haralahalli gauge station) as the term ($TD - 0.0123{*}P$) (where $TD =$ difference of mean daily maximum and mean daily minimum temperature, $P =$ precipitation) is generating negative value which is not feasible, but the other two methods are applicable for all the months. Whereas in the case of the second study sub-area, the Sutlej River Basin (up to Kasol gauge station), modified Hargreaves and the other two equations run smoothly there. A comparative study among the three methods (Table 7) shows that the use of modified Hargreaves method for

Table 6 | Baseline and calibrated values of Z of each catchment

Study area	Baseline value (Z)	Calibrated value (Z)	Calculated water yield (m^3/sec)	Observed water yield (m^3/sec)	% Error
Sutlej River Basin (up to Kasol gauge station)	13	Failed to calibrate	378.95	355.14	6.7
Tungabhadra River Basin (up to Haralahalli gauge station)	10	4	157.49	219.16	−28.14

Table 7 | Comparative study among three ET_0 calculation methods for both catchments

		Water yield (m^3/sec)		
		Model output	Observed value	% Error
Sutlej River Basin	Modified Hargreaves method	378.95	355.14	6.7
	Normal Hargreaves method	381.58	355.14	7.44
	Hamon's method	506.65	355.14	42.66
Tungabhadra River Basin	Modified Hargreaves method along with normal Hargreaves method (only where modified Hargreaves is not applicable)	157.49	219.16	−28.14
	Normal Hargreaves method	153.69	219.16	−29.87
	Hamon's method	295.66	219.16	34.91

calculating ET_0 in the Sutlej River Basin, generates the best result as compared to the other two methods. In the case of the Tungabhadra River Basin, use of modified Hargreaves method along with normal Hargreaves method (only where the modified Hargreaves method is not applicable) generates the best result. Therefore, the values of ET_0 calculated using modified Hargreaves method along with normal Hargreaves method (only where the modified Hargreaves method is not applicable) in the case of Tungabhadra River Basin and using modified Hargreaves equation in the case of Sutlej River Basin have been used. In Figure 6, the months along with their corresponding monthly precipitation (P) and TD (difference between mean daily maximum and mean daily minimum temperatures) are highlighted when the modified Hargreaves method is not applicable in the corresponding gauge stations. In Figure 6, it is shown that in the case of Tungabhadra River Basin (up to Haralahalli gauge station), modified Hargreaves is not applicable mainly in the months of June, July, and August. The months and their corresponding values of mean annual precipitation (P), mean monthly maximum (T_{max}) and minimum temperature (T_{min}), and difference between T_{max} and T_{min}, i.e., TD when the modified Hargreaves method is not applicable, are shown in Table 8.

The values of average mean monthly temperature remain well under zero degrees in certain months of the year in the Sutlej River Basin (up to Kasol gauge station). We have observed that both modified and normal Hargreaves equations generate significant values of ET_0 in some months whereas the method of calculating PET given by Thornthwaite & Mather (1955) is not applicable for those months. Previous studies also show that this method cannot be applied consistently in monsoon climates or in areas with a strong seasonal change in humidity or wind (Mather 1974). But this situation does not appear in the case of Tungabhadra River Basin. In Figure 7, it is shown that the values of ET_0 are significant although mean monthly temperature remains under °C in Sutlej River Basin (up to Kasol gauge station).

DISCUSSION

Sensitivity of the model to climate inputs, Z and K_C

From our study, it has been observed that the climate parameters precipitation and ET_0 are the most influential parameters as compared to Z and K_C, in both of the basins. The sensitivity of both P and ET_0 are comparatively higher in the case of Tungabhadra River Basin (up to Haralhalli gauge station). Moreover, our watersheds are gauged catchments and so any error in precipitation or ET_0 input will impart significant error in the water yield output. Thus we have to process and prepare the climatic inputs cautiously (i.e., choosing the proper method of calculation of ET_0, and proper method of interpolation of point data).

