Spatio-temporal assessment of annual water-balance model for Upper Ganga Basin

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Abstract

The Upper Ganga Basin, Uttarakhand, India has high hydropower potential and plays an important role in development of state economy. Thus, knowledge about water yield is of paramount importance to this region. The paper deals with use of contemporary water yield estimation models, such as the distributed model (InVEST), Lumped Zhang model and their validation to identify the most suited one for water yield estimation in this region. Earlier, while utilizing these models, water yield was estimated by considering a single value of some important model parameters which in fact show distributed variation at finer (pixel) scale. Therefore, in this study, pixel level computations are performed to assess and ascertain the need for incorporating spatial variation of such parameters in model applications. To validate the findings, the observed sub-basin discharge data is analyzed with the computed water yield for four decades, i.e. 1980, 1990, 2001 and 2015. The results obtained are in good agreement with the water yield obtained at pixel scale.

Keywords: Ecosystem, Evapotranspiration, Water Yield, Lumped Zhang model, InVEST model

1. Introduction

Accurate assessment of key ecosystem services (ES) such as water yield have gained focus in recent years in ES modelling as fresh water availability in a region are essential for agriculture, industry, human consumption, hydropower, etc., (Readhead et al., 2016). Hydrological ecosystem services generally include drinking water supply, power production, industrial use, irrigation, and many more. Accurate estimation of water yield further facilitates in identification of hotspots for stormwater harvesting in order to fulfill fresh water demand in the region (Pathak et al., 2017). These hydrological ES are dependent on different factors such as watershed characteristics (e.g. topography, land use land cover (LULC), soil type) and climatic condition. To incorporate these concepts into assessment and decision making, there has been a proliferation of ecosystem modelling tools and methods. Models for ES valuation often focus on using globally available data, accepting large number of spatially explicit inputs and producing spatially explicit output, and limiting the model structure to key biophysical processes involved in land-use change (Guswa et al. 2014). Precise estimation of ES using these models is a complicated task owing to spatial variability and dependence of ES on various topographical and climatic factors. Further, validation and uncertainty assessment in model output have proven to be a key obstacle to the application of ES models. In the literature, studies focusing on comparison of different ES models have projected some light over the model output validation issues, however, there still exist lack of studies highlighting validation of these models for Indian river basins. The benefits that can be derived from ES should be analyzed and quantified in a spatially explicit manner (Sanchez et al. 2012). The uncertainties in the determination of spatial and temporal distribution of the climatic variables, especially precipitation, constitute a major obstacle to the understanding of hydrological behaviour at the catchment scales (Milly et al. 2002).

The Integrated Valuation of ES and Tradeoffs (InVEST) model, developed by Natural Capital Project (Tallis et al. 2010) is a tool which provides a framework to planners and decision makers to assess trade-offs among ES and enables their comparison in various climate and land use change scenarios. It includes a biophysical component which facilitates the provision of freshwater or water yield by different parts of the landscape and a valuation component, representing the benefits of water provisioning to people. The model works on simplified Budyko theory, which has a long history and still continues to receive interest in the hydrological literature (Budyko 1979; Zhang et al. 2001; Zhang et al. 2004; Ojha et al. 2008; Zhou et al. 2012; Donohue et al. 2012; Xu et al. 2013; Wang et al. 2014). The InVEST model applies a one-parameter formulation of the Budyko theory in a semi-distributed manner (Zhang et al. 2004). The model is capable of quantifying the water yield of a catchment under the influence of change in different drivers viz. climate variables and catchment characteristics (e.g. land use change). Various studies have been carried out in the past demonstrating the application of InVEST model to different river basins around the world. Sanchez-Canales et al. (2012) carried out sensitivity analysis of three parameters i.e. *z* (seasonal precipitation coefficient), precipitation (annual) and ET_0 (annual reference evapotranspiration) using the InVEST model for a Mediterranean basin and found precipitation to be the most sensitive parameter for the study region. Later, Terrado et al. (2014) applied the InVEST model for heavily humanized Llobregat river basin. The model is applied for both extreme wet and dry conditions and the role of climatic parameters is emphasized. Hoyer et al. (2014), applied this model in Tualatin and Yamhill basins of northwestern Oregon under a series of urbanization and climate change scenarios. The results show that the climatic parameters have more sensitivity than other inputs for a water yield model. Hamel et al. (2014), applied the same water yield model for the Cape Fear catchment, North Carolina and concluded that the precipitation is the most influencing

parameter. Goyal et al. (2017) analyzed the InVEST water yield model for the hilly catchment by considering two catchments i.e. Sutlej river catchment and Tungabhadra river catchment. The climate parameters i.e. precipitation and ET_0 are observed to be most influencing parameters for water yield in both the river basins. With the aforementioned studies, there exist certain factors limiting the application of InVEST model such as the absence or inadequate comparison with observed data, calibration of the model without prior identification of sensitive parameters, and lack of validation of the predictive capabilities in the context of Land Use Land Cover change (Bai et al. 2012; Nelson et al. 2010; Su et al. 2013; Terrado et al. 2014).

The InVEST model operates on the principle of Budyko theory (Budyko, 1958, 1974). Based on works of Schreiber (1904) and Ol'Dekop (1911), Budyko proposed formulations explaining the relationship between precipitation and potential evapotranspiration (PET) in order to couple water and energy balances, defined as Budyko hypothesis. Several attempts have been made later to obtain an analytical solution of the Budyko hypothesis (Schreiber, 1904; Ol'Dekop, 1911; Turc, 1954; Mezentsev, 1955; Pike, 1964; Fu, 1981; Choudhury, 1999; Zhang et al., 2001, 2004; Porporato et al., 2004; Yang et al., 2008; Donohue et al., 2012; Wang and Tang, 2014; Zhou et al., 2015). Among these approaches, solutions provided by Fu (1981), called Fu's equation gained significant attention as the work represented the effect of catchment properties on water balance components by incorporating an addition parameter 'w'. Fu's equation can provide a full picture of the evaporation mechanism at the annual timescale. Therefore, Fu's equation could be used through top-down analysis for providing an insight into the dynamic interactions among climate, soils, and vegetation and their controls on the annual water balance at the regional scale (Yang et al., 2007).

Considering the lack of studies on analysis and validation of ES in Indian sub-continent especially for Himalayan catchments and to assess the applicability of various water-balance model to Himalayan catchments, the present work attempts to compute and analyse water yield in Upper Ganga basin using InVEST model. The work primarily considers in detail, the spatial variation of InVEST model parameters and uses different strategies to compute water yield. Accordingly, water yield is estimated for four years i.e. 1980, 1990, 2001 and 2015 and the most appropriate strategy is identified. The parameters that are computed at basin level scale in previous studies are estimated at pixel scale in order to avoid the dependence of model parameters on size of the catchment. In addition, pixel level estimations of water yield are expected to be more accurate than output obtained using conventional approach. The term 'finer scale' in the paper represents the incorporation of spatial variations through pixel level estimation of parameters involved in InVEST model which are otherwise taken as lumped. The work also attempts to compare the outcomes of spatially distributed water yield model and conventionally used lumped Zhang model.

2. Background Theory

2.1 Water Yield Models

In this section, two water yield models, i.e. InVEST water yield model, which is a distributed model and Lumped Zhang model are described.

2.1.1 InVEST model

The InVEST water yield model (Tallis *et al.* 2010) is designed to provide the information regarding the changes in the ecosystem that are likely to alter the flow. It is based upon the Budyko theory which is an empirical function that yields the ratio of actual to potential evapotranspiration (PET) (Budyko, 1979). To describe the degree to which long-term catchment water-balance deviates

from the theoretical limits, number of scholars have proposed one-parameter functions that can replicate the Budyko curve (Fu 1981, Choudhury 1999, Zhang et al. 2004, Wang et al. 2014). To observe and represent pixel-level changes to the landscape, InVEST model incorporates, explicitly, the spatial variability in precipitation, PET, soil depth and vegetation. The model operates at grid scale and acquire the inputs in raster format into a GIS environment such as ArcGIS.

