Comments to Anonymous Referee #1

The manuscript generates component of annual water balance based on a hydrologic model. The analysis is very routine and there is very little validation of output. Some of the concepts also needs to be corrected such as, the ET is calculated without considering wind and humidity. The manuscript, in this form, is not suitable to be published in HESS.

1. **There is no validation for variables such as ET and soil mositure. The authors must validate the model with satellite estimates of ET and soil moisture.**

Reply: As suggested by reviewers, estimated values of both AET and PET have been validated with available satellite estimates from GLDAS (AET) and CRU TS (PET). The final equation used for estimating water yield involves two ET estimates viz. AET and PET which both are been validated using satellite based estimates for the respective years.

Parameter					**InVEST model**			
(mm)		**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

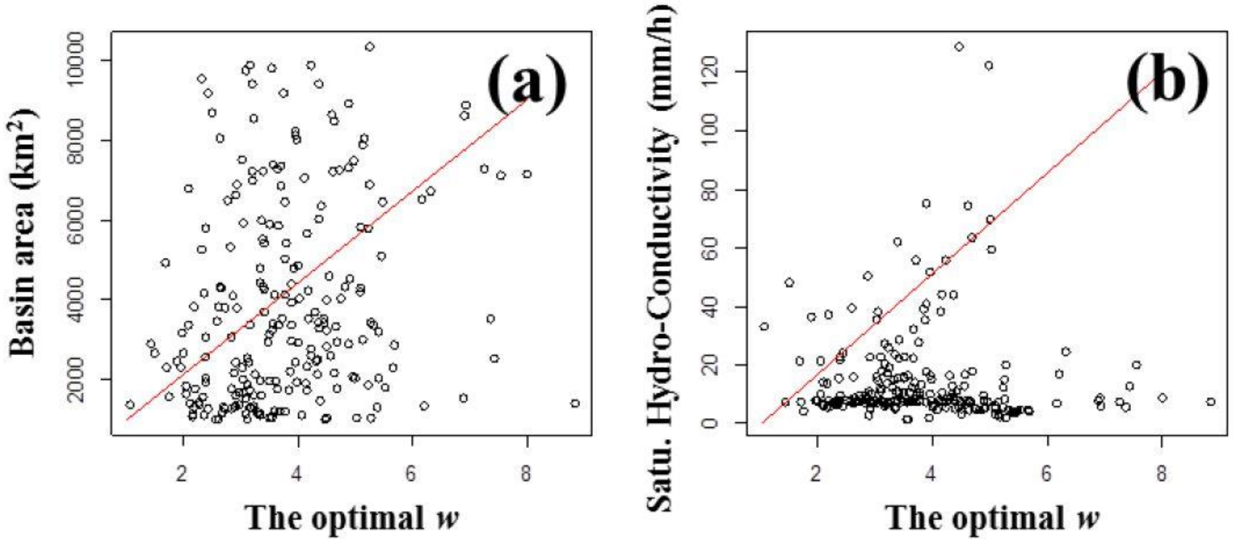
2. There is no specific scientific hypothesis, the article just reports results from some empirical equations without proper analysis.

Reply: Authors agree that the study lacks a precise scientific hypothesis. However, 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 few 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.

Authors also agree that 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). An illustrative summary of such studies has been added in the revised manuscript.

3. I do not see a proper conclusion coming out of this work.

Reply: Present study attempts to compute water yield from a Himalayan catchment using InVEST water yield model. 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 trend (see Fig 1), the study emphasizes water yield estimation using pixel based computations.



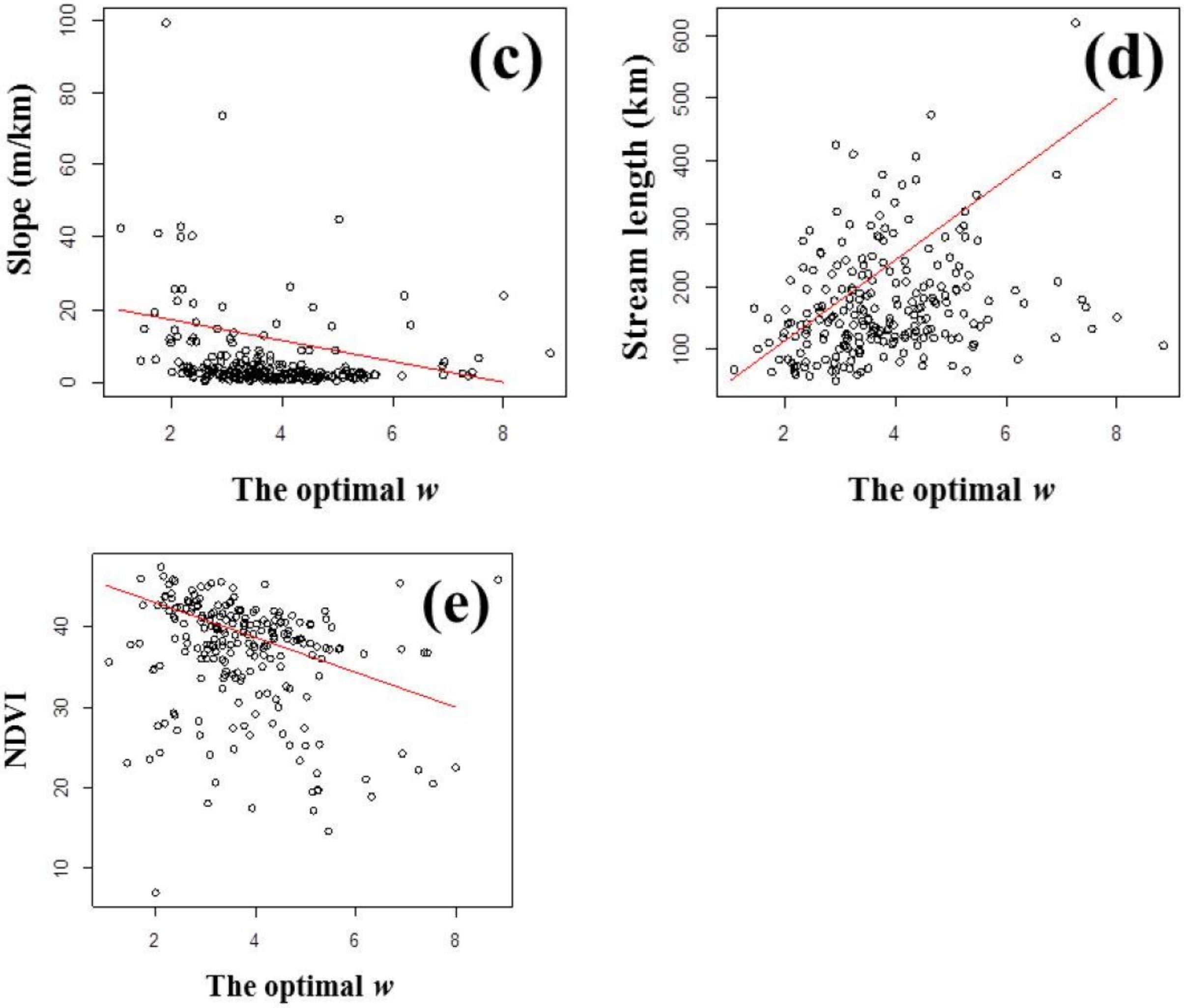


Figure 1: The relationship between basin characteristics and optimal w values (Source: Ahn and Merwade, 2017)

4. The write up is extremely poor and needs significant revision.

Reply: As per reviewer's suggestion, the write up has been improved wherever required. Our endeavor will be that the revised paper is much better than the current version.

References:

1. Ahn, K. H., and Merwade, V. (2017). "The Integrated Impact of Basin Characteristics on Changes in Hydrological Variables", Book Chapter 12 in "*Sustainable Water Resources Management*", American Society of Civil Engineers (ASCE), pp. 317-336. ISBN: 978-0-7844-1476-7.

2. Choudhury, B. J. (1999). “Evaluation of an empirical equation for annual evaporation using field observations and results from a biophysical model.” *J. Hydrol.*, 216(1–2), 99–110.
3. Li, D., Pan, M., Cong, Z., Zhang, L., and Wood, E. (2013). “Vegetation control on water and energy balance within the Budyko framework.” *Water Resources Research*, 49(2), 969-976.
4. Ma, Z. M., S. Z. Kang, L. Zhang, L. Tong, and X. L. Su (2008). “Analysis of impacts of climate variability and human activity on streamflow for a river basin in arid region of northwest China.” *J. Hydrol.*, 352(3–4), 239–249.
5. Ning, T., Li, Z., and Liu, W. (2017). “Vegetation dynamics and climate seasonality jointly control the interannual catchment water balance in the Loess Plateau under the Budyko framework.” *Hydrol. Earth Syst. Sci.*, 21, 1515-1526
6. Rouholahnejad Freund, E. and Kirchner, J. W. (2017). “A Budyko framework for estimating how spatial heterogeneity and lateral moisture redistribution affect average evapotranspiration rates as seen from the atmosphere.” *Hydrol. Earth Syst. Sci.*, 21, 217-233
7. Wang, X.-S. and Zhou, Y. (2017). “Shift of annual water balance in the Budyko space for catchments with groundwater-dependent evapotranspiration.” *Hydrol. Earth Syst. Sci.*, 20, 3673-3690
8. Zhang, L., N. Potter, K. Hickel, Y. Q. Zhang, and Q. X. Shao (2008). “Water balance modeling over variable time scales based on the Budyko framework–Model development and testing.” *J. Hydrol.*, 360(1–4), 117–131.

Comments to Anonymous Referee #2

This study estimates the water yield for the Upper Ganga basin using variations of the Budyko model that relates aridity index (ratio of long term potential evapotranspiration to precipitation) to evaporation ratio (ratio of long term actual evapotranspiration to precipitation). Several versions of a parameterized form of the Budyko curve, developed over the past years, are used to estimate long term streamflow for the basin. It is also assessed whether the inclusion of spatial variability of basin properties improves predictive skill. Though the study does not make any new contributions, it has the potential to contribute to understanding hydrology of this particular basin. However, in its present form it has major drawbacks:

1. Literature review: The study overlooks a significant body of literature in streamflow modeling in the region. Studies are available both at the scale of entire India, the Ganga basin as well as finer scales. In addition, the premise of the study is poorly developed and developments related to Budyko's theory are improperly explained. In fact, the work by Donohue et al. (2012) is cited but equations from InVEST's online documentation are instead used. It is not straightforward to connect the equations in the manuscript with Donohue et al. (2012) formulations. Overall, the introduction needs connection to a wider literature base, along with better exposition of developments in Budyko theory.

Reply: The present study focuses on incorporation of spatial variability of various parameters involved in computing water yield using InVEST model. The work does not involve modelling of streamflow rather it attempts to compare the outcomes of spatially distributed water yield model and conventionally used lumped Zhang model. Authors agree that the literature on hydrological modelling of water balance components is available for Ganga basin and its sub-catchments (finer scale), however, the term 'finer scale' in the paper represents incorporation of spatial variations through pixel level estimation of parameters involved in InVEST model which are otherwise taken as lumped. Authors agree that the parameter '*w*' in the equation involved in strategy "E" have been proposed by Donohue et al. (2012) which is also cited in online documentation of InVEST model, however, the final equation used for estimating water yield is from the InVEST model. Considering this fact, Donohue et al. (2012) has been cited in Strategy 'E'. If suggested by reviewer, the citation can be removed from the Strategy 'E'. Various advancements in the Budyko's theory have been addressed properly in revised manuscript.