From Equation (4), it is seen that Z has a linear relationship with ω. From the work of Zhang *et al.* (2004), it has also been seen that with increasing value of ω the sensitivity of ω decreases which, in turn, proves that as the value of Z increases the sensitivity of this parameter towards the model decreases. A change in the value of ω shifts the Zhang curve upwards or downwards, as shown in Figure 8. In the case of Sutlej River Basin (up to Kasol gauge station)

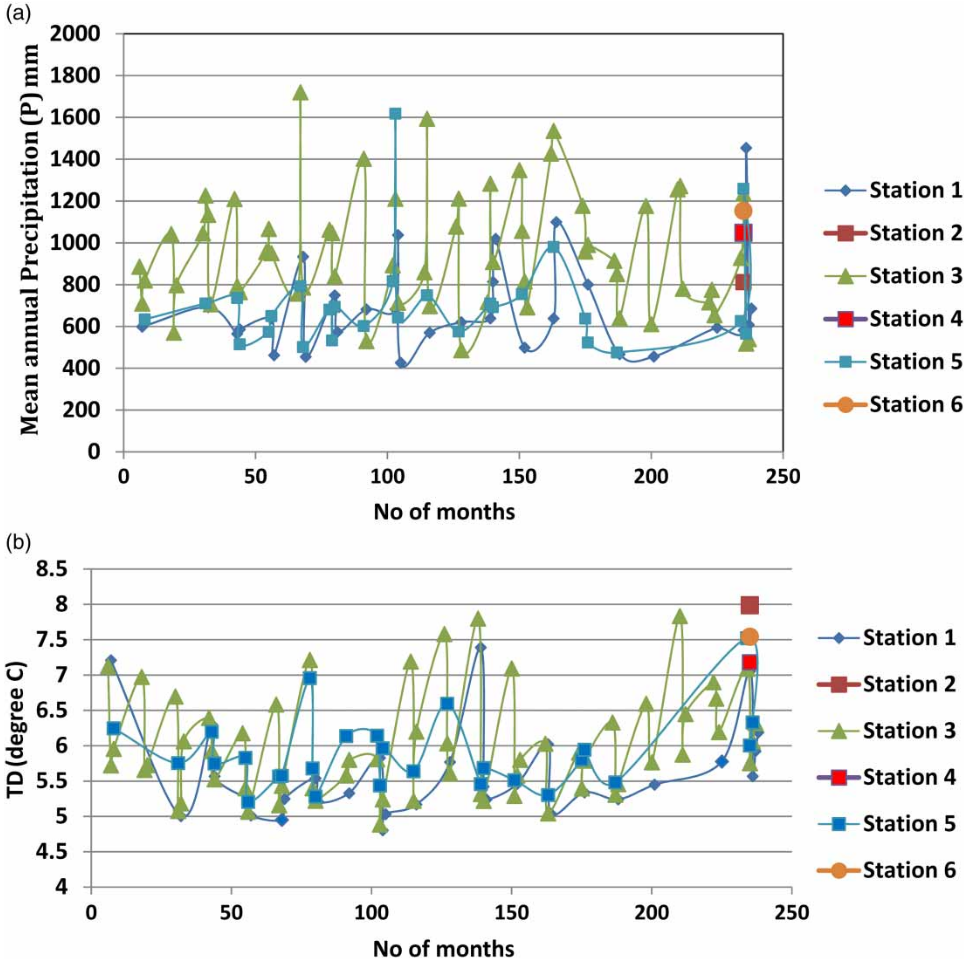

Figure 6 | (a) Variation of mean monthly precipitation (P) with the corresponding months when modified Hargreaves is not applicable. (b) Variation of TD with the corresponding months when modified Hargreaves is not applicable in Tungabhadra River Basin (up to Haralahalli gauge station) for 1986–2005.