The InVEST water yield model is based on an empirical function known as the Budyko curve (Budyko 1974). Annual Water yield, Y (x) is determined for each pixel for a landscape as follows:

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

where, $AET\ (x)$ is the actual annual evapotranspiration per pixel x; and $P\ (x)$ is the annual precipitation per pixel x. Actual evapotranspiration (AET) is essentially determined by climate factors (precipitation, temperature, etc.) and mediated by catchment characteristics (vegetation cover, soil characteristics, topography, etc.). On the other hand, potential evapotranspiration (PET) represents the evaporating potential of the climate system at a specific location and time of year without the consideration of catchment characteristics and soil properties (Allen et al., 1998). Several attempts have been made in past to establish a relationship between AET and PET among which solution provided by Fu (1981) is adopted worldwide. Fu (1981) provided an analytical solution to the Budyko hypothesis and related AET with PET by incorporating a dimensionless parameter '*w*' which denotes the effect of catchment characteristics.

The InVEST model uses the expression of the Budyko curve proposed by Fu (1981) and Zhang *et al.* (2004). The ratio of mean annual PET to annual precipitation, known as index of dryness, is expressed as:

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

where, $PET\ (x)$ is the annual potential evapotranspiration per pixel x (mm); and $w\ (x)$ is a non-physical parameter that influences the natural soil properties. The $PET\ (x)$ is calculated using the following expression:

$$PET\ (x) = Kc\ (x)\ \times ETo\ (x) \quad (3)$$

where, $ETo\ (x)$ is the annual reference evapotranspiration per pixel x which is computed based on evapotranspiration from grass of alfalfa grown at that location using equation (6). $Kc\ (x)$ is the vegetation evapotranspiration coefficient that is influenced by the change in characteristics of land use land cover at every pixel (Allen et al., 1998). The values of $ETo\ (x)$ are adjusted by $Kc\ (x)$ for each pixel over the land use land cover map. $w\ (x)$ is an empirial parameter and the expression given by Donohue et al. (2012) for the InVEST model has been applied to define $w\ (x)$ which is as follows:

$$w\ (x) = z\ \times \frac{AWC\ (x)}{P\ (x)} + 1.25 \quad (4)$$

Thus, the minimum value of the parameter $w\ (x)$ is 1.25 corresponding to bare soil where root depth is zero (Donohue et al. 2012) . The Donohue model was originally developed for Australia, however, the online documentation on InVEST model states its application globally. The parameter, *z* is known as seasonality factor whose value varies from 1 to 30. It represents the nature of local precipitation and other hydrogeological parameters. The parameter, $AWC\ (x)$ depicts volumetric plant available water content expressed in depth (mm) which can be expressed by following formula for each pixel x:

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

Root restricting layer depth is defined as the depth of the soil upto which the soil can allow the penetration of roots and root depth is defined as the depth where 95 percent of the root biomass occurs. Plant Available Water Content (PAWC) is generally taken as the difference between the field capacity and wilting point. It depends upon the soil properties and can be computed by the Soil-Plant-Air-Water (SPAW) software. PAWC is calculated using the method described by Mckenzie et al. (2003). Modified Hargreaves method and Hargreaves method were employed for computing the reference evapotranspiration for the study area at pixel scale.

Modified Hargreaves method

$$ET_o = 0.0013 \times 0.408 \times RA \times (T_{avg} + 17.0) \times (TD - 0.0123 \times P)^{0.76} \quad (6)$$

where, ET_o is reference evapotranspiration, T_{avg} is average daily temperature (^oC) defined as the average of mean daily maximum and mean daily minimum temperature, TD (^oC) is the temperature range computed as the difference between mean daily maximum and mean daily minimum temperature, and RA is extraterrestrial radiation expressed in [$MJm^{-2}d^{-1}$].

Hargreaves method

$$ET_o = 0.0023 \times 0.408 \times RA \times (T_{avg} + 17.8) \times TD^{0.5} \quad (7)$$

where, ET_o is reference evapotranspiration, T_{avg} is average daily temperature (^oC) defined as the average of mean daily maximum and mean daily minimum temperature, TD (^oC) is the temperature range computed as the difference between mean daily maximum and mean daily minimum temperature, and RA is extraterrestrial radiation expressed in ($MJm^{-2}d^{-1}$).

For computing the extraterrestrial radiation (RA), following equation is used

$$RA = \frac{24(60)}{\pi} \times G_{sc} \times d_r \times [w_s \sin(\varphi) \sin(\delta) + \cos(\varphi) \cos(\delta) \sin(w_s)] \quad (8)$$

where, RA is extraterrestrial radiation [$MJm^{-2}d^{-1}$], d_r is the inverse relative distance Earth-Sun, G_{sc} is solar constant equals to 0.0820 $MJm^{-2}min^{-1}$, w_s is sunset hour angle (rad), δ is solar declination (rad) and φ is latitude (rad).

Determination of Seasonality factor (z) parameter

The seasonality factor (z) parameter depends upon the local precipitation patterns such as the hydrological characteristics of the area, its rainfall intensity and topography. In the InVEST water yield model (Tallis et al. 2010), parameter *z* can be computed in three different ways. First method is suggested by Donohue *et al.* (2012), in which parameter *z* is expressed as one fifth of the number of rain events per year. Second method is suggested by Xu *et al.* (2013), which relates w (x) with latitude, NDVI (Normalized Difference Vegetation Index), area, etc. Third method experiments with various selections of w (one value of w for the entire study region) till there is a good match between observed and computed water yield. Unfortunately, this method is not suited for a pixel based analysis as the number of pixels will be extremely large making the method to be computationally intensive.

2.1.2 Lumped Zhang model

In this model, the mean value of the different parameters is used as an input to compute the average value of the water yield for the whole watershed. The averaged actual evapotranspiration, potential evapotranspiration, *w*, precipitation are described by Zhang *et al.* (2004).

3. Study Area and Data

3.1 Study Area

The Ganga river in India is ranked amongst the world's top 20 rivers in regards to the water discharge. The Ganga river is segregated into three zones, viz., Upper Ganga basin, Middle Ganga

basin and Lower Ganga basin. The area chosen for the present study, i.e., Upper Ganga basin is situated in the northern part of India within the geographical coordinates 30^0 38' - 31^0 24' N latitude and 78^0 29' - 80^0 22' E longitude covering an area of 22,292.1 km^2 upto Haridwar. The altitude of the study area varies from 7512 m in the Himalayan terrains to 275 m in the plains. Approximately 433 km^2 of entire region of the basin is under glacier landscape and 288 km^2 is under fluvial landscape. About 60% of the basin is utilized for agricultural, 20% of the basin is under the forest area, especially in the upper mountainous region. Nearly 2% of the basin is permanently covered with snow in the mountain peaks. Most predominant soil groups found in the region are sand, clay, loam and their compositions. In the Upper Ganga river basin, the average annual rainfall varies from 550 to 2500 mm (Bharati et al. 2011) where a major fraction of total annual rainfall is received during monsoon months (June-September). The geographical location and other information of the Upper Ganga river basin are represented in Fig. 1.