2. Methods: The methods rely on previously developed relationships between Budyko parameter and observable catchment properties. However, some of these relationships, such as those in Donohue et al. 2012 were developed for Australia. Similarly, Xu et al. (2013) report that the global model could explain only 53% of observed variation of Budyko's parameter in their dataset. The large basin model worked well but is the Upper Ganga basin large enough in comparison to the 32 basins used in Xu et al. (2013)?

Reply: The Donohue et al. (2012) model was developed for Australia, however, the online documentation on InVEST model also states its application globally. 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.

3. Climate data: The resolution of climate data used to compute fine scale variables is of concern. The introduction stresses on a stronger control of precipitation (and potential evapotranspiration) on runoff estimates, as compared to Budyko's parameter, but the analysis works with coarse climatic data. Though precipitation and temperature data were downscaled to the resolution of land use data (by a statistical technique that is not described well.), the effect of elevation on these variables was neglected (for example lapse rate was not accounted for in temperature estimates). As the basin has significant elevation variations, this may lead to biases in water yield estimates.

Reply: The climate datasets used in the present study is at 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 Spline interpolation technique. The details regarding Spline interpolation technique has been added in the revised manuscript. Gridded datasets of temperature and precipitation used in the present study has been developed using quality controlled stations and well-proven interpolation technique. Further details about the datasets are given in Srivastava et al. (2009) and Pai et al. (2014).

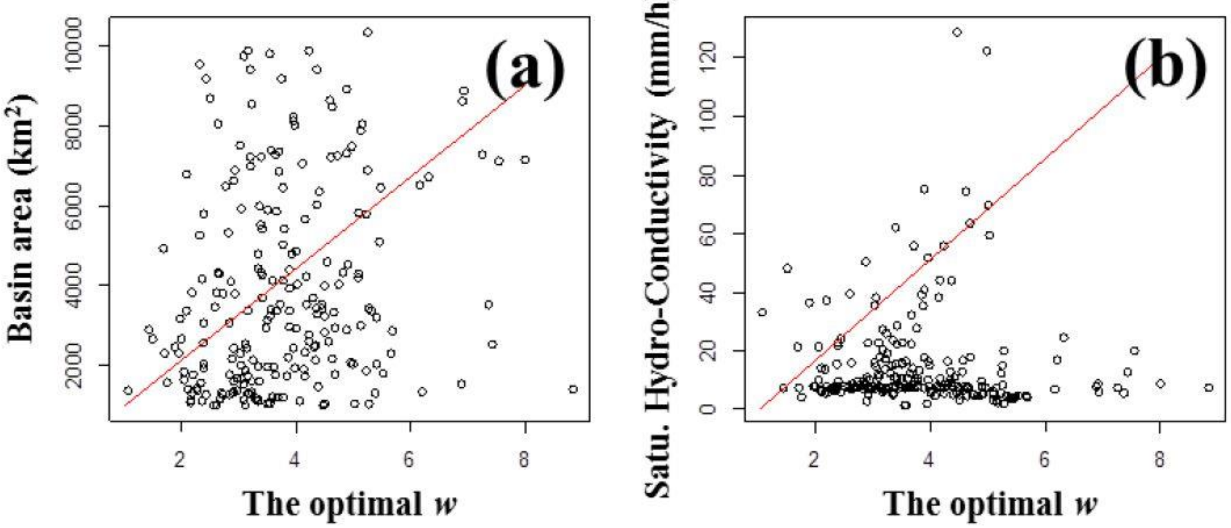
4. Validation: For the validation catchment, 32% of observed discharge is removed as it is assumed to be snowmelt. But snow melt still counts within the hydrological budget of the region as it is contributed by precipitation falling as snow, which is being used in the Budyko model. If the melt contribution was from long term glacier melts that contribute water to the region in addition to precipitation falling as rain or snow, one may remove it. Even that will be challenging at annual time scales if the basin has significant storage. Unless the distinction between glacier and snow melt is made, and some reasoning as to why Budyko's approach can be applied at annual time steps, it will be hard to justify this reduction. There is also the issue of claiming predictive skill over an entire basin by looking at performance at a single sub-basin in a single year. Note that most approaches based on the Budyko's curve must work with long term data as even at annual time scales, catchment's water storage changes may be significant and the Budyko model may be invalid (Donohue et al. 2007). The discussion should reflect the limitations of this approach.

Reply: Present work considers runoff from both precipitation as well as snowfall for the region, but 32% of the observed discharge has been removed as it is contributed by glacier ice melt to the streamflow for this catchment 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 snow melt contribution from that of the glacier melt (Maurya et al. 2011). The present study attempts to quantify annual water yield at pixel level irrespective of the size of catchment. Therefore, the proposed methodology is expected to perform well for the catchment of any given size. Changes in catchment's 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. This limitation of the proposed methodology has been added in the revised manuscript.

5. Interpretation of results: For some reason, as we move from strategy A to E, catchment water yield steadily increases, or, ET decreases. This indicates a systematic change in the Budyko parameter as we go from simpler to more complex relationships requiring more

data. Why would the Budyko parameter scale in this manner? This also seems to be in contradiction of the result by Choudhary (1999) who showed that as larger areas are used in a lumped form, Budyo's parameter changes such that actual evapotranspiration reduces. See also the discussion in Donohue et al. (2007). Given the limited data for validation, it is important to physically interpret the results instead of focusing on which method is the best.

Reply: Values of water yield estimated using strategy A to E are systematically increasing but are not steady in nature as water yield estimated using strategy A and B lies in range 650 – 750 mm whereas water yield from strategy C-E lies in range 1229 – 1231 mm for the year 1980 (see Table 1). Similar results are also evident for other years too. Also, water yield estimated using strategy C-E are more or less same for a given year as these strategies involve pixel based estimation of water yield considering spatial variation in Budyko parameters. Parameters involved in Budyko model such as 'w' are found to be dependent on various factors such as catchment characteristics, vegetation cover, etc. as well as climate seasonality (Li et al. 2013). Ahn and Merwade (2017) have analysed the relationship between basin characteristics and factor '*w'* for 175 stations spread over the USA. Results are shown in Fig. 1 (Ahn and Merwade, 2017). As evident from figure, no precise conclusion can be drawn regarding relationship between basin characteristics and value of 'w' especially in case of basin area characteristics. In that case, rationalizing the relationship between basin size and value of Budyko model parameters as documented by Choudhary (1999) is not appropriate. Moreover, no straight forward relationship has yet been identified between basin characteristics and model parameters and it is a subject matter for further study. Authors again want to emphasize over the fact that study focuses on analyzing estimates of water yield computed considering spatial variation in Budyko model parameters at pixel level with water yield computed considering model parameters as lumped for the entire catchment. Authors agree that the data available for validation of parameters estimated at various levels are limited, however, estimated values of AET and PET used in computation of water yield are validated using satellite estimate of the variables for corresponding years (Table 1). From the comparison, both AET (GLDAS) and PET (CRU TS) values are found to in agreement with the satellite estimates. Necessary tables are added to the revised manuscript.



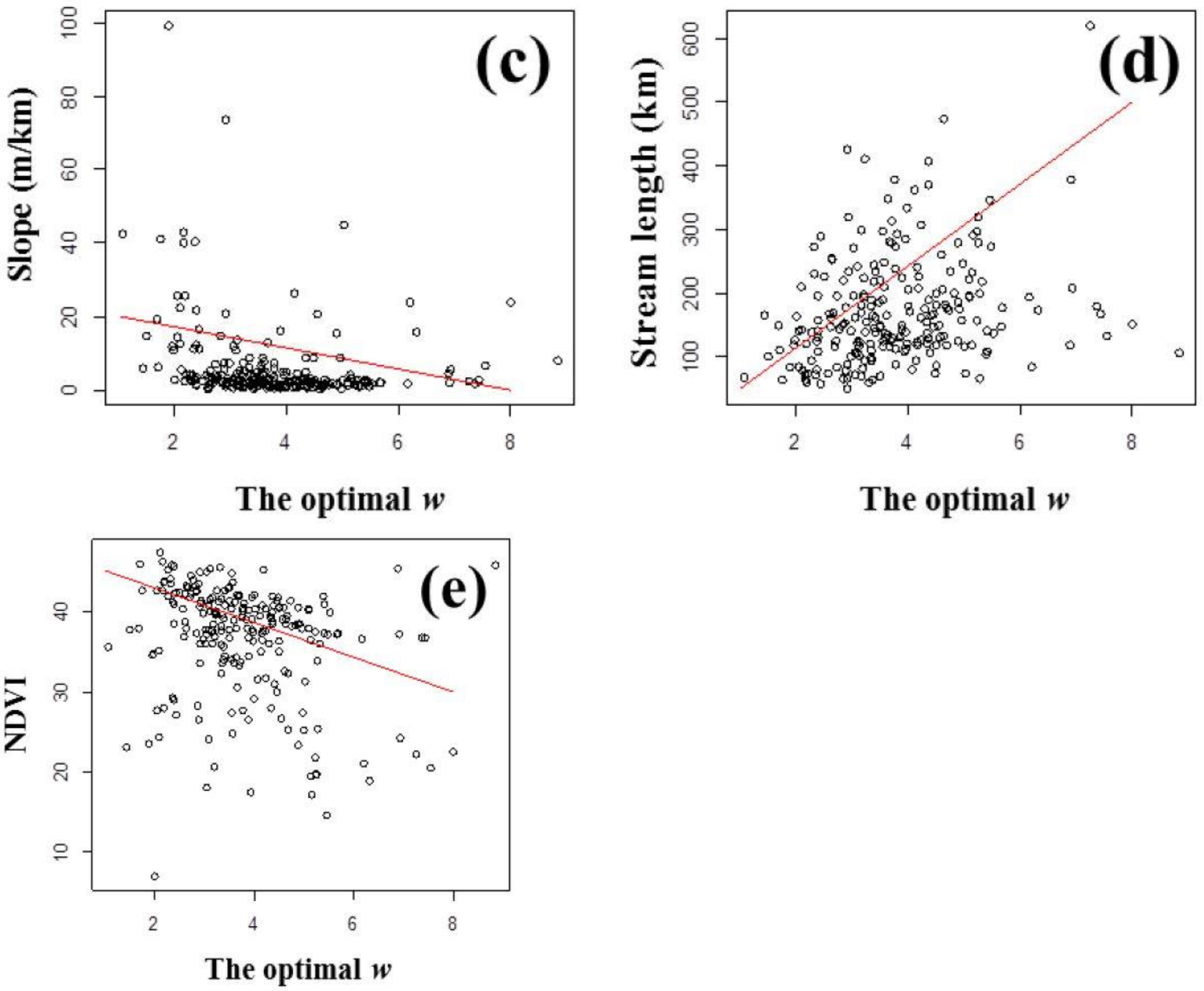


Figure 1: The relationship between basin characteristics and optimal w values (Source: Ahn and Merwade, 2017)

Table 1: 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

Minor Comment

Structure: The paper can be re-structured to improve clarity. Sections 2 and 4 have overlapping items, while ‘data’ generally goes better with ‘Study area’.

Reply: Review suggestions regarding modification of structure of the paper are duly considered in the revised manuscript. Our endeavor will be that the revised paper is much better than the current version.

