Improving the Budyko framework to better understand the drivers of interannual variability in water cycle

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Submitted By : Dr. Pushkar Ajaykumar Sharma
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Submission Date : 10-Aug-2023

PROPOSAL DETAILS

(PDF/2023/002763)

Principal Investigator	Mentor & Host Institution
Dr. Pushkar Ajaykumar Sharma pushkarsharma2014@gmail.com Research Associate(Interdisciplinary Centre for Water Research (ICWaR)) **Contact No** : +919106327724 **Date of Birth** : 25-Jan-1991 **Name of Father/Spouse :** Ajaykumar Sharma	**Bramha Dutt Vishwakarma** bramha@iisc.ac.in Assistant Professor(Interdisciplinary Centre for Water Research) **Indian Institute of Science** Cv raman rd, bengaluru, Bangalore urban district, Karnataka-560012 **Contact No.** : +919886149639 **Registrar Email** : registrar@iisc.ac.in **No. of PHD Scholars** : 5 **No. Post-Doctoral Fellow** : 1

Details of Post Doctorate

Ph.D. (Climate change, Hydrology)[Degree Awarded on : 03-Apr-2023]

Quantifying Climate and Catchment Effects on Streamflow Using Budyko Framework

Research Supervisor/Guide & Institution :

Dr. Arpita Mondal, Associate Professor, Indian Institute of Technology Bombay (IITB), Mumbai-400076
Indian Institute of Technology Bombay (IITB)

Brief details of Thesis work :

Quantifying the impacts of climate change and catchment activities on streamflow is necessary for long-term planning towards ensuring water security, particularly in water-stressed regions such as India. Climate change is expected to manifest in terms of altered precipitation and potential evapotranspiration, whereas direct catchment effect on streamflow results in changes in the partitioning of precipitation into evapotranspiration and runoff. Several methods are available for separating the individual impacts of climate change and catchment activities on streamflow variability. These techniques can be broadly classified into process-driven models, field experiments and empirical approach. Budyko-based methods comprise an empirical approach and have been widely used for such quantification due to their simplicity and efficacy. These methods divide the historical records into two periods based on observed or estimated changes- Period-1 and Period-2, and study the movement of the catchment from Period-1 to Period-2.
The work in the thesis first presents a comprehensive appraisal of the different equations and methods available under Budyko framework for segregation of climate and catchment effects. A comparison of such methods is done on four suitably chosen Model Parameter Estimation Experiment (MOPEX) catchments in the contiguous United States. This study delineates the sensitivities to the quantification method, generating function, and approximation technique available under the Budyko framework for such segregation. Additionally, the study summarizes critical assumptions, significance and limitations of the existing Budyko based quantification methods. Our findings show that the climate and catchment effect on streamflow for a catchment is sensitive to the selected disaggregation algorithm leading to variations in the estimated contribution. Thus, it is vital to take into account the uncertainty in the results since different methods and equations provide varying outcomes.
Budyko's hypothesis incorporates a catchment parameter and is calibrated using precipitation, potential evapotranspiration and streamflow averaged over long time series. The catchment parameter in the Budyko equation basically decides the shape of the Budyko curve and is of critical importance in estimating the streamflow of the catchment for a given aridity index. The uncertainty involved in the catchment parameter due to the varying climatic conditions needs to be addressed for quantification of climate and catchment effects on streamflow under the Budyko framework. The thesis proposes a new improved Two-stage Decomposition method to separate the role of climate and catchment changes on streamflow, considering the uncertainty in the catchment parameter. Here, the catchment parameter can be expressed probabilistically, to account for the uncertainty because of limited hydro-meteorological records. The proposed approach employs a bootstrap analysis to obtain the stochastic range of the catchment parameter, considering different choices of Budyko equations that further leads to a range of evaporative index values. Additionally, the range of evaporative indices derived for a catchment is utilized to predict the potential range of climate and catchment changes effects on streamflow. We argue that rather than relying on a single Budyko-based approach for separation of climate and catchment effects on streamflow, the proposed method offers a more robust way by considering the entire range of uncertainty of the catchment parameter.
Budyko framework for separating the climate and catchment effects on streamflow have been used in many studies for the historical periods. However, the Budyko framework has not been explored to check the streamflow response to climate and catchment effects for future socioeconomic scenarios. In the thesis, an approach under Budyko framework is proposed for the separation of climate and catchment effects on streamflow for future scenarios. Here we have developed a Generalized Linear Model (GLM) for estimating Budyko parameter which depends on various variables of climate and catchment features. Climate Model Intercomparison Project Version 6 (CMIP6) and Land Use Harmonization 2 (LUH2) dataset is used for future projections and the Budyko parameter is estimated for future socioeconomic scenarios SSP126, SSP245, SSP370 and SSP585. The effects of climate and catchment changes are quantified using the Two-stage Decomposition method for three time windows - the recent historical past, the near-future (2031-2065), and the far-future (2066-2100), using 1948-1970 as the baseline period. Our results show that the relative contributions of climate and catchment changes on streamflow can act with or against each other over time depending on catchment hydrology, and our proposed framework is capable of capturing such dynamic contributions.