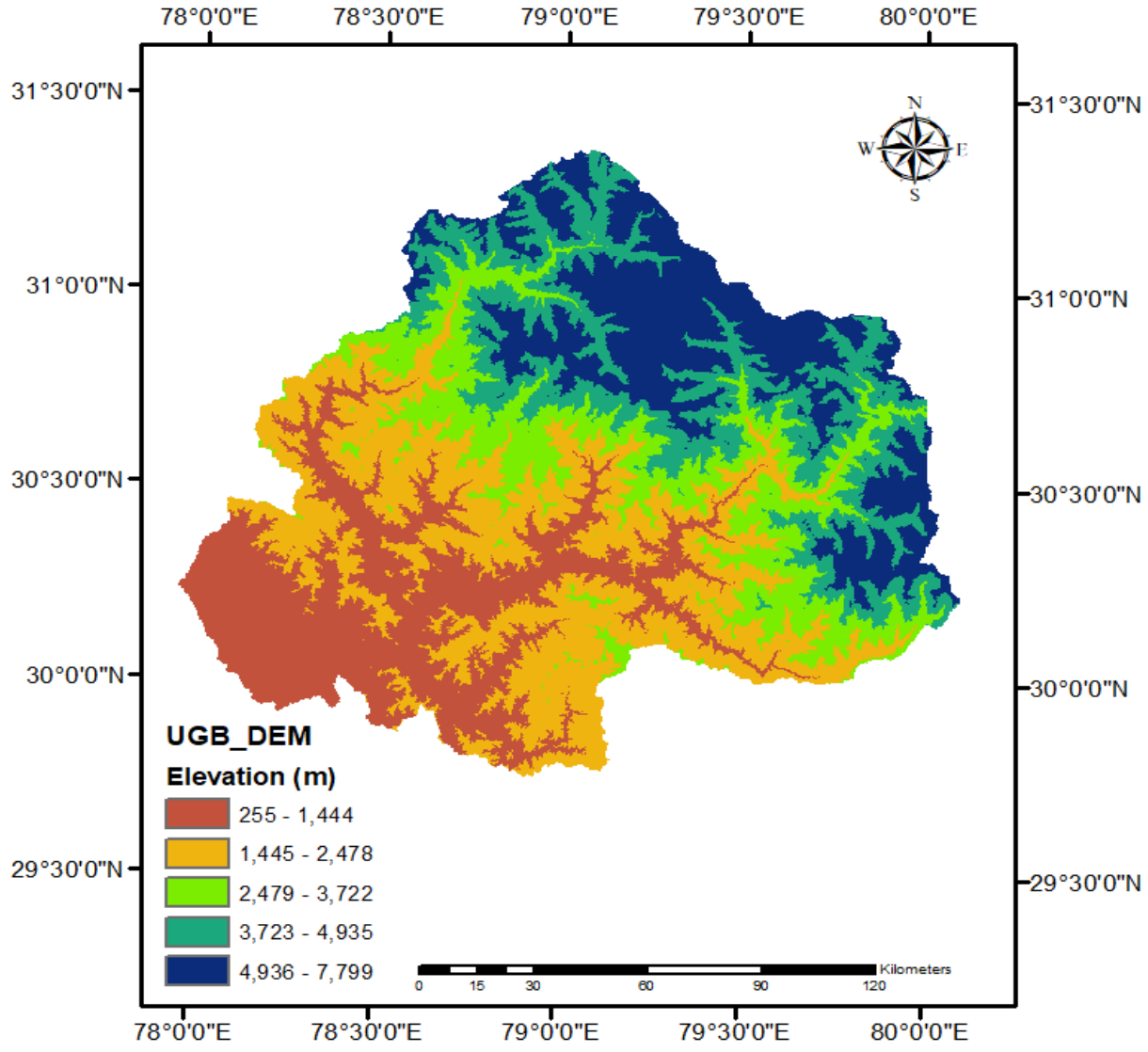


Figure 1. Graphical representation of study area, Upper Ganga basin

3.2 Data

3.2.1Precipitation and Temperature

The daily time series of precipitation and temperature for the study area is acquired from India Meteorological Department (IMD) at a grid size of 0.25 degrees and 1 degree, respectively. The Upper Ganga basin comes in the latitude ranging from 29.5 degrees north to 31.5 degrees north and longitude ranging from 77.75 degrees east to 80.25 degrees east. The daily time series of

219 precipitation was aggregated to obtain the annual time series at each grid point. Various analysis
220 in the study are carried out for four years i.e. 1980, 1990, 2001 and 2015.

221 *3.2.2 Soil Map*

222 Spatial maps of soil were collected from National Bureau of soil survey and land use planning
223 (NBSSLUP) at 1:250000. Digital maps of soil available at a resolution of 1200m×1200m were
224 resampled to the resolution of land use data i.e. 30m×30m using 'resample' tool in ArcGIS in order
225 to maintain the scale homogeneity. The attribute table of the raster layer contains fields like soil
226 depth, soil texture, percentage carbon content, drainage, slope, erosion, soil temperature and
227 mineralogy. The relevant feature, i.e. soil depth and soil texture are converted into the raster image
228 for the Upper ganga basin.

229 *3.2.3 LandUse/Land Cover map*

230 Satellite images were acquired from different sensors of Landsat viz. Landsat 3/4 MSS/TM,
231 Landsat 4 TM, Landsat 7 ETM and Landsat 8 OLI sensors for the year 1980, 1990, 2001 and
232 2015 respectively. The images are available at different resolution and for several bands out of
233 which Green (G), Red (R) and Near Infrared (NIR) band images are combined to create False
234 Colour Composite (FCC) for the study area in ERDAS Imagine. FCCs are then classified using
235 supervised classification in ERDAS in six different classes, i.e. Forest, Water, Agricultural,
236 Wasteland, Snow and Glacier and Built-up land. Classification of the area is based upon their
237 similar response under different bands. Each class is then recognized with the help of ground
238 truth and high resolution satellite images.

239 **4. Methodology**

In the present work, five different strategies are employed to compute water yield. For the ease of presentation, these strategies are referred as A, B, C, D and E. In strategy A, an average value of precipitation, temperature, extraterrestrial radiation and parameter '*w*' is used for the entire basin. This strategy is essentially based on Lumped Zhang Model. Strategies B, C, D and E are designated corresponding to a particular variation of InVEST model where water yield is computed using different approach for estimating *w* parameter. For computing parameter '*w*', Xu et al. (2013) relationship for large basin and global level is given by equation (9) and equation (10) respectively.

For Large basins:

$$w = 0.69387 - 0.01042 \times lat + 2.81063 \times NDVI + 0.146186 \times CTI \quad (9)$$

For global model:

$$w = 3.50412 - 0.09311 \times slp - 0.03288 \times lat + 1.12312 \times NDVI - 0.00205 \times long - 0.00026 \times elev \quad (10)$$

where, *slp* is slope gradient, *lat* is absolute latitude of basin center, *CTI* is compound topographic index, *NDVI* is normalized difference vegetation index, *long* is longitude and *elev* is elevation.

In strategy B, entire basin is considered for computing the parameter *w* for large basins by Xu et al. (2013) (equation 9). In strategy C, entire basin is considered for computing the parameter *w* for global model (equation 10) by Xu et al. (2013). In strategy D, parameter *w* is computed at each pixel in order to incorporate the spatial distribution of the hydrologic variables involved in the computations. In Strategy E, parameter *z* is computed according to the number of rain events in a year and subsequently equation (4) is used to compute the parameter *w*.

For all the strategies, extraterrestrial radiation (RA) parameter is computed for each month using equation (8) and a raster layer is generated. Precipitation data is obtained from Indian Meteorological Department (IMD) at grid size of 0.25 degree for the study area. It has been interpreted and converted to raster format by using Inverse Distance Weighted (IDW) interpolation technique in ArcGIS environment for obtaining the values for all pixels at a resolution equal to the resolution of the Landsat satellite images. The temperature dataset is obtained from IMD at grid size of $1^o \times 1^o$ for the study area and has been interpreted and converted to raster format by using IDW interpolation technique for obtaining the values for all pixels. Subsequently, the mean monthly value of average temperature (Tavg) and the difference between mean daily maximum and mean daily minimum (TD) is obtained. The climate datasets used in the present study are of the finest resolution available so far for the study region. The precipitation and temperature data sets were downscaled to a resolution of land use data using IDW interpolation technique. Gridded datasets of temperature and precipitation used in the present study have been developed using quality controlled stations and well-proven interpolation technique. Further details about the datasets of precipitation and temperature are given in Srivastava et al. (2009) and Pai et al. (2014), respectively.

Modified Hargreaves method is applied for obtaining the value of reference evapotranspiration at each pixel for each month (Droogers et al. 2002). In this method, the inputs are RA, precipitation, T_{avg} and TD. Some of the months, i.e. July 1980, July 1990, August 1990, June 2001, July 2001, August 2001, June 2015, July 2015 and August 2015 showed negative values of reference evapotranspiration as obtained from Modified Hargreaves method. For the above months, the Hargreaves method as recommended by Droogers et al. (2002) is applied for obtaining the positive values for the reference evapotranspiration. Thus, all the mean values for a month are added up to

get the mean yearly values for the year 1980, 1990, 2001 and 2015. To computed potential evapotranspiration, the yearly values obtained for the reference evapotranspiration have been multiplied by the vegetation evapotranspiration coefficient (K_c) which varies with the LULC characteristics as expressed in equation (3). The value of the K_c is taken from Allen *et al.* (1998) as shown in Table 1. In this study, Kc is taken same for all the four years as shown in Table. 1 and is used to obtain potential evapotranspiration which is subsequently used to obtain the annual water yield at each pixel of the study area.