and for Tungabhadra River Basin (up to Haralahalli gauge station) the values of Z are 13 and 10, respectively. As a result, the Z parameter is more sensitive in the Tungabhadra River Basin. As Z is also correlated to AWC, root depth and topographical and hydrological properties, so error in these values may also impart some error to the model. In a previous study, Hamel & Guswa (2014) found Z parameter to be less sensitive when it remains within the moderate range of 14–22 for Cape Fear Catchment, North Carolina. We have also found the same, i.e., less sensitivity of Z parameter to the model output in both the regions where $Z =$ 13 (up to Kasol gauge station of the Sutlej River Basin) and $Z = 10$ (Tungabhadra River Basin (up to Haralahalli gauge station)) which is beyond the range of 14–22. This result also supports the conclusion, drawn by Sánchez-Canales *et al.* (2012), where Z parameter, being within the range of 7 to 9, shows low sensitivity to the model. In our study, we have varied the value of K_C for forest (for both the catchments) and K_C of crop land (for Tungabhadra River Basin). In the Tungabhadra River Basin, almost 17% area is forest and in the case of up to Kasol gauge station of Sutlej River Basin, about 2.5% is forest area. Thus change in K_C of forest, has comparatively greater impact in Tungabhadra River Basin (up to Haralahalli gauge station). Tungabhadra River Basin has about 62.5% of crop land which indicates that change of K_C of crop has greater impact than change in K_C of forest in that watershed and a combined change of K_C of both crop and forest results

Table 8 | Statistics of climatic parameters of the months when modified Hargreaves method is not applicable in Tungabhadra River Basin (up to Haralahalli gauge station)

Station No.	Month No.	P (mm)	T_{max} (°)	T_{min} (°C)	TD (°C)	Station No.	Month No.	P (mm)	T_{max} (°C)	T_{min} (°C)	TD (°C)
1	7	598.5	30.5	23.3	7.2	3	116	696.4	28.6	22.4	6.2
	32	692.3	28.1	23.1	5		126	1,077.8	30.5	22.9	7.6
	43	564.4	29.4	23.1	6.3		127	1,211.4	28.2	22.1	6
	44	586	28.3	22.8	5.6		128	486.2	27.6	22	5.6
	56	637.9	28	22.8	5.2		138	716.9	30.8	23	7.8
	57	461.8	27.3	22.3	5		139	1,283.1	28.1	22.8	5.3
	68	933.8	27.6	22.6	5		140	908	27.7	22.5	5.2
	69	454.8	27.7	22.4	5.2		150	1,347.4	30.8	23.8	7.1
	80	748.4	28.6	23	5.5		151	1,057.3	28.4	23.1	5.3
	81	573.5	27.9	22.7	5.2		152	815.8	28.7	23.1	5.6
	92	681.7	28.1	22.8	5.3		153	691.1	28.4	22.6	5.8
	103	682	29.2	23.3	5.8		162	1,427.1	28.6	22.6	6
	104	1,037.6	27.6	22.8	4.8		163	1,535.5	27.4	22.4	5
	105	426.3	27.8	22.8	5		174	1,176.8	28.8	22.9	5.9
	116	569.9	28	22.9	5.2		175	958.4	27.4	22	5.4
	128	620.2	28.6	22.8	5.8		176	989.9	27.8	22	5.8
	139	638	30.8	23.4	7.4		186	913.9	29.4	23.1	6.3
	140	813.5	28.7	23.3	5.4		187	850.3	27.7	22.4	5.3
	141	1,018.7	28.1	22.8	5.2		188	639.4	27.7	22.2	5.5
	152	498.6	28.9	23.5	5.5		198	1,175.9	29.6	23	6.6
	163	637.8	29	22.9	6		200	610.3	27.6	21.8	5.8
	164	1,099.4	27.8	22.8	5		210	1,255.9	30.9	23.1	7.8
	176	800	27.7	22.4	5.3		211	1,271.7	28.2	22.3	5.9
	188	466.9	28.1	22.8	5.2		212	779.7	28.7	22.2	6.4
	201	455.6	28	22.6	5.4		222	714.9	29.3	22.4	6.9
	225	593.9	28.1	22.3	5.8		223	775.3	28.5	21.8	6.7
	235	581.7	30.8	23.7	7.1		224	653.1	27.6	21.5	6.2
	236	1,453.9	28.4	22.8	5.6		234	928	30.2	23.1	7.1
	237	607.4	28.4	22.5	5.9		235	1,236.2	27.9	22.2	5.8
	238	685.6	28.5	22.3	6.2		236	517.8	28.2	22.1	6.1
2	235	812.5	30.2	22.3	8		237	539.2	28.3	21.9	6.3
3	6	885.4	30	22.9	7.1	4	235	1,047.8	27.7	20.6	7.2
	7	709.6	28	22.3	5.7	5	8	633.5	26	19.8	6.2
	8	820.1	27.4	21.4	6		31	709.5	26.3	20.6	5.8
	18	1,041.5	29.9	22.9	7		43	736.3	26.4	20.2	6.2
	19	569.7	28.8	23.1	5.7		44	514.1	25.6	19.9	5.7
	20	797	28.4	22.6	5.7		55	573.3	25.6	19.8	5.8
	30	1,045.3	29.8	23.1	6.7		56	649.4	25	19.8	5.2
	31	1,225.7	27.7	22.7	5.1		67	792.3	25.4	19.9	5.6
	32	1,133.2	27.7	22.5	5.2		68	500.9	25.3	19.7	5.6
	33	706.2	28.5	22.5	6.1		78	680.2	28.1	21.1	7
	42	1,209.9	29	22.6	6.4		79	532.7	26.2	20.6	5.7
	43	793.3	28.1	22.2	5.9		80	693.7	25.8	20.5	5.3
	44	763.9	27.3	21.8	5.5		91	601.7	26.1	19.9	6.1
	54	956.5	28.8	22.6	6.2		102	816.1	26.7	20.6	6.1
	55	1,066.3	27.4	22	5.4		103	1,617.6	25.5	20.1	5.4
	56	950.3	26.8	21.7	5.1		104	641.9	26	20.1	6