References:

1. Ahn, K. H., and Merwade, V. (2017). “The Integrated Impact of Basin Characteristics on Changes in Hydrological Variables”, Book Chapter 12 in “*Sustainable Water Resources Management*”, American Society of Civil Engineers (ASCE), pp. 317-336. ISBN: 978-0-7844-1476-7.
2. Choudhury, B. (1999). “Evaluation of an empirical equation for annual evaporation using field observations and results from a biophysical model.” *Journal of Hydrology,* 216(1), 99-110.
3. Donohue, R. J., Roderick, M. L., and McVicar, T. R. (2012). “Roots, storms and soil pores: Incorporating key ecohydrological processes into Budyko’s hydrological model.” *Journal of Hydrology*, 436, 35-50.
4. Li, D., Pan, M., Cong, Z., Zhang, L., and Wood, E. (2013). “Vegetation control on water and energy balance within the Budyko framework.” *Water Resources Research*, 49(2), 969-976.
5. Maurya, A. S., Shah, M., Deshpande, R. D., Bhardwaj, R. M., Prasad, A., and Gupta, S. K. (2011). “Hydrograph separation and precipitation source identification using stable water isotopes and conductivity: River Ganga at Himalayan foothills.” *Hydrological Processes,* 25(10), 1521-1530.
6. Pai, D. S., Sridhar, L., Rajeevan, M., Sreejith, O. P., Satbhai, N. S., and Mukhopadhyay, B. (2014). “Development of a new high spatial resolution (0.25× 0.25) long period (1901–2010) daily gridded rainfall data set over India and its comparison with existing data sets over the region.” *Mausam*, 65(1), 1-18.
7. Srivastava, A. K., Rajeevan, M., and Kshirsagar, S. R. (2009). “Development of a high resolution daily gridded temperature data set (1969–2005) for the Indian region.” *Atmospheric Science Letters*, 10(4), 249-254.
8. Xu, X., Liu, W., Scanlon, B. R., Zhang, L., and Pan, M. (2013). “Local and global factors controlling water-energy balances within the Budyko framework.” *Geophysical Research Letters*, 40(23), 6123-6129.

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

Anoop Kumar Shukla[1], Shray Pathak[1], Lalit Pal[1], Chandra Shekhar Prasad Ojha[1], Ana Mijic[2], Rahul Dev Garg[1]

[1]Department of Civil Engineering, Indian Institute of Technology Roorkee, Uttarakhand, India

[2]Department of Civil and Environmental Engineering, Imperial College London, London, UK

E-mail- anoopgeomatics@gmail.com, shraypathak@gmail.com, lalitpl4@gmail.com, cspojha@gmail.com, ana.mijic@imperial.ac.uk, rdgarg@gmail.com

Field Code Changed

Formatted: No underline, Font color: Auto

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, attempts were made to consider a single value of some important model parameters which in fact show a variation at a pixel level scale. Therefore, in this study, the pixel level computations are performed to assess and ascertain their need 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 yields obtained at pixel scale.

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

1. Introduction

~~Efficient development and optimum utilization of water resources is of great significance to the overall development of any country. Many rivers, springs and lakes in the mountain regions are fed by the significant contribution of runoff from the snow melt and glacier melt. High spatial and temporal variability in hydro-metrological conditions in mountainous environments requires spatial models that are physically realistic and computationally efficient (Liston et al. 2006).~~

~~Hydrological ecosystem services (ES) often include drinking waters supply, power production, industrial use, irrigation, and many more. These hydrological ES are dependent on the characteristics of different watersheds such a topography, land use land cover (LULC), soil type and its climatic condition.~~

~~To quantify the impact of land-use and land management decisions on ecosystem services, a number of tools have been developed by various researchers (Bagstad et al. 2013). Accordingly, models for ecosystem service 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).~~

~~Due to the spatial variability and dependency on so many topographical and climatic factors, the proper analysis of ES happens to be a complicated task. 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 constitutes a major obstacle to the understanding of hydrological behavior at the catchment scales (Milly et al. 2002).~~

~~The literature indicates attempts to develop different ecosystem assessment tools. In this respect, Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST), developed by Natural Capital Project (Tallis et al. 2010) is worth mention. It includes a biophysical component, computing 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. This model is very simplified and is based upon the Budyko theory, which has a long history and still continues to receive interest in the hydrological literature (Budyko 1979; Zhou et al. 2012; Zhang et al. 2004; Ojha et al. 2008; Zhang et al. 2001; Donohue et al. 2012; Xu et al. 2013; Wang et al. 2014). The InVEST model applies a one-parameter formulation of the theory in a semi-distributed way (Zhang et al. 2004).~~

~~In literature, some of the limitations related to InVEST annual water yield model, are that there is an 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).~~

~~In 2012, the sensitivity analysis is done by Sanchez-Canales *et al.* using the InVEST model for a Mediterranean region basin for three parameters i.e. Z (seasonal precipitation coefficient), precipitation (annual) and ET$_0$ (annual reference precipitation) and found that precipitation as the most sensitive parameter. Later in 2014, Terrado et al., applied the InVEST model for the 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 the 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 taking 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. However, spatial variability of some of the model parameters is not accounted for in this work.~~

~~This work primarily considers in detail, the spatial variation of used model parameters and uses different strategies to compute water yield. Such water yield estimates are computed for four years i.e. 1980, 1990, 2001 and 2015 to identify most successful strategy. The parameters that are earlier computed at basins level scale are reduced to pixel level scale in order to study hydrological processes of catchment at pixel level to increase the efficiency of the results.~~

Accurate assessment of key ecosystem services (ES) such as water yield have gained focus in recent years in ecosystem service modelling as fresh water availability in a region are essential for agriculture, industry, human consumption, hydropower, etc. (Readhead et al., 2016). Hydrological ecosystem services often include drinking waters supply, power production, industrial use, irrigation, and many more. 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 ecosystem services 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 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 basins. Further, 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 constitutes a major obstacle to the understanding of hydrological behaviour at the catchment scales (Milly et al. 2002).

The Integrated Valuation of Ecosystem Services 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 ecosystem services and enables their comparison in various climate and land use change scenarios. It includes a biophysical component, computing 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. This model works on simplified Budyko theory, which has a long history and still continues to receive interest in the hydrological literature (Budyko 1979; Zhou et al. 2012; Zhang et al. 2004; Ojha et al. 2008; Zhang et al. 2001; Donohue et al. 2012; Xu et al. 2013; Wang et al. 2014). The InVEST model applies a one-parameter formulation of the theory in a semi-distributed way (Zhang et al. 2004). The model is capable of quantifying water yield of a catchment under the influence of change in drivers viz. climate variable and catchment characteristics (e.g. land use change). Various studies have been carried out in the past demonstrating application of InVEST model. 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 precipitation) using the InVEST model for a

Formatted: Font: Italic

Formatted: Subscript

Mediterranean region basin and found precipitation to be the most sensitive parameter for the study region. Later, Terrado et al. (2014) applied the InVEST model for the 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 the 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 taking 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. However, there exist certain factors limiting the application of InVEST models 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).

Formatted: Subscript

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 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 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 basins 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 accurate than output obtained using conventional approach. The term ‘finer scale’ in the paper represents 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 ~~is~~are described~~ as follows~~.

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 flows. It is based upon the Budyko theory which is an empirical function that yields the ratio of actual to potential evapotranspiration (Budyko, 1979). To describe the degree to which long-term catchment water-balances deviate from the theoretical limits, a 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~~parcel~~ -level changes to the landscape, InVEST model incorporates~~represents~~ explicitly the spatial variability in precipitation and PET, soil depth and vegetation. The model operates at grid scale ~~runs in the gridded format~~ and acquires the inputs in the raster format into a GIS environment such as ArcGIS. ~~which in turn helps to understand the heterogeneity of the factors influencing the water yield such as precipitation, land use land cover, soil type, etc. GIS and remote sensing plays a very crucial role in gathering the spatial and temporal information of any hydrological processes. GIS could be utilized as a suitable tool for solving water resources problems from local to global scale, spatially as well as temporally (Khatami et al. 2014).~~

The InVEST water yield model is based on an empirical function ~~which is~~ known as the Budyko curve (Budyko 1974). ~~The model takes the input as raster format and runs on the gridded map.~~ Water yield Y (x) is determined for each pixel annually for~~on~~ a landscape as follows:

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

~~W~~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 prevail 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 relationship between AET and PET, among which solution provided by Fu (1981) are 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.

~~Mean annual evapotranspiration of any catchment is strongly determined by precipitation and potential evapotranspiration. The secondary role is played by the catchment characteristics, i.e. soil, topography, etc.~~

The InVEST model uses the~~an~~ expression of the Budyko curve proposed by Fu (1981) and Zhang *et al.* (2004). The ratio of mean annual potential evapotranspiration to annual precipitation, known as index of dryness, is expressed as:~~can be used to determine the mean annual evapotranspiration by using one additional parameter.~~

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

~~W~~where, $PET\ (x)$ is the annual potential evapotranspiration per pixel x (mm); and w~~ω~~ (x) is a non-physical parameter that influences the natural climatic soil properties.

The $PET\ (x)$ is calculated using~~by~~ the following expression:

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

w~~W~~here, $ETo\ (x)$ is the annual reference evapotranspiration per pixel x which is calculated based on evapotranspiration of grass of alfalfa grown at that location shown in the equation (6). $Kc\ (x)$ is the vegetation evapotranspiration coefficient that is influenced by the change in characteristics of land use land cover for 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~~ω~~ (x) is an empirial parameter and the expression given by Donohue et al. (2012) for the InVEST model has been applied to define $\omega\ (x)$ which is as follows:

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

Thus, the minimum value of the parameter w~~ω~~ (x) is 1.25 corresponding to ~~for~~ bare soil where root depth is zero (Donohue et al. 2012) ~~which is evident from the above expression~~. The Donohue model was developed for Australia, however, the online documentation on InVEST model states its application globally. The ~~Other~~ parameter z is known as seasonality factor whose values vary 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 which is expressed in depth (mm) which can be expressed by following formula for each pixel x:

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

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 ~~F~~for computing the ~~pixel wise~~ reference evapotranspiration for the study area at pixel scale.~~, two methods are applied, i.e. modified Hargreaves method and Hargreaves method.~~

Modified Hargreaves method

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

w~~W~~here, ET$_o$ is reference evapotranspiration, T$_{avg}$ is average daily temperature (^{o}C) defined as the average of the mean daily maximum and mean daily minimum temperature, TD (^{o}C) 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

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

w~~W~~here, ET$_o$ is reference evapotranspiration, T$_{avg}$ is average daily temperature (^{o}C) defined as the average of the mean daily maximum and mean daily minimum temperature, TD (^{o}C) 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 ~~parameter~~ extraterrestrial radiation (RA), following equation is used ~~is shown in the equation (8).~~

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

w~~W~~here, 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 varies depending upon the local precipitation patterns such as the hydrological characteristics of the area, its rainfall intensity and topography. According to the InVEST water yield model ~~InVEST~~ (Tallis et al. 2010), ~~the~~ parameter z can be computed in three different ways. First method is suggested by Donohue *et al.* (2012), in which ~~that the~~ parameter z is ~~can be~~ expressed as the one fifth of the number of rain events per year. Second method is suggested by Xu *et al.* (2013), which relates $\omega(x)$ with latitude, NDVI (Normalized Difference Vegetation Index), ~~A~~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 to 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 all the mean values of the parameters are used as an input to compute the average value of the water yield for the whole watershed. In this model the averaged actual transpiration, potential evapotranspiration, w, precipitation is used as described by Zhang *et al.* (2004)

3. Study Area

~~In India, t~~The Gang~~a~~es river in India is rank~~ed~~s amongst the world's top 20 rivers in regards to the flow discharge. The ~~River~~ Ganga river is segregated into three zones, viz., Upper Ganga basin, Middle Ganga basin and Lower Ganga basin. The area choosen for the present study, i.e., Upper

Ganga river basin is situated in the n~~N~~orthern part of India within the geographical coordinates 30^0 38’ - 31^0 24’ N latitude and 78^0 29’ - 80^0 22’ E longitude with an area of 22,292.1 km^2 upto Haridwar.~~which encompasses an area of around 22,292.1 km^2~~. 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~~ the~~ entire region of the basin is under glacier landscape and 288 km^2 is under fluvial landscape. ~~The river basin of Ganga is located in the state of Uttarakhand, India within the geographical coordinates 30^0 38’ - 31^0 24’ N latitude and 78^0 29’ - 80^0 22’ E longitude with an area of 22,292.1 km^2 upto Haridwar.~~ About 60% of the basin is utilized for agricultural, 20% of the basin is under the forest area, especially ~~majorly~~ in the upper mountainous region.~~, and~~ N~~n~~early 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. ~~Due to favorable agricultural conditions majority of the population practices agriculture and horticulture. However, a large portion of the total population lives in cities along Ganga river.~~ In the Upper Ganga river basin, the average annual rainfall varies from 550 to 2500 mm (Bharati et al. 2011) and a major fraction of total annual rainfall is received during monsoon months (June-September). ~~part of the rains is due to the south-westerly monsoon that prevails from July to late September.~~ The geographical location and other information of the study area Upper Ganga river basin are represented in Fig. 1.