Table 1. Value of K_c corresponding to LandUse/LandCover classes

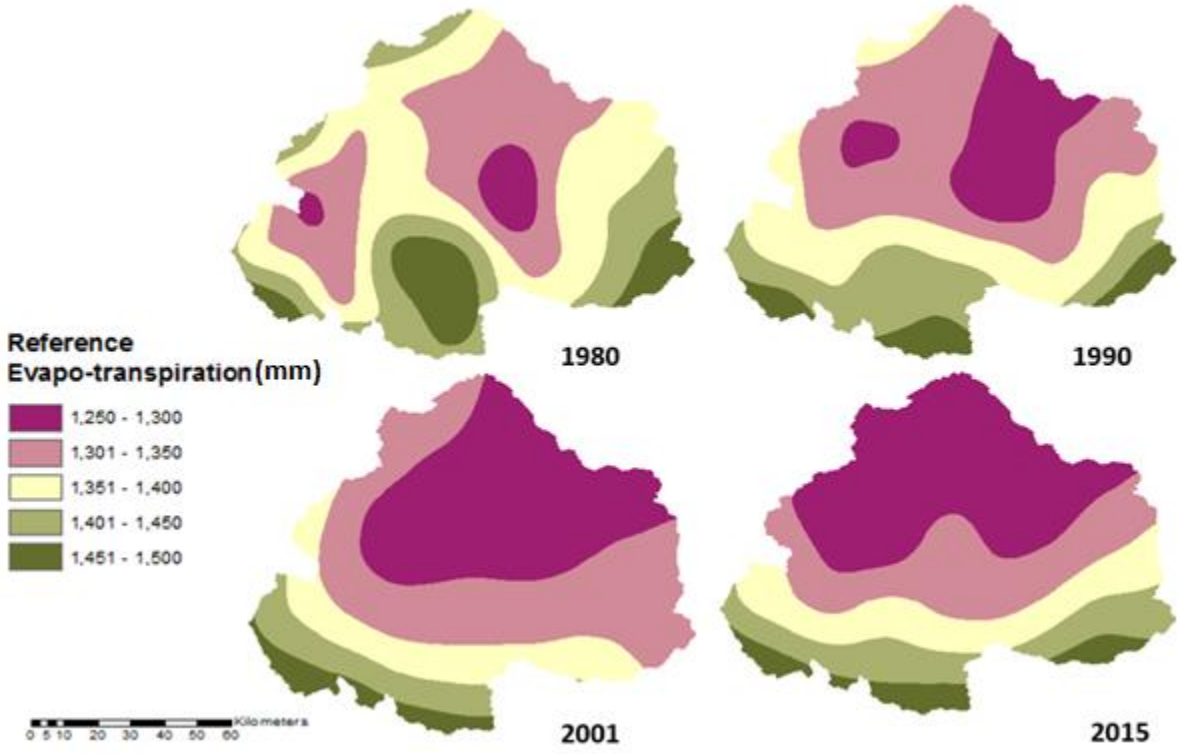
S.No.	LandUse/LandCover	Percentage cover (1980)	Percentage cover (1990)	Percentage cover (2001)	Percentage cover (2015)	K_c
1	Forest	17.84	16.32	15.78	15.19	1
2	Water	21.87	21.27	19.47	17.65	1
3	Wastelands	51.1	52.36	54.18	55.46	0.2
4	Built-up Area	2.07	2.14	2.27	2.49	0.4
5	Agricultural	3.67	4.04	3.76	4.22	0.75
6	Snow and Glacier	3.45	3.87	4.54	4.99	2

5. Results

5.1 Reference Evapotranspiration, ETo (x)

Reference Evapotranspiration (ET_0) is computed for the upper Ganga Basin using a high-resolution monthly climate dataset. Modified Hargreaves method is applied for obtaining the values of reference evapotranspiration at each pixel for each month (Droogers et al. 2002). ET_0 is

297 a function of RA, precipitation, Tavg and TD which are already computed pixel wise for each
298 month for the year 1980, 1990, 2001 and 2015. Some of the months i.e. July 1980, July 1990,
299 August 1990, June 2001, July 2001, August 2001, June 2015, July 2015 and August 2015 showed
300 negative values of reference evapotranspiration on applying Modified Hargreaves method. Thus,
301 for the above months, the Hargreaves method is applied for obtaining the positive results. Hence,
302 all the mean values for the months are added up to get the mean yearly values of evapotranspiration
303 for the years 1980, 1990, 2001 and 2015, as represented in Fig 2.



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305 **Figure 2.** Reference Evapotranspiration (mm) of Upper Ganga Basin for the years 1980, 1990,
306 2001 and 2015.

307 ***5.2 Potential Evapotranspiration, PET (x)***

The annual values obtained for the ET_0 is multiplied by the vegetation evapotranspiration coefficient (Kc) which varies with the Land Use Land Cover characteristics, as expressed in equation (3). The value of the K_c is taken from Allen et al. (1998). The values of the vegetation evapotranspiration coefficient are taken from the Table 1. Thus, the potential evapotranspiration is computed for Upper Ganga Basin for the years 1980, 1990, 2001 and 2015 as represented in Fig. 3.

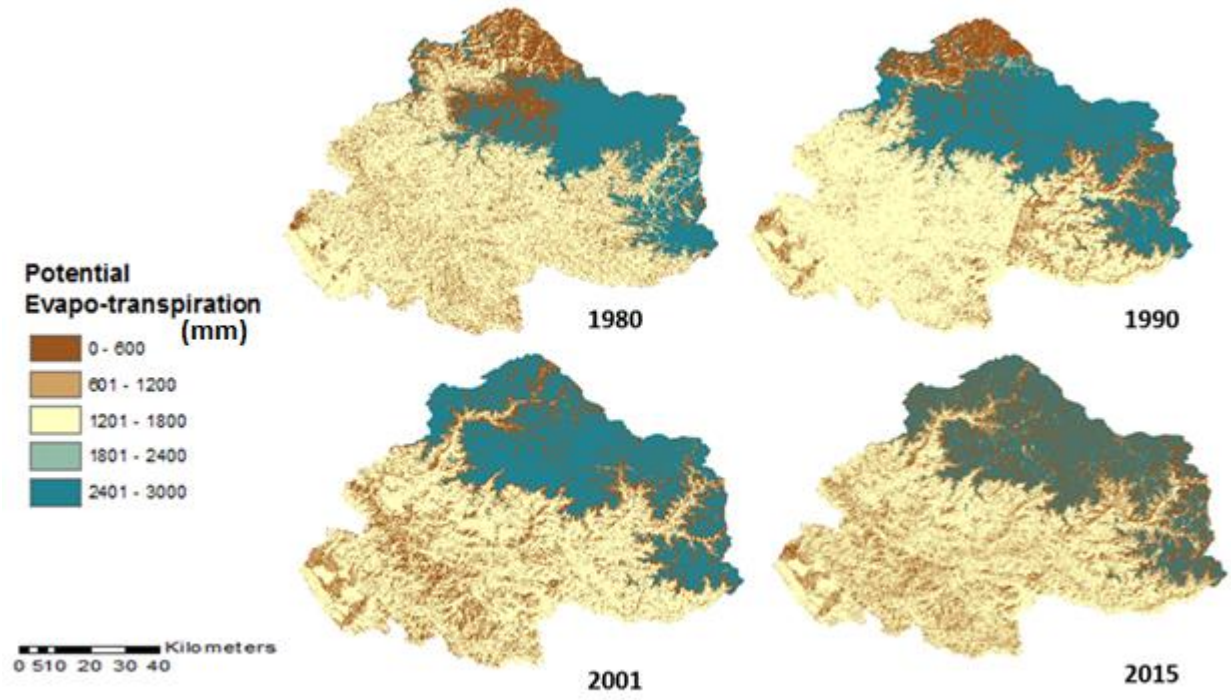


Figure 3. Potential Evapotranspiration (mm) of Upper Ganga Basin for the years 1980, 1990, 2001 and 2015.