Technical Details :

Research Area : Earth & Atmospheric Sciences (Earth & Atmospheric Sciences)

Project Summary :

The spatiotemporal pattern of the global terrestrial water cycle is changing in response to climate change and direct human interventions, causing changes in the mean state and trade-offs among the water cycle components. Understanding the partitioning of precipitation into other water budget components is vital for water resource management and predicting catchment's hydrological response to climate change. Hydro-climatic modeling can help us investigate the drivers and characteristics of changes in the hydrological regime, but these models are computationally expensive and suffer from large uncertainties. Therefore, simple empirical framework such as the Budyko framework gained a lot of attention. Budyko framework, which relates the evaporative index to the aridity index assuming zero storage change, has been widely used to study shifts in catchment climatic zones, catchment resilience, and disentangle impact of climate and humans on water yield. The efficacy of Budyko framework is good for human-interference free catchments, where the assumption of zero long-term water storage change is valid. Several studies show that human interference in the water cycle has increased substantially in the last two decades and GRACE satellite data has established that assuming storage change to be zero is inaccurate for the majority of the river catchments. In such catchments, the Budyko framework loses its efficacy and the water limit or/and energy limits are often violated. Hence, several efforts have been made to include the storage change term in the Budyko framework, but they lack a sound physical and mathematical basis. In this proposed work, I will develop a novel water-partitioning framework along the lines of Budyko framework from the first principles. I will include storage term (mass conservation) and use the atmospheric water –flux and land water-budget equations to derive a relation between evaporative index, aridity index. The developed theoretical framework will be validated comprehensively in a closed-loop simulation environment developed with the SWAT model. It has been shown that large-scale irrigation can feed back to the tropical catchments as recycled precipitation, meaning the effective water input to the catchment from outside is smaller than the observed precipitation. I will investigate the impact of recycled precipitation on the updated Budyko framework for the first time. Including recycled precipitation will enhance the efficacy of the water-partitioning framework over Indian catchments. The updated Budyko framework will effectively identify the driver of catchment aridity and compute resilience of the catchment to climate change. To sum-up, I aim to improve the Budyko framework by including storage and recycled precipitation, then use it to predict catchment's response to climate change and human intervention over Indian river basins, which will help us ensure water security in a changing climate.

Objectives :

The Budyko framework links evaporative index with aridity index of a catchment via a Budyko parameter with three components of water budget viz. precipitation, evapotranspiration and streamflow. This study aims to enhance the foundation of the Budyko framework and devise approaches to address global water yield challenges in various catchments. The modifications to the framework will let us explore the link between aridity and evaporation indices in a catchment, vital for deciding how precipitation is divided between streamflow and evaporation. The entire project is structured around three main objectives, outlined as follows:

- Integrating storage change and recycled precipitation into the Budyko framework.
- Utilize the updated Budyko framework to create a categorical map that identifies the primary driver (human or climate) responsible for systematic shifts in aridity within major river basins.
- Examine the resilience of Indian catchments to both climate change and human interventions using data from multiple sources. The first objective is centered around theoretical developments, which will be validated in a closed loop simulated environment. Once, the updated framework is ready, the deviations from the theoretical mean will be investigated to identify the drivers, i.e. climate change or human intervention. The resilience of the Indian catchment will also be estimated following the work by Creed et al., (2014), with the updated framework.

Keywords :

water storage, Budyko framework, streamflow, climate change, human activities, evapotranspiration.

Expected Output and Outcome of the proposal :

I will revisit the assumptions and approximation in the Budyko framework that are not valid anymore due to the Anthropocene and climate change and update the framework to surpass conventional empirical hydrological models, leading to a transformative advancement in hydrological sciences. Additionally, the model can be utilized to project changes in water availability under various climate scenarios, thus facilitating improved future planning and water resource management. With the enhanced framework and given relevant data such as precipitation, streamflow, temperature, and storage change, we can easily identify the dominant factor impacting evapotranspiration and streamflow. Moreover, the updated-Budyko framework can serve as a valuable tool for the initial spin-up of hydrological models, enhancing the accuracy of streamflow estimation during the initial years of simulation. The tangible outcomes from this project is to publish at least two peer-reviewed articles in esteemed journals such as Water Resources Research, and Nature or Science. All the associated codes will be made publicly accessible to fellow researchers through open-access repositories like GitHub. This proposed research builds upon my prior work on the Budyko framework and presents a valuable chance to work with GRACE and other remote sensing datasets, helping my academic growth.