Formatted: Superscript

Formatted: Superscript

Formatted: Superscript

Formatted: Superscript

Formatted: Superscript

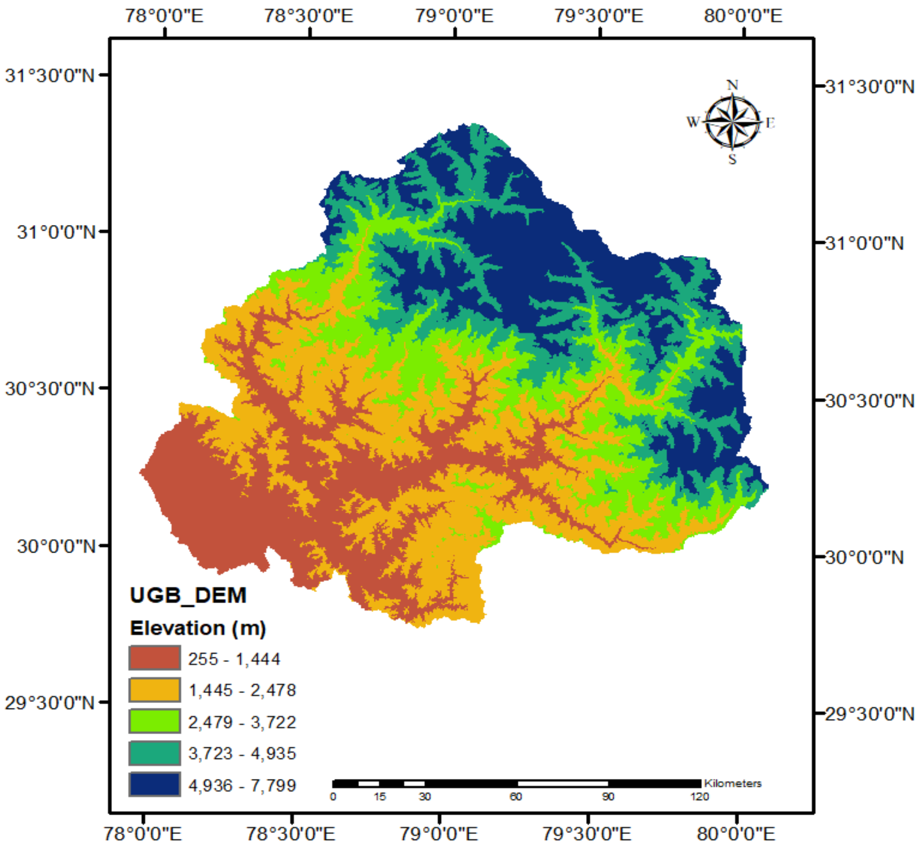


Figure 1. Graphical representation of study area, Upper Ganga basin

4. Methodology

4.1 Data

Formatted: Font: Italic

4.1.1Precipitation and Temperature

The daily time series ~~data~~ 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 ~~study area~~ Upper Ganga basin comes in the latitude ranging from 29.5 degrees to 31.5 degrees and longitude ranging from 77.75 degrees to 80.25 degrees. The daily time series of precipitation was aggregated to obtain the annual time series at each grid point. Various analysis in the study are carried out for four years ~~The data is extracted for all the four years,~~ i.e. 1980, 1990, 2001 and 2015.

4.1.2 Soil Map

Spatial maps~~Data~~ of soil were~~is~~ collected from National Bureau of soil survey and land use planning (NBSSLUP) at 1:250000. Digital maps of soil available at a resolution of 1200m×1200m were resampled to the resolution of land use data i.e. 30m×30m using ‘resample’ tool in ArcGIS in order to maintain the scale homogeneity. ~~The cell size of this data is 1200m×1200m which is different from that of land use data which has a cell size of 30m×30m. So this data is resampled using ‘resample’ tool in ArcGIS.~~ The attribute table of the raster~~vector~~ layer contains fields like soil depth, soil texture, percentage carbon content, drainage, slope, erosion, soil temperature and mineralogy. The relevant feature, i.e. of soil depth and soil texture are converted into the raster image for the Upper ganga basin.

4.1.3 LandUse/Land Cover map

~~Different sensors are used for obtaining the satellite images for different years. For the year 1980, 1990, 2001 and 2015, Landsat 3/4 ETM, Landsat 4 ETM, Landsat 7 and Landsat 8 ETM sensors are used to download the image.~~ Satellite images were acquired from different sensors of Landsat viz. Landsat 3/4 MSS/TM, Landsat 4 TM, Landsat 7 ETM and Landsat 8 OLI sensors for the year 1980, 1990, 2001 and 2015 respectively. The images are available at different resolution and for several bands out of which Green (G), Red (R) and Near Infrared (NIR) band images are combined to create False Colour Composite (FCC) for the study area in ERDAS Imagine.

~~These satellite images are different in their grid size and all the satellite data is taken as raw data from USGS. This data is available in form of different bands combinations and different resolutions depending upon the type of sensors. As per the type of sensors, the bands are stacked in ERDAS and a new stacked image is generated.~~ FCCs are then ~~This image is now~~ classified using supervised classification in ERDAS in six different classes, i.e. Forest, Water, Agricultural, Wasteland, Snow and Glacier and Built-up land. Classification of the area is based upon their similar response under different bands. Each class is then recognized with the help of ground truth and high resolution satellite images.

4.2 Methodology to compute water yield ~~involves the following steps.~~

In the present work, five different strategies are employed to compute water yield.. ~~For computing water yield five strategies are considered here.~~ For the ease of presentation, these strategies are referred as A, B, C, D, E. In strategy A, an average value of p~~P~~recipitation, t~~T~~emperature, e~~E~~xtraterrestrial r~~R~~adiation 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 particular variation of InVEST model where water yield is computed using different approach for estimating ‘w’ parameter. ~~“w” is estimated differently.~~ 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:

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

For global model:

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

w~~W~~here, *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 (equation 9) by Xu et al. (2013). 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. ~~considered pixel wise as all the hydrological parameters involved in the computations vary spatially.~~ 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, ~~other steps involving computation of Extraterrestrial Radiation, Precipitation, Temperature, Reference Evapotranspiration and Potential Evapotranspiration are briefly described as follows:~~

~~*4.2.1*~~ e~~E~~xtraterrestrial r~~R~~adiation (RA) ~~*(x)*~~

~~The value of this~~ parameter is computed ~~at a monthly interval in a raster format for different pixels~~ for each month using equation (8)~~.~~ and a raster layer is generated.

~~*4.2.2*~~ Precipitation~~; *P(x)*~~

~~The~~ data is obtained from Indian Meteorological Department (IMD) at grid size of 0.25 degree for the study area and has been interpreted and converted to raster format by using Inverse Distance

Formatted: Font: Italic

Formatted: Font: Italic

Formatted: Font: Italic

Formatted: Font: Italic

Formatted: Font: Italic

Formatted: Font: Italic

Formatted: Font: Not Italic

Formatted: Font: Not Italic

Formatted: Font: Not Italic

Formatted: Font: Not Italic

Weighted (IDW) ~~IWD~~ interpolation technique in ArcGIS environment for obtaining the values for all pixels at a resolution equal to the resolution of the ~~l~~Landsat satellite image ~~for the study area.~~ 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 at a resolution equal to the resolution of the Landsat satellite images. 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 Spline interpolation technique.

Formatted: Superscript

Formatted: Superscript

~~*4.2.3 Temperature T_{avg} (x) and TD (x)*~~

~~The temperature data is obtained from IMD at grid size 1 degree for the study area and has been interpreted and converted to raster format by using IWD interpolation technique for obtaining the values for all pixels at a resolution equal to the resolution of the landsat satellite image for the study area. Subsequently, the mean monthly value (T_{avg}) and the difference between mean daily maximum and mean daily minimum (TD) is obtained.~~ Gridded datasets of temperature and precipitation used in the present study has been developed using quality controlled stations and well-proven interpolation technique. Further details about the datasets are given in Srivastava et al. (2009) and Pai et al. (2014).

~~*4.2.4 Reference Evapotranspiration (ET_o)*~~

Modified Hargreaves method is applied for obtaining the values of reference evapotranspiration at each pixel ~~for the study area~~ for each month (Droogers et al. 2002). ~~It is calculated based on the~~

~~evapotranspiration of grass of the study area.~~ In this method, the inputs are R_a, 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 the negative values of reference evapotranspiration as obtained from ~~by applying~~ Modified Hargreaves method. Thus, for the above months the Hargreaves method~~,~~ as ~~previously~~ recommended by ~~(~~Droogers et al. (2002)~~,~~ is applied for obtaining the positive values for the reference evapotranspiration.

Thus, all the mean values for the month are added up to get the mean yearly values for the year 1980, 1990, 2001 and 2015.

~~*4.2.5 Potential Evapotranspiration PET (x)*~~

To computed potential evapotranspiration, ~~T~~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 vegetation evapotranspiration coefficient is taken from Allen *et al.* (1998) as shown in ~~. The~~ Table 1~~. shows the values taken for the coefficient of various classes of landuse/landcover~~. In this study, Kc is taken same for all the four years from Table. 1 and is used to obtain potential evapotranspiration which is subsequently used to obtain the yearly potential evapotranspiration 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

~~1. In this study, K_c is taken same for all the four years from Table. 1 and is used to obtain potential evapotranspiration which is subsequently used to obtain the yearly potential evapotranspiration at each pixel of the study area.~~

~~6.~~5. Results

~~6.1~~5.1 Reference Evapotranspiration, ~~;~~ ETo (x)

Reference Evapotranspiration 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 the study area~~ for each month (Droogers et al. 2002). The reference evapotranspiration is a function of R$_E$~~a~~, precipitation, Tavg and TD which are already computed pixel wise for each month for the year 1980, 1990, 2001 and 2015.

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~~d the~~ negative values of reference evapotranspiration ~~by~~on applying Modified Hargreaves method. Thus, for the above months, the Hargreaves method is applied for obtaining the positive results. Hence, all the mean values for the months are added up to get the mean yearly values of evapotranspiration for the years 1980, 1990, 2001 and 2015, as represented in Fig 2.