5.3 Water Yield, Y(x)

As mentioned in the methodology, the water yield for the Upper Ganga basin are computed using five strategies namely A, B, C, D and E:

Strategy A: Water yield computed using Lumped Zhang Model

Here, the basin average values of all the input parameters are considered and the water yield is computed for the Upper Ganga basin for the year 1980, 1990, 2001 and 2015 which are obtained as 658.52 mm, 925.68 mm, 603.71 mm and 1194.25 mm, respectively.

Strategy B: Water yield obtained by taking the single weighted mean value of parameter 'w' from Xu et al. (2013) for Large basins.

By considering a single value of the parameter *w* for the whole basin, the water yield is computed for Upper Ganga basin (equation 9). The weighted mean value for the parameter *w* for the years 1980, 1990, 2001 and 2015 are obtained as 1.507, 1.541, 1.403 and 1.507, respectively. The spatial distribution of water yield for the Upper Ganga basin for different years is represented in Fig. 4. The mean values of water yield as obtained using this method for the year 1980, 1990, 2001 and 2015 are 755.65 mm, 959.48 mm, 742.39 mm and 1131.42 mm, respectively.

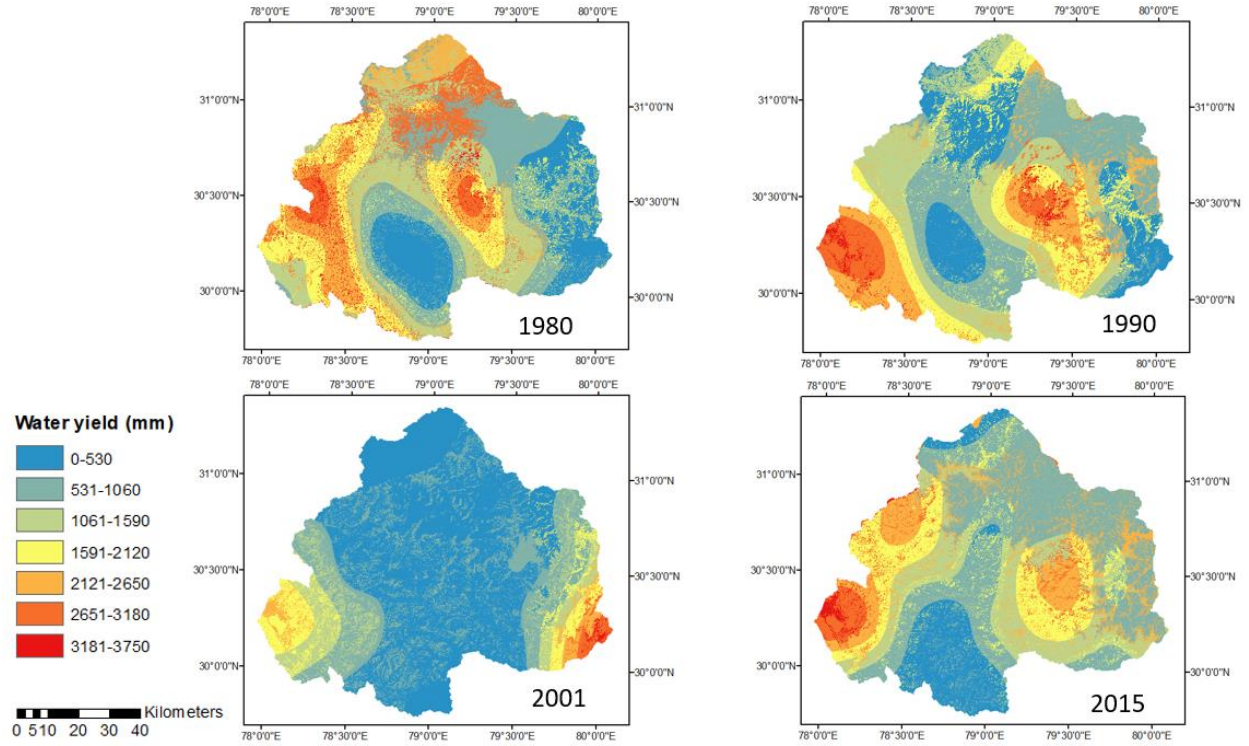


Figure 4. Water yield obtained by taking the single weighted mean value of parameter *w* from Xu et al. (2013) for large basins.

Strategy C: Water yield obtained by taking the single weighted mean value of parameter 'w' from Xu et al. (2013) for global model.

In this strategy, water yield is computed by considering a single value of the parameter *w* for the entire Upper Ganga basin using equation 10. The weighted mean value for the parameter *w* for the years 1980, 1990, 2001 and 2015 are obtained as -0.967, -0.955, -1.010 and -0.968, respectively. The spatial distribution of water yield for the Upper Ganga basin for aforesaid years is shown in Fig. 5. The mean values of water yield for the year 1980, 1990, 2001 and 2015 are 1239.92 mm, 1549.46 mm, 1149.93 mm and 1754.59 mm, respectively.

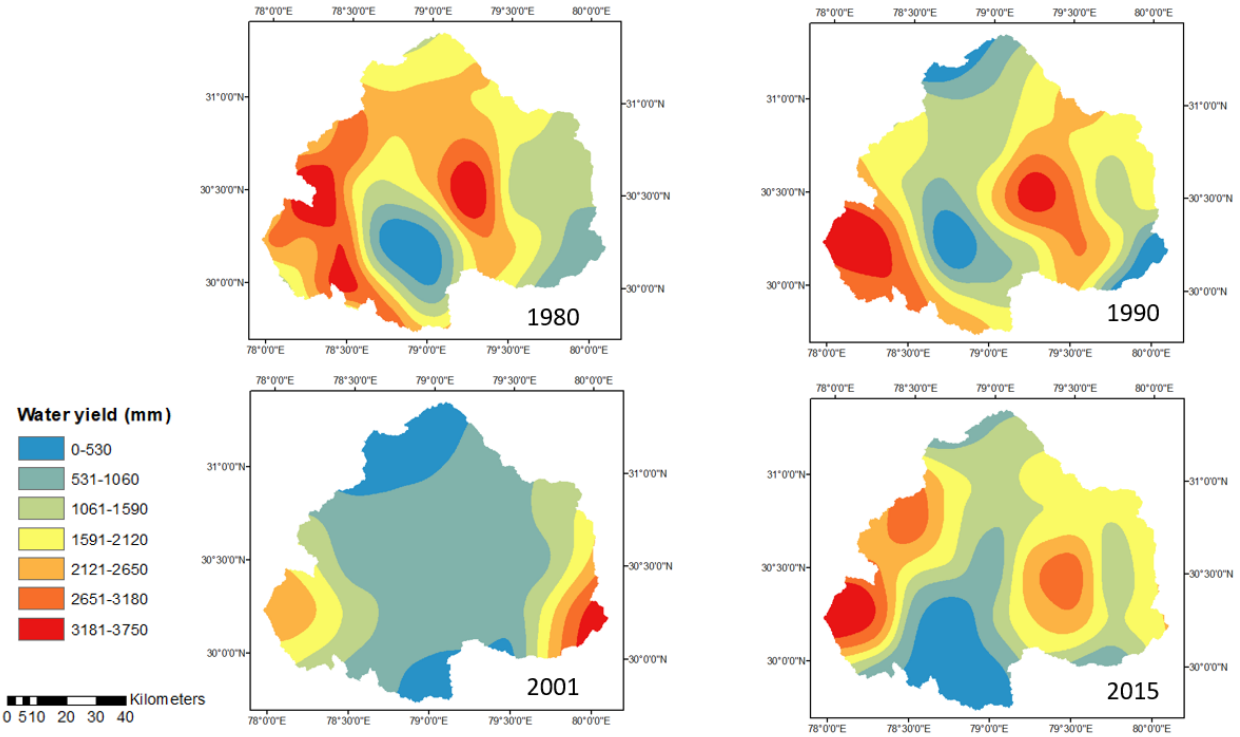
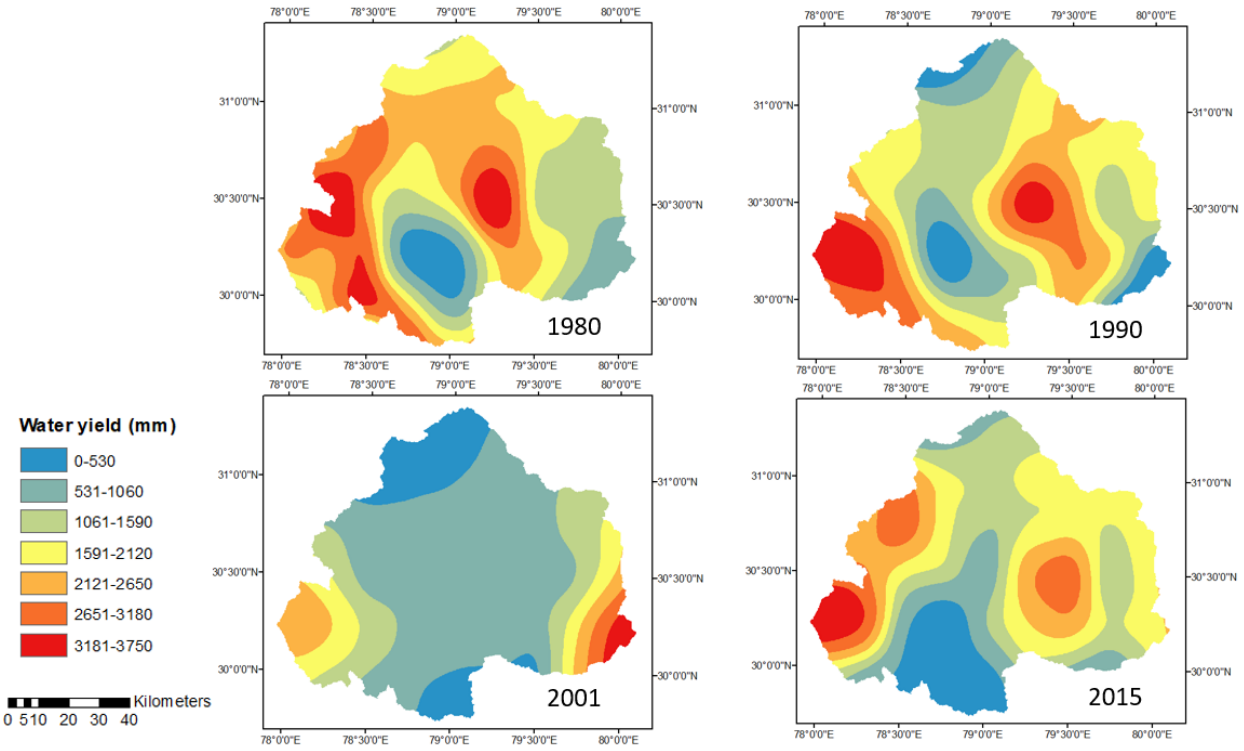