Reference Details :

S.No	Reference Details
1	**Dr. Sanskriti Mujumdar,** **Department of Civil Engineering, The Maharaja Sayajirao University of Baroda, Vadodara, Gujarat, India. [+9998077111]** ssmujumdar-ced@msubaroda.ac.in
2	**Dr. Arpita Mondal,** **Room no 23, Department of Civil Engineering, Indian Institute of Technology Bombay, Mumbai-400076, Maharashtra, India.[+02225769305]** marpita@iitb.ac.in

Work Methodology and Research Plan

Several efforts have been made to incorporate GRACE-based storage change into the Budyko framework (Chen et al., 2013, Du et al., 2016, Gao et al., 2020, Xing et al., 2018). These attempts involve substituting equivalent precipitation (P_{eq}) for precipitation (P), where P_{eq} is calculated by subtracting the change in water storage (ΔS) from P. Based on previous literature, I show the impact of including storage for Ganga and Godavari basin in Fig. 1. The position of the catchment in Fig. 1 is plotted using ECMWF reanalysis-ERA5 data and Total water storage (TWS) anomaly was derived from the Gravity Recovery and Climate Experiment (GRACE) mission data (Hersbach et al., 2023, Vishwakarma et al., 2021). From the Fig. 1(a,b), In Ganga basin it can be seen that for year 2018 (black box), the catchment shifts the maximum towards the arid region when storage term is included and in similarly for year 2017 (red box), the catchment shifts maximum towards humid region. Thus, including storage change term moves the catchment towards arid or humid regime. In the present framework, the precipitation term is only altered with respect to the storage change because of which when the storage increases as in the case of Ganga basin for year 2018, the catchment becomes more arid, which does not represent the real scenario, as when the storage increases the catchment should move towards humid zone rather than arid. Also, we can observe that there is no change considered for total supply and demand of water in the catchment due to storage from antecedent conditions. Including storage change, will need to account for maximum storage of catchment which adds up to the demand of water, and the previous time step storage which adds up to the supply. Thus, we need to revisit the current framework and update it accordingly.

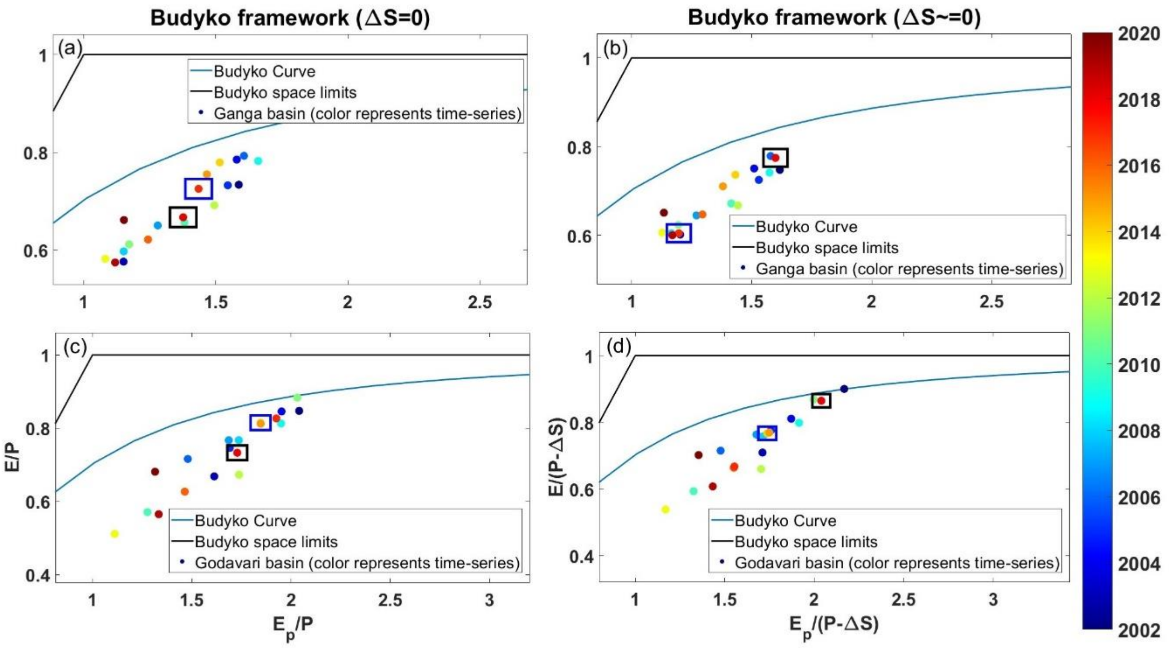

Figure 1: Annual catchment position of (a) Ganga basin without storage change term, (b) Ganga basin with storage change term considered, (c) Godavari basin without storage change term, and (d) Godavari basin with storage change term considered over the Budyko space. Black box denotes the maximum shift in catchment position towards increasing aridity index side and the red box demotes the maximum shift in catchment position towards decreasing aridity index side.