Formatted: Normal, Left, Line spacing: single, No bullets or numbering

Formatted: Font: (Default) Times New Roman, 12 pt

Formatted: List Paragraph, Left, Indent: Left: 0", Line spacing: single, Outline numbered + Level: 1 + Numbering Style: 1, 2, 3, … + Start at: 1 + Alignment: Left + Aligned at: 0.25" + Indent at: 0.5"

Formatted: Left

Formatted: Font: Bold

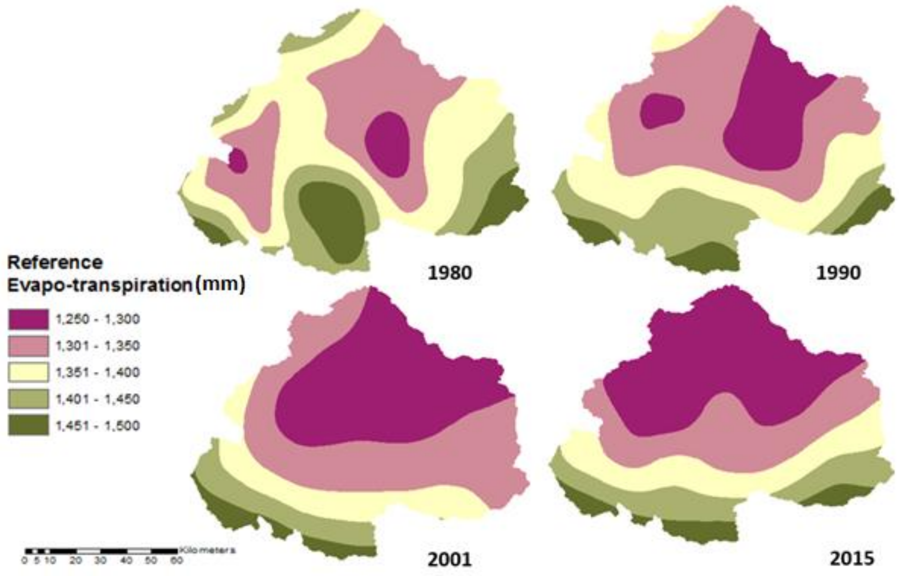


Figure 2. Reference Evapotranspiration (mm) of Upper Ganga Basin for the years 1980, 1990, 2001 and 2015.

~~6.2~~5.2 *Potential Evapotranspiration,~~;~~ PET (x)*

The annual ~~yearly~~ values obtained for the reference evapotranspiration 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 vegetation evapotranspiration coefficient 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.

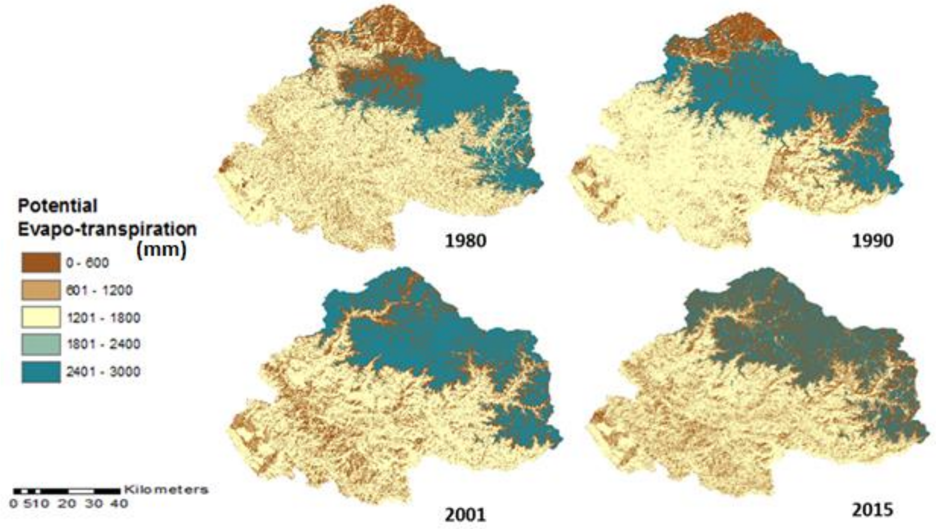


Figure 3. Potential Evapotranspiration (mm) of Upper Ganga Basin for the years 1980, 1990, 2001 and 2015.

5.3 Water Yield~~:~~, Y(x)

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

Strategy A: ~~By computing w~~Water yield computed using ~~from~~ Lumped Zhang Model

Here, the basin average ~~mean~~ values of all the input parameters are considered and the water yield is computed for the Upper Ganga basin for the year~~s~~ 1980, 1990, 2001 and 2015 which~~and~~ ~~is~~ 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~~the~~ 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~~the~~ years are represented in Fig. 4. The mean values of water yield as obtained using this method for the year~~s~~ 1980, 1990, 2001 and 2015 are 755.65 mm, 959.48 mm, 742.39 mm and 1131.42 mm respectively.

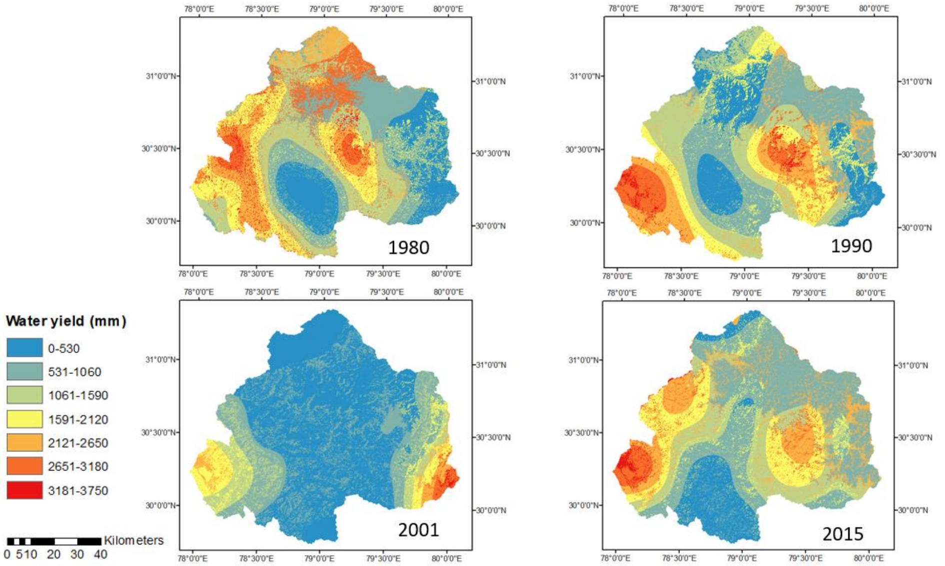


Figure 4. Water yield obtained by taking the single weighted mean value of parameter ‘~~“~~w’~~”~~ from Xu et al. (2013) for large basins.

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

By considering a~~the~~ single value of the parameter ‘~~“~~w’~~”~~ for the whole basin the water yield is computed for Upper Ganga basin (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 the years are shown~~represented~~ in Fig. 5. The mean values of water yield for the year~~s~~ 1980, 1990, 2001 and 2015 are 1239.92 mm, 1549.46 mm, 1149.93 mm and 1754.59 mm respectively.

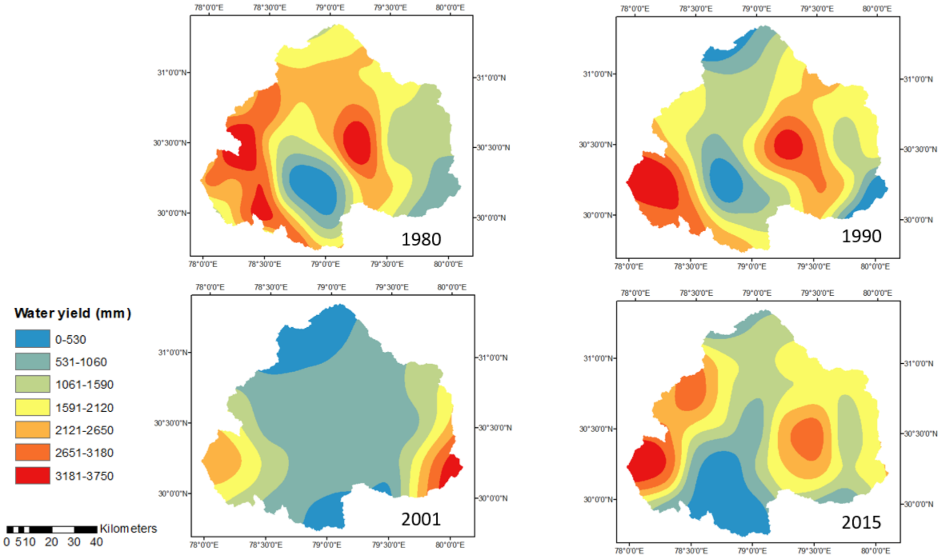


Figure 5. Water yield obtained by taking the single weighted mean value of parameter “w” from Xu et al. (2013) for global model.

Strategy D: Water yield obtained ~~by~~ using~~computing~~ pixel level estimation ~~wise value~~ of parameter ‘~~“~~w’~~”~~ from Xu et al. (2013)

In this strategy, ~~T~~the values of parameter ~~“~~‘w’~~”~~ is computed at pixel level. The water yield computed for the years 1980, 1990, 2001 and 2015 for the Upper Ganga Basin are represented in Fig. 6. The mean values of water yield for the year~~s~~ 1980, 1990, 2001 and 2015 are 1240.02 mm, 1549.44 mm, 1149.89 mm and 1754.62 mm respectively.

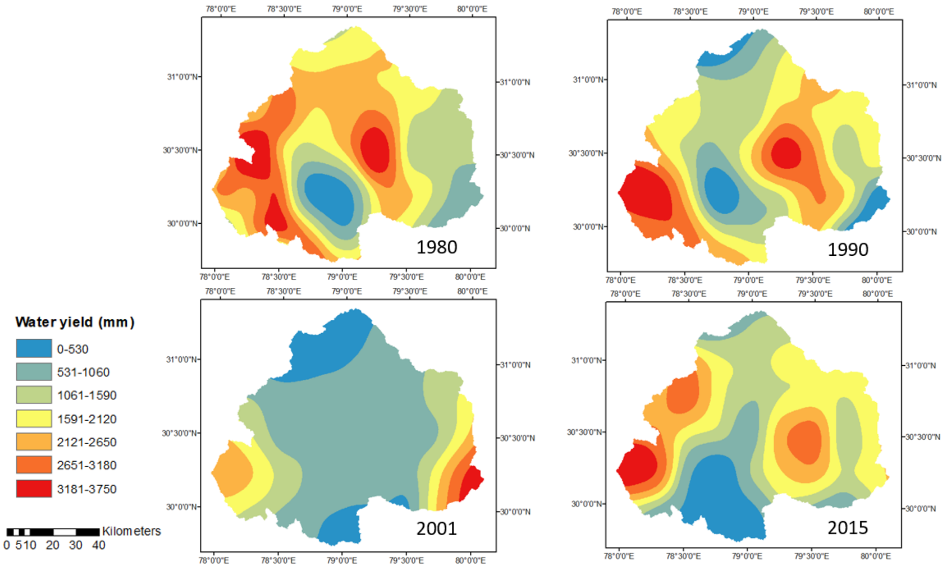


Figure 6. Water yield obtained by computing pixel wise value of parameter “w” from Xu et al. (2013)

Strategy E: Water yield obtained using ~~by computing~~ pixel level estimation ~~wise value~~ of parameter ‘~~“~~w~~”~~’ from Donohue et al. (2012)

The equation (4), represents the parameter ‘~~“~~w~~”~~’ which is a~~the~~ function of the parameters ‘z’, AWC and P. The parameter ‘w’ in the equation involved in strategy ‘E’ have been proposed by Donohue et al. (2012) which is also cited in online documentation of InVEST model, however, the final equation used for estimating water yield is from the InVEST model. Considering this fact, Donohue et al. (2012) has been cited in Strategy ‘E’.~~Thus, t~~The water yield is computed for Upper Ganga Basin for the years are shown in Fig. 7. The mean values of water yield for the years 1980, 1990, 2001 and 2015 are 1241.09 mm, 1552.38 mm, 1153.95 mm and 1753.53 mm respectively.