Figure 5. Water yield obtained by taking the single weighted mean value of parameter "w" from Xu et al. (2013) for global model.

Strategy D: Water yield obtained using pixel level estimation of parameter 'w' from Xu et al. (2013)

In this strategy, the values of parameter *w* are computed at pixel level. The water yield computed for the years 1980, 1990, 2001 and 2015 for the Upper Ganga Basin is shown in Fig. 6. The mean values of water yield for the year 1980, 1990, 2001 and 2015 are 1240.02 mm, 1549.44 mm, 1149.89 mm and 1754.62 mm, respectively.



352

353 **Figure 6.** Water yield obtained by computing pixel wise value of parameter *w* from Xu et al.

354 (2013)

355 ***Strategy E: Water yield obtained using pixel level estimation of parameter 'w' from Donohue et***

356 ***al. (2012)***

357 Equation (4) represents the parameter *w* as a function of the parameters 'z', AWC and

358 precipitation. The parameter *w* in the equation used in strategy 'E' has been proposed by Donohue

359 et al. (2012) which is also cited in online documentation of InVEST model, however, the final

360 equation used for estimating water yield is obtained from the InVEST model. Considering this

361 fact, Donohue et al. (2012) has been cited in Strategy 'E'. The water yield is computed for Upper

362 Ganga Basin for different years is shown in Fig. 7. The mean values of water yield for the years

363 1980, 1990, 2001 and 2015 are 1241.09 mm, 1552.38 mm, 1153.95 mm and 1753.53 mm,

364 respectively.

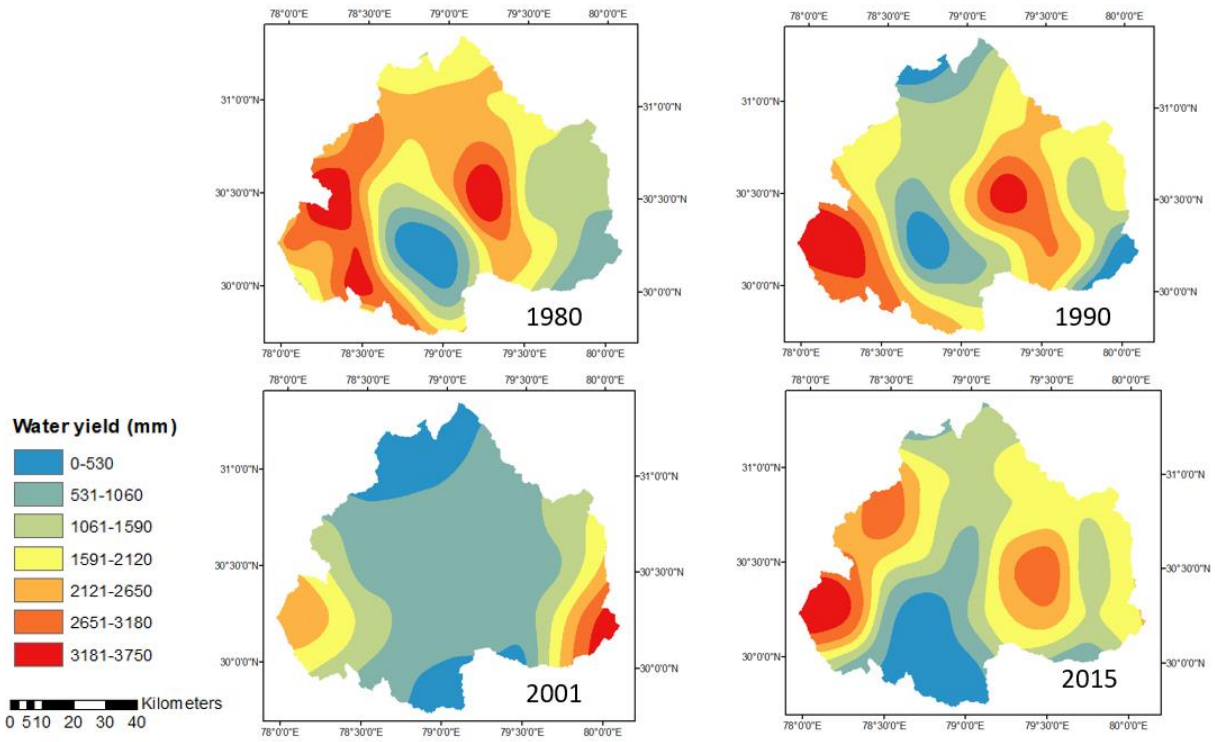


Figure 7. Water yield obtained by computing pixel wise value of parameter "w" from Donohue *et al.* (2012)

5.2 Validation of ET and water yield estimates

For validation purpose, the basin average annual values of PET and AET estimated using various strategies are compared with the corresponding basin average values obtained from available global datasets (Table 2). Model simulated AET values are obtained from GLDAS global ET datasets from Noah model outputs. Basin average values of PET dataset are obtained from Climate Research Unit (CRU) PET datasets (CRU TS v. 4.01) available at resolution of 0.5^{o}. From the comparison, both AET (GLDAS) and PET (CRU TS) values are found to be in agreement with the satellite estimated values. Spatial maps of Global datasets of AET and PET are shown in Figure 8 and 9, respectively.