(*continued*)

Table 8 | continued

Station No.	Month No.	*P* (mm)	T_{max} (°)	T_{min} (°C)	*TD* (°C)	Station No.	Month No.	*P* (mm)	T_{max} (°C)	T_{min} (°C)	*TD* (°C)
	66	757.3	29.9	23.4	6.6		115	748.6	25.8	20.2	5.6
	67	1,719.6	27.3	22.1	5.2		127	575	26.6	20	6.6
	68	785.9	27.2	21.8	5.4		139	708.8	26.1	20.6	5.5
	78	1,062.7	30.2	23	7.2		140	692.2	26.1	20.4	5.7
	79	1,046.4	28	22.6	5.4		151	754.1	26.5	21	5.5
	80	839.6	27.4	22.2	5.2		163	979.7	25.8	20.5	5.3
	91	1,402.4	27.6	22	5.6		175	637.6	26	20.2	5.8
	92	529.6	27.7	21.9	5.8		176	522.4	26.3	20.3	5.9
	102	892.2	28.6	22.8	5.8		187	474.9	25.9	20.4	5.5
	103	1,211.1	27.1	22.2	4.9		234	625.3	28.6	21.1	7.5
	104	713.2	27.4	22.2	5.2		235	1,258.3	26.4	20.4	6
	114	858.8	30.8	23.6	7.2		236	564.9	26.5	20.2	6.3
	115	1,593.1	27.5	22.3	5.2	6	235	1,152.8	27.4	19.8	7.5

P = precipitation, T_{max} = mean monthly maximum, T_{min} = mean monthly minimum temperature, *TD* = difference of T_{max} and T_{min}.

in change from baseline water yield by 1–8%. Thus when the combined effect of K_C for both forest and crop is considered, then K_C has greater influence in Tungabhadra River Basin than Sutlej River Basin (up to Kasol gauge station). As *PET* is the product of K_C and ET_0, so a change in K_C results in variation along the Zhang curve for a given value of ω.