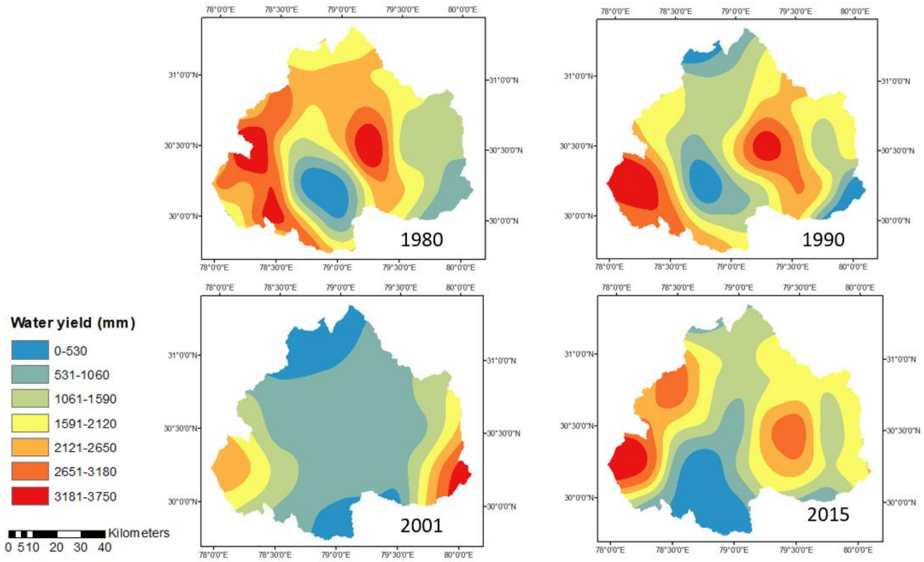


Figure 7. Water yield obtained by computing pixel wise value of parameter "w" from Donohue *et al.* (2012)

5.2 Validation of ~~results in sub-basin Rishikesh of Upper Ganga Basin.~~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 in agreement with the satellite estimated values. Spatial of Global datasets of AET and PET are shown in Figure 8 and 9, respectively.

Formatted: Superscript

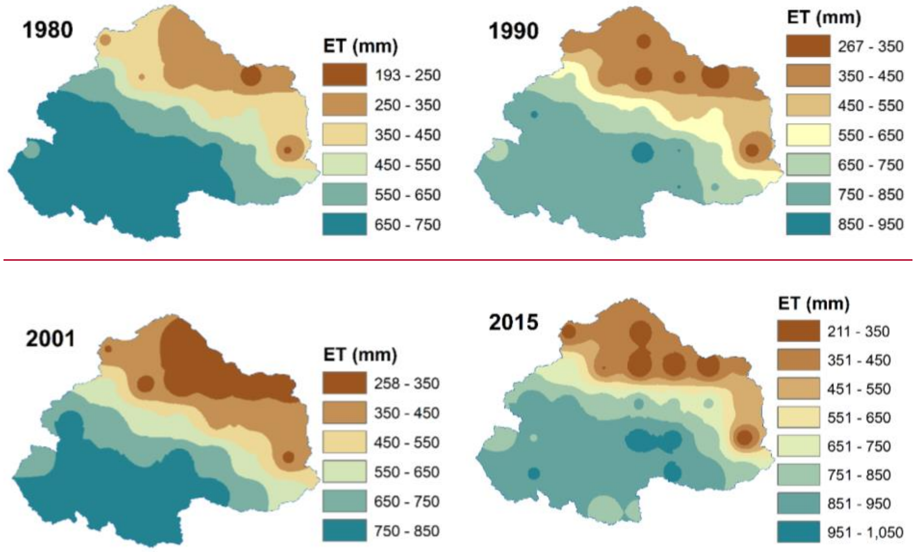


Figure 8. Spatial distribution of AET obtained from GLDAS Noah output datasets.

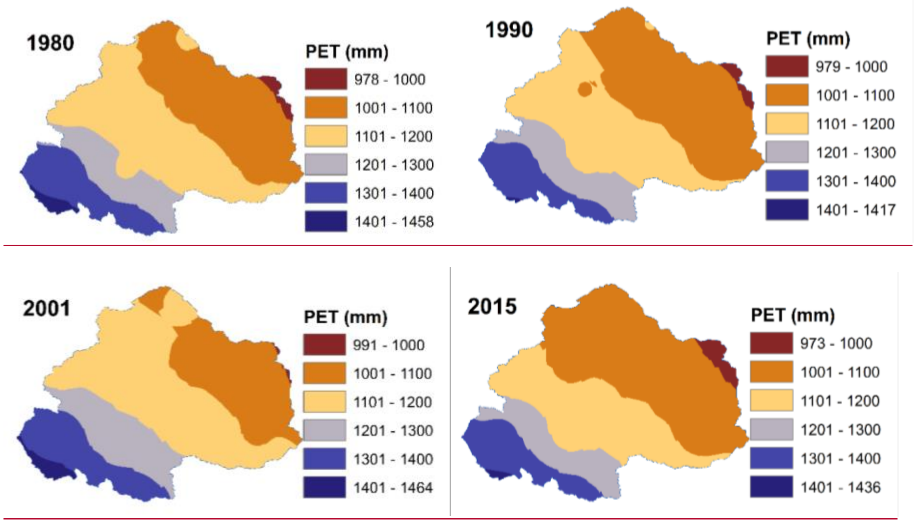


Figure 9. Spatial distribution of PET obtained from CRU datasets.

Formatted: Font: (Default) Times New Roman, 12 pt

Formatted: Font: (Default) Times New Roman, 12 pt, Not Bold

Formatted: Font: (Default) Times New Roman, 12 pt

Formatted: Font: (Default) Times New Roman, 12 pt

Formatted: Font: (Default) Times New Roman, 12 pt, Not Bold

Formatted: Font: (Default) Times New Roman, 12 pt

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

Formatted: Left

Formatted: Font: Not Bold

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 the water yield~~s~~ obtained from variou~~s~~s~~ proposed~~ strategies is~~are~~ performed upto~~for~~ Rishikesh gauging site~~(Fig. 8), a sub-basins~~ of Upper Ganga basin (Fig. 10). ~~As the data of the study area is classified and thus, the representation of complete data is forbidden.~~ The discharge data of the basin is obtained from Irrigation department of~~,~~ Uttarakhand state. ~~The surface runoff data is extracted from the snow melting data from the discharge data as the snow melting contributes about 32 percent in study area as suggested by Maurya et al. (2011).~~ Present work considers runoff from both precipitation as well as snowfall for the region, but 32% of the observed discharge has been removed as it is contributed by glacier ice melt to the streamflow for this catchment 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 snow melt contribution from that of the glacier melt (Maurya et al., 2011). A comprehensive work on water balance of Upper Ganga Basin has been discussed by Jain et al. (2017)~~, with reference to~~ (Table 4~~.,~~ in Jain et al., ~~(~~2017). For a p~~P~~recipitation value of 1236.1 mm, ~~G~~ground water contributes by an amount of~~flow of~~ 293.92 mm and snow melt contributes by 73.84 mm. It is apprehended that g~~G~~round water flow and snow melt equals to 367.76 mm which is approximately equals to 29.75 percent of Precipitation. Subsequently~~Indirectly~~, this percentage contribution is also supported by the value reported by Maurya et al. (2011). A comparison of ~~Thus,~~ the water yield computed and observed for the study region ~~has been validated~~ for different years by various proposed strategies are~~s~~ shown in Table 3~~2~~.

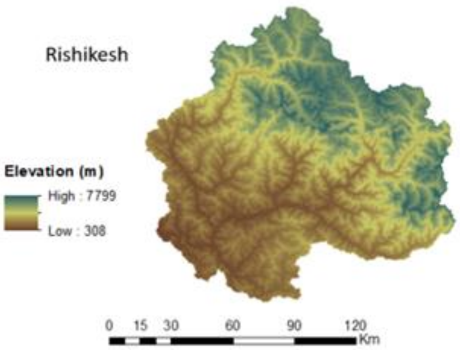


Figure 10~~8~~. Graphical representation of sub-basin Rishikesh

Table 3~~2~~. Observed vs computed water yield by various proposed strategies for Rishikesh sub-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

Formatted Table

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

Values of water yield estimated using strategy A to E are systematically increasing but are not steady in nature as water yield estimated using strategy A and B lies in range 650 – 750 mm whereas water yield from strategy C-E lies in range 1229 – 1231 mm for the year 1980 (see Table 3). Similar results are also evident for other years too. Also, water yield estimated using strategy C-E are more or less same for a given year as these strategies involve pixel based estimation of water yield considering spatial variation in Budyko parameters. Parameters involved in Budyko model such as ‘w’ are found to be dependent on various factors such as catchment characteristics, vegetation cover, etc. as well as climate seasonality (Li et al. 2013). Ahn and Merwade (2017) have analysed the relationship between basin characteristics and factor ‘w’ for 175 stations spread over the USA results are presented in Ahn and Merwade, (2017). As evident from their study, no precise conclusion can be drawn regarding relationship between basin characteristics and value of ‘w’ especially in case of basin area characteristics. Moreover, no straight forward relationship has yet been identified between basin characteristics and model parameters and it is a subject matter for further study.

Formatted: Justified

~~7.~~6. Discussion

The study aimed to apply the InVEST water yield model, a tool that is gaining interest in ecosystem services community for Upper Ganga Basin, having the variability in the topography and consisting of hilly areas, plain areas and the regions which are totally covered with snow. The

InVEST model is based upon Budyko theory which requires low amount of data and low level of expertise, thus making it acceptable world-wide. Monthly precipitation, monthly average value of temperature, monthly value of difference of mean daily maximum and mean daily minimum and extraterrestrial radiation parameters are computed for the Upper Ganga Basin for each month of all the four years i.e. 1980, 1990, 2001 and 2015 and converted into the raster format for the further analysis. The monthly reference evapotranspiration is thus computed using input parameters in the GIS environment by applying the modified Hargreaves equation for all the months except some months where the modified 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 the monthly values of different years are added up to obtain the yearly value of reference evapotranspiration. K_c is the 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. Thus, the yearly value of potential evapotranspiration is obtained for the study area for the years 1980, 1990, 2001 and 2015.

The paper focuses on all the methodologies 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’” are computed in 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. ~~The purpose to introduce the value of parameter “w” at pixel level so that it does not seem logical to compute a single value of parameter “w” for such a large basin.~~ Thus, two pixel wise values of parameter ‘~~“~~w’~~”~~ is computed for the Upper Ganga basin for years 1980, 1990, 2001 and 2015 by considering two approaches as given by ~~from~~ 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 indulged in the computations of water yield. Thus, in five ways water yield are computed for the Upper Ganga basin for the years 1980, 1990, 2001 and 2015.

At ~~For site~~ Rishikesh gauging site, ~~the contributing area to water yield is extracted from the Upper Ganga basin and the discharge data is taken from the irrigation department, Uttarakhand to compare the results. The~~ surface runoff data is obtained by extracting~~ed from~~ the snow melt~~ing data~~ from the discharge data as the snow melting contributes about 32 percent of total runoff~~in study area as suggested by~~ (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 represented in Table ~~2~~3.

The results obtained from Donohue et al. (2012) and Xu et al. (2013) computed at pixel level (Strategy C, Strategy D and Strategy E), thus represents better performance than other and are in good agreement with the observed data. It is clear that in order to go for~~do~~ hydrological processing for any watershed, pixel wise ~~classification and~~ computation is advisable ~~necessary~~. –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 few 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 ~~level~~ scale rather than adopting the mean values for entire watershed.