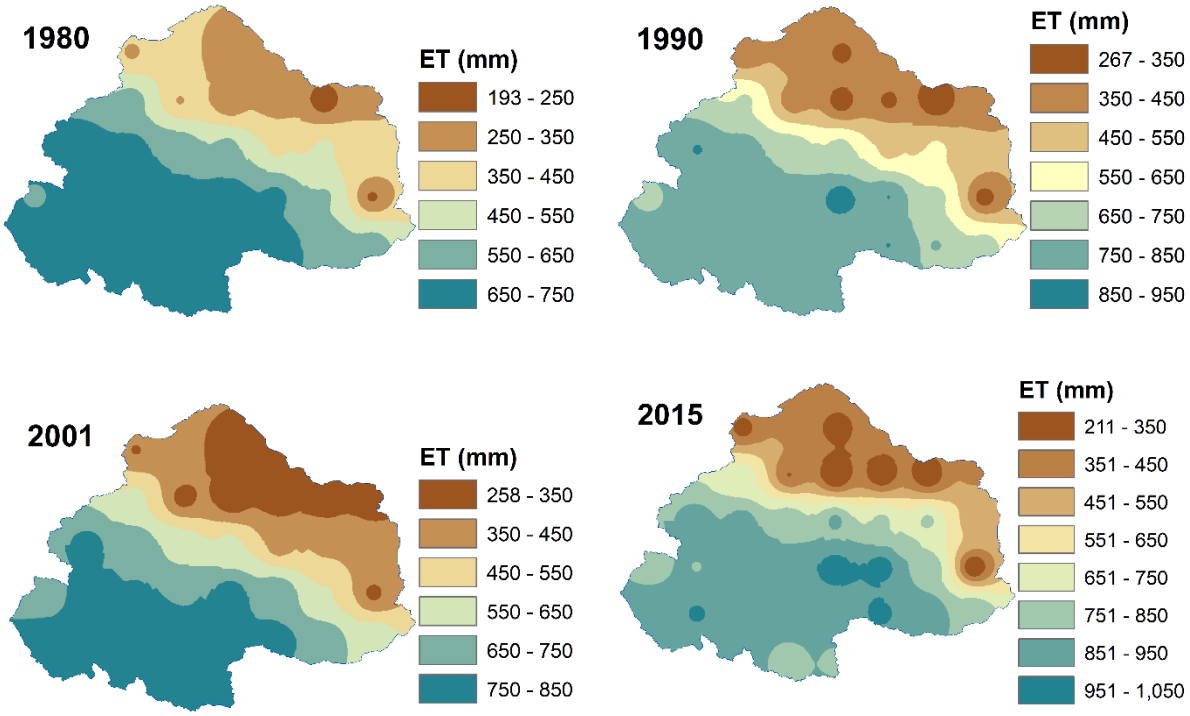


Figure 8. Spatial distribution of AET obtained from GLDAS Noah output datasets.

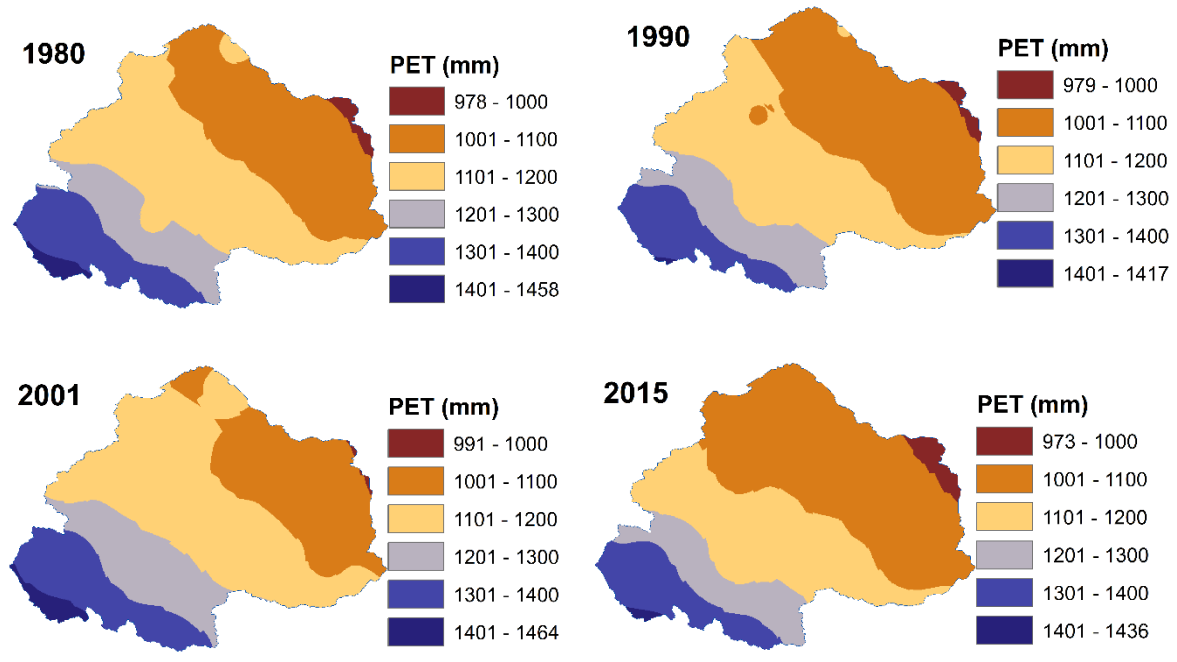
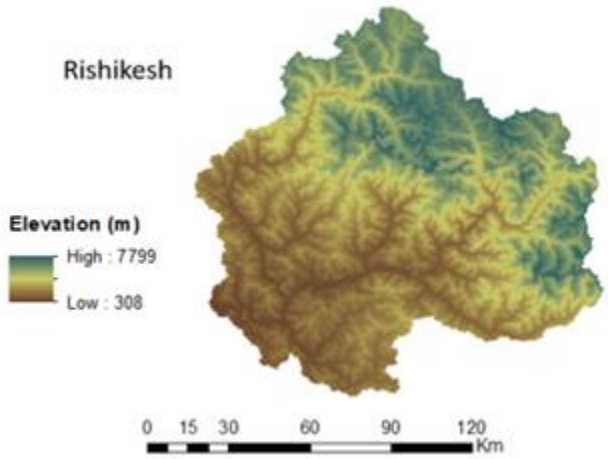


Figure 9. Spatial distribution of PET obtained from CRU datasets.

Table 2: Comparison of model estimated PET and AET with satellite estimates

Parameter					InVEST model			
(mm)	Year	Source 2 (GLDAS)	Source 2 (CRU)	Strategy A (Lumped Zhang Model)	Strategy B (Large Model)	Strategy C (Global model)	Strategy D (Xu et al. 2013)	Strategy E (Donohue et al. 2012)
AET	**1980**	555.0355		696.84	486.07	679.52	679.68	680.01
	1990	646.168		815.02	592.3	735.23	735.27	736.25
	2001	588.084		680.76	408.86	548.28	548.39	550.38
	2015	716.8316		900.11	625.41	743.48	743.52	744.34
PET	**1980**		1175.964	1376.64	1382.12	1382.12	1382.12	1382.12
	1990		1156.497	1456.16	1461.86	1461.86	1461.86	1461.86
	2001		1184.847	1457.08	1462.96	1462.96	1462.96	1462.96
	2015		1156.686	1544.20	1550.42	1550.42	1550.42	1550.42

The validation of water yield obtained from various strategies is performed upto Rishikesh gauging site of Upper Ganga basin (Fig. 10). The discharge data of the basin is obtained from Irrigation department of Uttarakhand state. Present work considers runoff from both precipitation as well as snowfall for the region, where 32% of the observed discharge has been removed as it is contributed by glacier ice melt as explained by Maurya et al. (2011) for our study area. The above mentioned fraction of discharge had been quantified using isotope study which separates the contribution of glacier melt in quantifying discharge (Maurya et al., 2011). A comparison of the water yield computed and observed for the study region for different years by various proposed strategies is shown in Table 3.



398

399 **Figure 10.** Graphical representation of sub-basin Rishikesh

400 **Table 3.** Observed vs computed water yield by various proposed strategies for Rishikesh sub-

401 basin.