Comparison of lumped Zhang model and distributed InVEST model

First, this gives an insight into the difference using the InVEST model which runs the Budyko theory at pixel to pixel level using Equation (2) in a spatially explicit manner and the Zhang lumped model which calculates the water yield at watershed level using the average values of *P*, *PET*, *AWC*, and *Z*. Our first study sub-area, Sutlej River Basin (up to Kasol gauge station), is a hilly catchment with almost 24% snow and glacier. The lumped Zhang model is underpredicting compared to the InVEST model with underprediction of 29.1% for Sutlej River Basin (up to Kasol gauge station) and 15.4% for Tungabhadra River Basin. The difference between the results of the spatially explicit InVEST model output and manually calculated lumped Zhang model output on which the InVEST model is based, suggests that the InVEST model could not fully capture the lumped Zhang model characteristics applied at watershed level with mean values of parameters, averaged over the whole watershed, otherwise the two model outputs would have produced the same output results. The reason behind the significant underestimation by the Zhang model may be due to overestimation from the non-vegetated LULC, which is consistent with the findings of Hamel & Guswa (2014) in the Cape Fear catchment, North Carolina. This is also due to non-linearity of Equation (2) and differences between values of ω used in the lumped model and explicit model, as mean value of ω has been considered for the lumped model whereas the value of ω varies from pixel to pixel in the InVEST model according to Equation (4).

The model does not consider the contribution of snowmelt separately but we have tried to capture the contribution of the snow and glacial portion by using a high value of K_C (= 2) for the snow and glacial part of the watershed. The global PET data have been downloaded from the website of CGIAR CSI (Consultative Group on International Agricultural Research Consortium on Spatial Information) (Trabucco & Zomer 2009) and the *PET* data for the snow and glacial portion of Sutlej River Basin has been extracted. The ET_0 has been calculated using the modified Hargreaves method for the basin and the ET_0 data for the snow and glacier portion of the basin has been extracted from these calculated data. The value of K_C has been found