~~8.~~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~~with~~ low requirements for data, high ~~and~~ level of expertise are needed for practical applications ~~use~~ of such model as ~~with~~ a single representative value of model parameter for the entire basin does not provide good estimates of water yield. On the other hand, 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 ~~Regarding the use of parameter~~ ‘~~“~~w’ ~~”~~is concerned, global model works better than other representation of ‘~~“~~w~~”~~’ available in literature.

The water yield is computed using~~in~~ five different strategies~~ ways~~ and results are analyzed with the observed data of sub-basins of Upper Ganga Basin. The present study attempts to quantify annual water yield at pixel level irrespective of the size of catchment. Therefore, the proposed methodology is expected to perform well for the catchment of any given size. Changes in catchment's 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.

Thus it can~~is~~ inferred that: (i)~~,~~

~~1) B~~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) ~~.~~

Formatted: Normal, No bullets or numbering

~~2)~~ ~~I~~in pixel level based computations, results further improved with the use of ~~-~~a parameter ‘~~“~~w’~~”~~ based on ~~–~~a global model than regional models of ‘~~“~~w’~~”~~ for large basins in Himalayan basin.

Acknowledgement

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

References

Ahn, K. H., and Merwade, V. (2017). “The Integrated Impact of Basin Characteristics on Changes in Hydrological Variables”, Book Chapter 12 in “*Sustainable Water Resources Management*”, American Society of Civil Engineers (ASCE), pp. 317-336. ISBN: 978-0-7844-1476-7.

Allen, R. G., Pereira, L. S., Raes, D., and Smith, M. (1998). “Crop evapotranspiration-Guidelines for computing crop water requirements”-FAO Irrigation and drainage paper 56. FAO, Rome, 300(9), D05109.

Bai, Y., Ouyang, Y., and Pang, J. S. (2012). “Biofuel supply chain design under competitive agricultural land use and feedstock market equilibrium.” *Energy Economics*, 34(5), 1623-1633.

Berghuijs, W. R., Woods, R. A., and Hrachowitz, M. (2014). “A precipitation shift from snow towards rain leads to a decrease in streamflow.” *Nature Climate Change*, 4(7), 583-586.

Bharati, Luna, Guillaume Lacombe, Pabitra Gurung, Priyantha Jayakody, Chu Thai Hoanh, and Vladimir Smakhtin (2011). *The impacts of water infrastructure and climate change on the hydrology of the Upper Ganges River Basin*. Vol. 142. IWMI, 2011.

Budyko, M. (1958). *The Heat Balance of the Earth, Leningrad*, 1956 (in Russian), Translation by N. A. Stepanova, US Weather Bureau, Washington, p. 255.

Formatted: Font: Italic

Formatted: Font: Not Bold

Formatted: Font: Not Bold, Italic

Formatted: Font: Not Bold

Formatted: Font: Not Bold

Formatted: Font: Not Bold, Italic

Formatted: Font: Not Bold

Budyko, M. I. (1974). *Climate and Life*, Academic Press, New York, USA, 1-507.

Budyko, M. I., and Ronov, A. B. (1979). “Evolution of chemical composition of the atmosphere during the Phanerozoic.” *Geokhimiya*, (5), 643-653.

Burkhard, B., Crossman, N., Nedkov, S., Petz, K., and Alkemade, R. (2013). “*Mapping and modelling ecosystem services for science, policy and practice*. (4), 1-3.

Chen, X., Alimohammadi, N., and Wang, D. (2013). “Modeling interannual variability of seasonal evaporation and storage change based on the extended Budyko framework.” *Water Resources Research*, 49(9), 6067-6078.

Choudhury, B. (1999). “Evaluation of an empirical equation for annual evaporation using field observations and results from a biophysical model.” *Journal of Hydrology*, 216(1), 99-110.

Donohue, R. J., Roderick, M. L., and McVicar, T. R. (2006). “On the importance of including vegetation dynamics in Budyko? s hydrological model.” *Hydrology and Earth System Sciences Discussions*, 3(4), 1517-1551.

Donohue, R. J., Roderick, M. L., and McVicar, T. R. (2012). “Roots, storms and soil pores: Incorporating key ecohydrological processes into Budyko’s hydrological model.” *Journal of Hydrology*, 436, 35-50.

Droogers, P., and Allen, R. G. (2002). “Estimating reference evapotranspiration under inaccurate data conditions.” *Irrigation and drainage systems*, 16(1), 33-45.

Fu, B. P. (1981). “On the calculation of the evaporation from land surface.” *Sci. Atmos. Sin*, 5(1), 23-31.

Formatted: Font: Not Bold

Formatted: Font: Not Bold, Italic

Formatted: Font: Not Bold

Formatted: Font: Not Bold

Formatted: Font: Not Bold, Italic

Formatted: Font: Not Bold

Formatted: Font: Italic

Gentine, P., D'Odorico, P., Lintner, B. R., Sivandran, G., and Salvucci, G. (2012). "Interdependence of climate, soil, and vegetation as constrained by the Budyko curve." *Geophysical Research Letters*, 39(19), L19404.

Goyal, M. K., and Khan, M. (2017). "Assessment of spatially explicit annual water-balance model for Sutlej River Basin in eastern Himalayas and Tungabhadra River Basin in peninsular India." *Hydrology Research*, 48(2), 542-558.

Guswa, A. J., Brauman, K. A., Brown, C., Hamel, P., Keeler, B. L., and Sayre, S. S. (2014). "Ecosystem services: Challenges and opportunities for hydrologic modeling to support decision making." *Water Resources Research*, 50(5), 4535-4544.

Hamel, P., and Guswa, A. J. (2014). "Uncertainty analysis of a spatially-explicit annual water-balance model: case study of the Cape Fear catchment, NC." *Hydrology and Earth System Sciences*, 11, 11001-11036.

Hoyer, R., and Chang, H. (2014). "Assessment of freshwater ecosystem services in the Tualatin and Yamhill basins under climate change and urbanization." *Applied Geography*, 53, 402-416.

Jain, S. K., Jain, S. K., Jain, N., and Xu, C. Y. (2017). "Hydrologic modeling of a Himalayan mountain basin by using the SWAT model." *Hydrology and Earth System Sciences*, *https://doi.org/10.5194/hess-2017-100*

Khatami, S., and Khazaei, B. (2014). "Benefits of GIS Application in Hydrological Modeling: A Brief summary." *VATTEN–Journal of Water Management and Research*, 70, 41-49.

Li, D., Pan, M., Cong, Z., Zhang, L., and Wood, E. (2013). "Vegetation control on water and energy balance within the Budyko framework." *Water Resources Research*, 49(2), 969-976.

Formatted: Font: Not Bold

Formatted: Font: Not Bold, Italic

Formatted: Font: Not Bold

Formatted: Font: Italic

Liston, G. E., and Elder, K. (2006). “A distributed snow-evolution modeling system (SnowModel).” *Journal of Hydrometeorology*, 7(6), 1259-1276.

Ma, Z. M., S. Z. Kang, L. Zhang, L. Tong, and X. L. Su (2008). “Analysis of impacts of climate variability and human activity on streamflow for a river basin in arid region of northwest China.” *Journal of Hydrology*, 352(3–4), 239–249.

Maurya, A. S., Shah, M., Deshpande, R. D., Bhardwaj, R. M., Prasad, A., and Gupta, S. K. (2011). “Hydrograph separation and precipitation source identification using stable water isotopes and conductivity: River Ganga at Himalayan foothills.” *Hydrological Processes*, 25(10), 1521-1530.

McKenzie, N. J., Gallant, J., and Gregory, L. (2003). “*Estimating water storage capacities in soil at catchment scales*.” CRC for Catchment Hydrology.

Mezentsev, V. (1955). “More on the computation of total evaporation (Yechio raz o rastchetie srednevo summarnovo ispareniia)” *Meteorog. i Gridrolog.*, 5, 24–26, 1955.

Milly, P. C. D. (1994). “Climate, soil water storage, and the average annual water balance.” *Water Resources Research*, 30(7), 2143-2156.

Milly, P. C. D., and Dunne, K. A. (2002). “Macroscale water fluxes 2. Water and energy supply control of their interannual variability.” *Water Resources Research*, 38(10), 241-249.

Nelson, E., Sander, H., Hawthorne, P., Conte, M., Ennaanay, D., Wolny, S., ... and Polasky, S. (2010). “Projecting global land-use change and its effect on ecosystem service provision and biodiversity with simple models.” *PloS one*, 5(12), E14327.

Formatted: Font: Italic

Formatted: Font: Italic

Formatted: Font: Not Bold

Formatted: Font: Not Bold, Italic

Formatted: Font: Not Bold

Formatted: Font: Not Bold, Italic

Formatted: Font: Not Bold

Ning, T., Li, Z., and Liu, W. (2017). "Vegetation dynamics and climate seasonality jointly control the interannual catchment water balance in the Loess Plateau under the Budyko framework." *Hydrology and Earth System Sciences*, 21, 1515-1526

Ojha C.S.P., Bhunya P., and Berndtsson R. (2008). *Engineering Hydrology*, 1st Ed., Oxford University Press, UK, 1-459.

Ol'Dekop, E. M. (1911). *On Evaporation from the Surface of River Basins*, Univ. of Tartu, Tartu, Estonia, p. 209.

Pai, D. S., Sridhar, L., Rajeevan, M., Sreejith, O. P., Satbhai, N. S., and Mukhopadhyay, B. (2014). "Development of a new high spatial resolution (0.25× 0.25) long period (1901–2010) daily gridded rainfall data set over India and its comparison with existing data sets over the region." *Mausam*, 65(1), 1-18.

Pike, J. G. (1964). "The estimation of annual run-off from meteorological data in a tropical climate." *Journal of Hydrology*, 2(2), 116-123.

Porporato, A., Daly, E., and Rodriguez-Iturbe, I. (2004). "Soil water balance and ecosystem response to climate change." *The American Naturalist*, 164(5), 625-632.

Potter, N. J., Zhang, L., Milly, P. C. D., McMahon, T. A., and Jakeman, A. J. (2005). "Effects of rainfall seasonality and soil moisture capacity on mean annual water balance for Australian catchments." *Water Resources Research*, 41(6), 1-11.

Rouholahnejad Freund, E. and Kirchner, J. W. (2017). "A Budyko framework for estimating how spatial heterogeneity and lateral moisture redistribution affect average evapotranspiration rates as seen from the atmosphere." *Hydrology and Earth System Sciences*, 21, 217-233

Formatted: Font: Not Bold

Formatted: Font: Not Bold, Italic

Formatted: Font: Not Bold

Formatted: Font: Italic

Formatted: Font: Not Bold

Formatted: Font: Not Bold, Italic

Formatted: Font: Not Bold

Formatted: Font: Not Bold, Italic

Formatted: Font: Not Bold

Formatted: Font: Not Bold, Italic

Formatted: Font: Not Bold

Sánchez-Canales, M., Benito, A. L., Passuello, A., Terrado, M., Ziv, G., Acuña, V., ... and Elorza, F. J. (2012). “Sensitivity analysis of ecosystem service valuation in a Mediterranean watershed.” *Science of the total environment*, 440, 140-153.

Schreiber, P. (1904). “Über die Beziehungen zwischen dem Niederschlag und der Wasserführung der Flüsse in Mitteleuropa.” *Z. Meteorol*, 21(10), 441-452.

Shao, Q., Traylen, A., and Zhang, L. (2012). “Nonparametric method for estimating the effects of climatic and catchment characteristics on mean annual evapotranspiration.” *Water Resources Research*, 48(3), W03517.