Strategies	1980	1990	2001	2015
Observed discharge (mm)	1831.31	2422.43	2187.22	2835.81
Observed (mm) (after reducing approx. 32% snow melting contribution)	1245.29	1647.25	1487.31	1928.35
Water Yield_Strategy A (mm)	652.47	914.35	598.25	1189.72
Water Yield_Strategy B (mm)	745.38	917.77	697.75	1092.17
Water Yield_Strategy C (mm)	1229.90	1506.82	1102.62	1718.17
Water Yield_Strategy D (mm)	1229.99	1506.74	1102.61	1718.18
Water Yield_Strategy E (mm)	1230.77	1508.88	1106.86	1720.16

402

403 As can be seen in Table 3, values of water yield estimated using strategy A to E are systematically

404 increasing but are not steady in nature as water yield estimated using strategy A and B lies in range

405 650 – 750 mm whereas water yield from strategy C-E lies in range 1229 – 1231 mm for the year
406 1980 (see Table 3). Similar results are also evident for other years too. Also, water yield estimated
407 using strategy C-E are more or less same for a given year as these strategies involve pixel based
408 estimation of water yield considering spatial variation in Budyko parameters. The parameters
409 involved in Budyko model such as *w* are found to be dependent on various factors such as
410 catchment characteristics, vegetation cover, etc. as well as climate seasonality (Li et al. 2013). Ahn
411 and Merwade (2017) have analyzed the relationship between basin characteristics and parameter
412 *w* for 175 stations spread over the USA. Considering their study, no precise conclusion can be
413 drawn regarding relationship between basin characteristics and value of parameter *w* especially in
414 case of basin area characteristics. Moreover, no definite relationship has been yet identified
415 between basin characteristics and model parameters and is a subject matter for further study.

416 ## 6. Discussion

417 The study aimed to apply the InVEST water yield model, a tool that is gaining interest in ecosystem
418 services community for Upper Ganga Basin having highly variable topography consisting of hilly
419 areas, plain areas and the regions which are totally covered with snow. The InVEST model is based
420 upon Budyko theory which requires low amount of data and low level of expertise, thus making it
421 acceptable world-wide. Monthly precipitation, monthly average value of temperature, monthly
422 value of difference of mean daily maximum and mean daily minimum and extraterrestrial radiation
423 parameters for the Upper Ganga Basin for each month of all the four years i.e. 1980, 1990, 2001
424 and 2015 are converted into raster format for various analysis. The monthly reference
425 evapotranspiration is thus computed using input parameters in GIS environment by applying the
426 modified Hargreaves equation for all the months except some months where the modified
427 Hargreaves equation shows the negative results for the reference evapotranspiration value. For

those months, Hargreaves method is applied to obtain the positive value of reference evapotranspiration as also suggested by Goyal et al. (2017). Reference evapotranspiration when multiplied with K_c gives the potential evapotranspiration. All monthly values are added up to obtain the annual value of reference evapotranspiration. K_c is a function of Land Use Land Cover, thus, supervised classification is done to prepare the raster Land Use Land Cover map for the Upper Ganga Basin. Subsequently, the annual value of potential evapotranspiration is obtained for the study area for the years 1980, 1990, 2001 and 2015.

The paper focuses on various methodologies used for water yield estimation as discussed in the paper and is applied on the Upper Ganga basin. Thus, water yield is computed both from InVEST model as well as Lumped Zhang model. The value of the parameter *w* is computed using four ways, i.e. mean single value obtained from Xu et al. (2013) for large basins and global model, pixel wise value of parameter *w* from Xu et al. (2013) and pixel wise value of parameter *w* from Donohue et al. (2012). Although, the Upper Ganga basin lies in large basin category as per the definition from Xu et al. (2013), but, the yield computed using global model is in good agreement with the observed data for the Upper Ganga basin. In the study, pixel level estimation of parameter *w* is made in order to incorporate the spatial variability of the parameter in water yield estimation. Thus, two pixel wise values of parameter *w* are computed for the Upper Ganga basin for years 1980, 1990, 2001 and 2015 by considering two approaches as given by Xu et al. (2013) and Donohue et al. (2012). Also, the water yield is computed from Lumped Zhang model which works on the approach of considering mean values of all the parameters involved in the computation of water yield. Thus, water yield is computed in five different ways for the Upper Ganga basin for the years 1980, 1990, 2001 and 2015.

At Rishikesh gauging site, surface runoff data is obtained by extracting the snow melt from the discharge data as the snow melting contributes about 32 percent of total runoff (Maurya et al., 2011). Using this fact, the observed yield is compared with the computed water yield based on different proposed strategies for the years 1980, 1990, 2001 and 2015 as represented in Table 3. The results obtained from Donohue et al. (2012) and Xu et al. (2013) are computed at pixel level (Strategy C, Strategy D and Strategy E), thus, exhibit better performance than other approaches and are in good agreement with the observed data. It is clear that in order to go for hydrological analysis for any watershed, pixel wise computation is advisable. The parameters involved in the Budyko model are dependent on various factors such as basin characteristics (size, topography, stream length, slope, etc.), climate seasonality, etc. (Li et al., 2013). The factors affecting model parameters again vary both spatially and temporally. Moreover, the relationship between these factors and model parameters are not yet well defined (Ahn and Merwade, 2017). In such scenario, adopting a hypothesis by assuming either of these controlling factors (such as '*w*') to be constant spatially or temporally is inappropriate. Considering these facts, the present study attempts to incorporate the spatial variability of model parameter for estimation of water yield at pixel level. As the computations are made at pixel level in GIS environment, the assumption of dependence of model parameters over scale of the catchment may also be disregarded. The computations made in present work are based on empirical equations, however, the application of these equations has been well documented worldwide for estimation of various water balance components at various basin scales (Zhang et al., 2008; Ma et al., 2008; Ning et al., 2017; Rouholahnejad et al., 2017; Wang et al., 2017). Hence, it is recommended that for such a large basin there is a strong need to compute all the parameters involved in the computations of water yield at pixel scale rather than adopting mean values for entire watershed.

7. Summary and Conclusions

The present study aimed to apply the InVEST annual water yield model, a tool that is gaining interest in the ecosystem services community. While such simple models having low requirements for data, high level of expertise are needed for practical applications of such model as a single representative value of model parameter for the entire basin does not provide accurate estimates of water yield. In addition, performing pixel scale computation of water yield indicates a better performance and results obtained show better agreement with the observed water yield. As far as parameter *w* is concerned, global model works better than other representations of parameter *w* available in literature. In the study, the water yield is computed using five different strategies and results are analyzed with the observed data at the outlet of Upper Ganga Basin. The present study attempts to quantify annual water yield at pixel level making the computations independent of the size of catchment. Therefore, the proposed methodology is expected to perform well for the catchment of any given size. Changes in catchment water storage over time are required to be quantified in order to validate the applicability of Budyko's model to long term data for the catchment under study. Earlier, some of the important parameters for the water yield used to be computed at a basin level scale which brings noise in the results. Thus, by considering all the parameters involved in the model at pixel level scale, the results obtained are higher in accuracy.

The study attempts to incorporate the spatial variability of parameters involved in the model thorough pixel level estimation of parameters which are otherwise taken as lumped in the previous studies. Study results show that the water yield estimated considering spatial variability in model parameters are in better agreement with the observed water yield as compared to the water yield estimated by considering the parameters to be lumped over the study region. Further, the computations of various parameters are made at pixel level, therefore, the estimates of water

balance components using this approach are expected to be independent of the assumption of dependence of parameters on catchment size. As the variation between Budyko's model parameters and their controlling factors has not shown well defined relationship (Ahn and Merwade, 2017), the study emphasizes water yield estimation using pixel based computations. Therefore, it can be inferred that: (i) between two approaches used, i.e. considering entire basin and pixel level approach, the pixel level approach is found to provide better results and (ii) in pixel based computations, results are further improved with the use of a parameter *w* based on a global model rather than regional models of parameter *w* for large basins in Himalayan region.

Acknowledgement

Authors are thankful to Executive Engineer, Irrigation Department, Uttarakhand, for providing the discharge data for the Rishikesh sub-basin of Upper Ganga Basin.

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