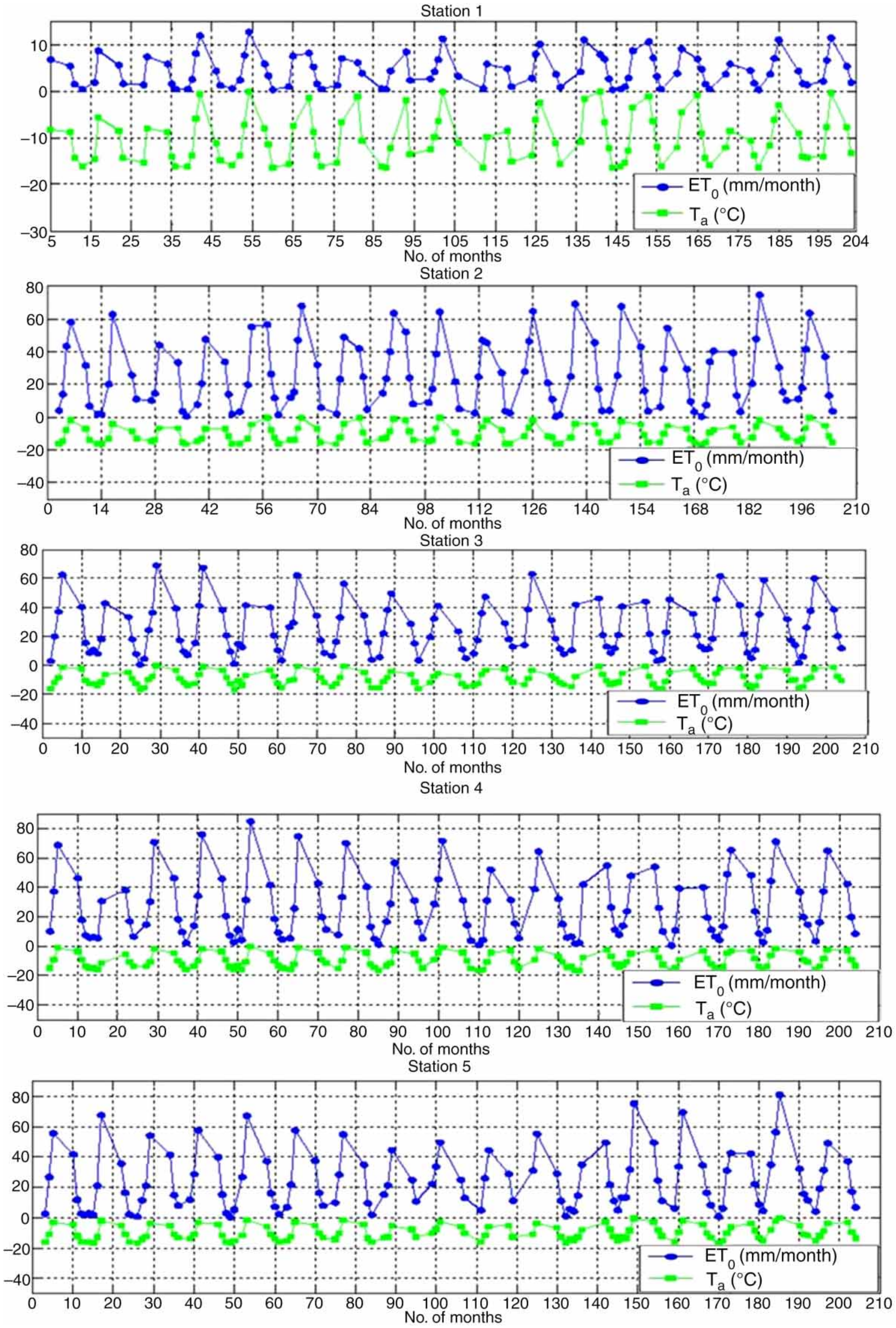

Figure 7 | Variation of ET_0 (mm/month) for the months when mean monthly temperature (T_{avg}) remains under zero for 1989–2005 in Sutlej River Basin (up to Kasol gauge station).

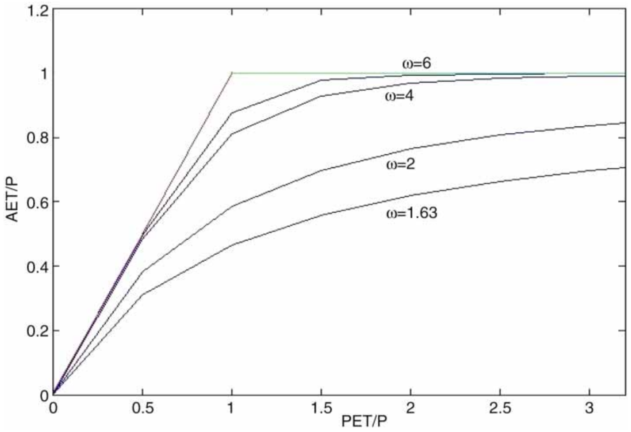

Figure 8 | Zhang model showing variation of PET/P with AET/P with the variation of ω.

by taking the mean value of the raster obtained by dividing the *PET* raster by ET_0 raster $[PET(x) = K_C(x) \times ETo(x)]$ in ArcGIS which gave us a value of K_C around 2 for the snow and glacier portion. The error due to ground water withdrawals is also not considered due to lack of reliable data. However, the results obtained from our analysis are satisfactory as far as the simplicity of the InVEST model is concerned.

CONCLUSION

In this study, an attempt has been made to determine the compatibility of the model and sensitivity of the parameters involved in it for hilly terrain as well as a peninsular region. From this study, the following may be inferred:

1. Precipitation is the most sensitive climatic input parameter in this model and has comparatively greater impact in the Tungabhadra River Basin. As a result, errors in precipitation inputs may impart major discrepancy in water yield in regions with high rainfall.
2. Modified Hargreaves method has been proved to be the most reliable method in calculating ET_0 under limited data conditions especially in the hilly catchment although it has been observed that in certain months this method is not applicable in Tungabhadra River Basin where the modified Hargreaves method along with normal Hargreaves method can be used as replacement for those months. We can also conclude that the method given by Thornthwaite & Mather (1955) is also not applicable in this hilly catchment where temperature in certain months remains well under 0 °C.
3. The sensitivity of Z parameter is much smaller in all the regions, especially in the hilly catchment and it is quite difficult to calibrate the model when sensitivity of Z parameter is less, as happened in the case of Sutlej River Basin (up to Kasol gauge station). It suggests that application of this model depends upon the sensitivity of Z parameter especially in hilly catchments.
4. From the results, we may conclude that the model is generating satisfactory results at watershed level which is a good aspect for any model.
5. Lumped Zhang model could not consistently match the distributed model especially in the hilly catchment.

Although this study is catchment specific, we believe that these results may be utilized in the study of water-balance equations in hilly catchments as well as in peninsular catchments using InVEST.

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