Srivastava, A. K., Rajeevan, M., and Kshirsagar, S. R. (2009). “Development of a high resolution daily gridded temperature data set (1969–2005) for the Indian region.” *Atmospheric Science Letters*, 10(4), 249-254.

Su, C., and Fu, B. (2013). “Evolution of ecosystem services in the Chinese Loess Plateau under climatic and land use changes.” *Global and Planetary Change*, 101, 119-128.

Tallis, H.T., Ricketts, T., Nelson, E., Ennaanay, D., Wolny, S., Olwero, N., Vigerstol, K., Pennington, D., Mendoza, G., Aukema, J. and Foster, J., (2010). *InVEST 1.004 beta User’s Guide*. The Natural Capital Project.

Terrado, M., Acuña, V., Ennaanay, D., Tallis, H., and Sabater, S. (2014). “Impact of climate extremes on hydrological ecosystem services in a heavily humanized Mediterranean basin.” *Ecological Indicators*, 37, 199-209.

Turc, L. (1954). “Le bilan d’eau des sols: relations entre les précipitations, l’évaporation et l’écoulement.” *Annales Agronomiques A*, 20, 491–595.

Formatted: Font: Not Bold

Formatted: Font: Not Bold, Italic

Formatted: Font: Not Bold

Formatted: Font: Not Bold, Italic

Formatted: Font: Not Bold

Formatted: Font: Italic

Formatted: Font: Not Bold

Formatted: Font: Not Bold, Italic

Formatted: Font: Not Bold

Formatted: Font: Not Bold

Wang, D., and Tang, Y. (2014). “A one-parameter Budyko model for water balance captures emergent behavior in darwinian hydrologic models.” *Geophysical Research Letters*, 41(13), 4569-4577.

Wang, X.-S. and Zhou, Y. (2017). “Shift of annual water balance in the Budyko space for catchments with groundwater-dependent evapotranspiration.” *Hydrology and Earth System Sciences*, 20, 3673-3690

Williams, C. A., Reichstein, M., Buchmann, N., Baldocchi, D., Beer, C., Schwalm, C., ... and Papale, D. (2012). “Climate and vegetation controls on the surface water balance: Synthesis of evapotranspiration measured across a global network of flux towers.” *Water Resources Research*, 48(6), W06523.

Xu, X., Liu, W., Scanlon, B. R., Zhang, L., and Pan, M. (2013). “Local and global factors controlling water-energy balances within the Budyko framework.” *Geophysical Research Letters*, 40(23), 6123-6129.

Yang, D., Sun, F., Liu, Z., Cong, Z., Ni, G., and Lei, Z. (2007). “Analyzing spatial and temporal variability of annual water-energy balance in nonhumid regions of China using the Budyko hypothesis.” *Water Resources Research*, 43(4), W04426.

Yang, H., Yang, D., Lei, Z., and Sun, F. (2008). “New analytical derivation of the mean annual water-energy balance equation.” *Water Resources Research*, 44(3), W03410.

Zhang, L., Dawes, W. R., and Walker, G. R. (2001). “Response of mean annual evapotranspiration to vegetation changes at catchment scale.” *Water resources research*, 37(3), 701-708.

Formatted: Font: Not Bold

Formatted: Font: Not Bold, Italic

Formatted: Font: Not Bold

Formatted: Font: Not Bold

Formatted: Font: Not Bold, Italic

Formatted: Font: Not Bold

Formatted: Font: Not Bold

Formatted: Font: Not Bold, Italic

Formatted: Font: Not Bold

Zhang, L., Hickel, K., Dawes, W. R., Chiew, F. H., Western, A. W., and Briggs, P. R. (2004). “A rational function approach for estimating mean annual evapotranspiration.” *Water Resources Research*, 40(2), W02502.

Zhang, L., N. Potter, K. Hickel, Y. Q. Zhang, and Q. X. Shao (2008). “Water balance modeling over variable time scales based on the Budyko framework–Model development and testing.” *Journal of Hydrology*, 360(1–4), 117–131.

Zhou, G., Wei, X., Chen, X., Zhou, P., Liu, X., Xiao, Y., ... and Su, Y. (2015). “Global pattern for the effect of climate and land cover on water yield.” *Nature communications*, 6, 5918.

Zhou, S., Yu, B., Huang, Y., and Wang, G. (2015). “The complementary relationship and generation of the Budyko functions.” *Geophysical Research Letters*, 42(6), 1781-1790.

Zhou, X., Zhang, Y., Wang, Y., Zhang, H., Vaze, J., Zhang, L., ... and Zhou, Y. (2012). “Benchmarking global land surface models against the observed mean annual runoff from 150 large basins.” *Journal of Hydrology*, 470, 269-279.

~~Allen, R. G., Pereira, L. S., Raes, D., and Smith, M. (1998). “Crop evapotranspiration-Guidelines for computing crop water requirements” FAO Irrigation and drainage paper 56. FAO, Rome, 300(9), D05109.~~

~~Bai, Y., Ouyang, Y., and Pang, J. S. (2012). “Biofuel supply chain design under competitive agricultural land use and feedstock market equilibrium.” *Energy Economics*, 34(5), 1623-1633.~~

~~Bharati, Luna, Guillaume Lacombe, Pabitra Gurung, Priyantha Jayakody, Chu Thai Hoanh, and Vladimir Smakhtin (2011). *The impacts of water infrastructure and climate change on the hydrology of the Upper Ganges River Basin*. Vol. 142. IWMI, 2011.~~

Formatted: Font: Not Bold

Formatted: Font: Not Bold, Italic

Formatted: Font: Not Bold

Formatted: Font: Not Bold, Italic

Formatted: Font: Not Bold

~~Budyko, M. I. (1974). *Climate and Life*, Academic Press, New York, USA, 1-507.~~

~~Budyko, M. I., and Ronov, A. B. (1979). "Evolution of chemical composition of the atmosphere during the Phanerozoic." *Geokhimiya*, (5), 643-653.~~

~~Burkhard, B., Crossman, N., Nedkov, S., Petz, K., and Alkemade, R. (2013). "*Mapping and modelling ecosystem services for science, policy and practice*.1-3.~~

~~Choudhury, B. (1999). "Evaluation of an empirical equation for annual evaporation using field observations and results from a biophysical model." *Journal of Hydrology*, 216(1), 99-110.~~

~~Donohue, R. J., Roderick, M. L., and McVicar, T. R. (2012). "Roots, storms and soil pores: Incorporating key ecohydrological processes into Budyko's hydrological model." *Journal of Hydrology*, 436, 35-50.~~

~~Droogers, P., and Allen, R. G. (2002). "Estimating reference evapotranspiration under inaccurate data conditions." *Irrigation and drainage systems*, 16(1), 33-45.~~

~~Fu, B. P. (1981). "On the calculation of the evaporation from land surface." *Sci. Atmos. Sin*, 5(1), 23-31.~~

~~Goyal, M. K., and Khan, M. (2017). "Assessment of spatially explicit annual water-balance model for Sutlej River Basin in eastern Himalayas and Tungabhadra River Basin in peninsular India." *Hydrology Research*, 48(2), 542-558.~~

~~Guswa, A. J., Brauman, K. A., Brown, C., Hamel, P., Keeler, B. L., and Sayre, S. S. (2014). "Ecosystem services: Challenges and opportunities for hydrologic modeling to support decision making." *Water Resources Research*, 50(5), 4535-4544.~~

~~Hamel, P., and Guswa, A. J. (2014). "Uncertainty analysis of a spatially explicit annual water-balance model: case study of the Cape Fear catchment, NC." *Hydrology and Earth System Sciences*, 11, 11001-11036.~~

~~Hoyer, R., and Chang, H. (2014). "Assessment of freshwater ecosystem services in the Tualatin and Yamhill basins under climate change and urbanization." *Applied Geography*, 53, 402-416.~~

~~Jain, S. K., Jain, S. K., Jain, N., and Xu, C. Y. (2017). "Hydrologic modeling of a Himalayan mountain basin by using the SWAT mode." *Hydrology and Earth System Sciences*, *https://doi.org/10.5194/hess-2017-100*~~

~~Khatami, S., and Khazaei, B. (2014). "Benefits of GIS Application in Hydrological Modeling: A Brief summary." *VATTEN Journal of Water Management and Research*, 70, 41-49.~~

~~Liston, G. E., and Elder, K. (2006). "A distributed snow-evolution modeling system (SnowModel)." *Journal of Hydrometeorology*, 7(6), 1259-1276.~~

~~Maurya, A. S., Shah, M., Deshpande, R. D., Bhardwaj, R. M., Prasad, A., and Gupta, S. K. (2011). "Hydrograph separation and precipitation source identification using stable water isotopes and conductivity: River Ganga at Himalayan foothills." *Hydrological Processes*, 25(10), 1521-1530.~~

~~McKenzie, N. J., Gallant, J., and Gregory, L. (2003). "Estimating water storage capacities in soil at catchment scales." CRC for Catchment Hydrology.~~

~~Milly, P. C. D., and Dunne, K. A. (2002). "Macroscale water fluxes 2. Water and energy supply control of their interannual variability." *Water Resources Research*, 38(10).~~

~~Nelson, E., Sander, H., Hawthorne, P., Conte, M., Ennaanay, D., Wolny, S., ... and Polasky, S. (2010). "Projecting global land use change and its effect on ecosystem service provision and biodiversity with simple models." *PloS one*, 5(12), e14327.~~

~~Ojha C.S.P., Bhunya P., and Berndtsson R. (2008). *Engineering Hydrology*, 1st Ed., Oxford University Press, UK, 1-459.~~

~~Sánchez-Canales, M., Benito, A. L., Passuello, A., Terrado, M., Ziv, G., Acuña, V., ... and Elorza, F. J. (2012). "Sensitivity analysis of ecosystem service valuation in a Mediterranean watershed." *Science of the total environment*, 440, 140-153.~~

~~Su, C., and Fu, B. (2013). "Evolution of ecosystem services in the Chinese Loess Plateau under climatic and land use changes." *Global and Planetary Change*, 101, 119-128.~~

~~Tallis, H.T., Ricketts, T., Nelson, E., Ennaanay, D., Wolny, S., Olwero, N., Vigerstol, K., Pennington, D., Mendoza, G., Aukema, J. and Foster, J., (2010). *InVEST 1.004 beta User's Guide*. The Natural Capital Project.~~

~~Terrado, M., Acuña, V., Ennaanay, D., Tallis, H., and Sabater, S. (2014). "Impact of climate extremes on hydrological ecosystem services in a heavily humanized Mediterranean basin." *Ecological Indicators*, 37, 199-209.~~

~~Wang, D., and Tang, Y. (2014). "A one-parameter Budyko model for water balance captures emergent behavior in darwinian hydrologic models." *Geophysical Research Letters*, 41(13), 4569-4577.~~

~~Xu, X., Liu, W., Scanlon, B. R., Zhang, L., and Pan, M. (2013). “Local and global factors controlling water-energy balances within the Budyko framework.” *Geophysical Research Letters*, 40(23), 6123-6129.~~

~~Zhang, L., Dawes, W. R., and Walker, G. R. (2001). “Response of mean annual evapotranspiration to vegetation changes at catchment scale.” *Water resources research*, 37(3), 701-708.~~

~~Zhang, L., Hickel, K., Dawes, W. R., Chiew, F. H., Western, A. W., and Briggs, P. R. (2004). “A rational function approach for estimating mean annual evapotranspiration.” *Water Resources Research*, 40(2).~~

~~Zhou, X., Zhang, Y., Wang, Y., Zhang, H., Vaze, J., Zhang, L., ... and Zhou, Y. (2012). “Benchmarking global land surface models against the observed mean annual runoff from 150 large basins.” *Journal of Hydrology*, 470, 269-279.~~