The present state of Budyko equation is derived using the water budget equation constituting precipitation, evapotranspiration and streamflow (Budyko, 1974). I will revisit the derivation of the Budyko equation and attempt to derive it from the first principles of conservation of mass and water flux within the catchment with more water budget terms included. To validate my theoretical developments, I will use a hydrological model, Soil Water Assessment Tool (SWAT), to verify the assumptions included in the Budyko framework in a closed loop simulation environment. SWAT is specifically designed to assess the impacts of land management practices, climate change, and land use changes on water resources at various spatial and temporal scales (Xu et al., 2023). In the end, the output from the Budyko framework would be compared with the output from the hydrological model-SWAT, to check the variation in results from an empirical and process-based models.

Another key aspect around inefficacy of the Budyko framework for tropical catchments, such as in India, has been ignoring the recycled precipitation, which is a catchment-driven component. Studies related to precipitation recycling at different spatio-temporal scales in India have been conducted by Navale & Karthikeyan, 2023, and Pathak et al., 2014. The next question to ask is: what impact would including recycled precipitation have on the Budyko framework? The recycled precipitation reaches up to 30% of the observed precipitation in the monsoon months. Since the law of conservation of mass should not be violated, the effective water input to the catchment should be smaller than the observed precipitation. Also, in the current state of the Budyko framework, the entire precipitation variable is assumed to be climate driven. Therefore, in this project, I further aim at accounting for recycled precipitation term in the Budyko framework to better understand the shifts in catchment's aridity due to climate change and human intervention. The net precipitation considered to be climate-driven will be derived after removing the portion of recycled precipitation from the observed precipitation. This modification will allow for a more accurate representation of the climate and catchment influences on the water cycle of the catchment.

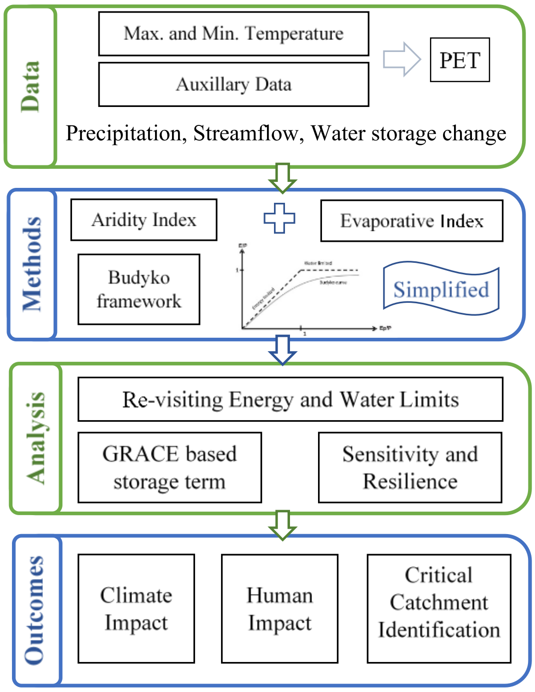

Figure 2: Illustration of the proposed workflow, input datasets, various methods, and proposed analysis.

I hypothesize that the present two-dimensional Budyko space can be extended to a generalized n-dimensional space by including more axes i.e., $\Delta S/P$ (storage index) and $P_{recycled}/P$ (recycling index). I will test this hypothesis and develop an empirical relation between various indices. I expect that Budyko will be a special case of the general framework, when we have zero/negligible storage change and recycled precipitation.

Budyko framework has been used to analyse and assess the resilience of catchments to various climatic and anthropogenic changes by using a resilience index (Creed et al., 2014). The Creed et al., 2014 have defined the hydrological resilience as the ability of a catchment to absorb the effects of climate change and still maintain hydrological function as predicted by the traditional Budyko curve. Once I have the updated

Budyko framework, the position of Budyko curve and state space of the catchment will change and accordingly the resilience index of the catchment will change. Thus, the resilience of the catchments to return to their mean state over a long period will be assessed under the updated framework. This will help the policy makers in determining the tipping point of catchments hydroclimatic variables beyond which catchment will not remain resilient to extreme changes.

The developed framework will be used on the Indian catchments to check for the relative contributions of anthropogenic activities and climatic variabilities on the hydrological characteristics of the catchment under study. The revised framework will offer a complete method for examining alterations in the average water-related conditions of the given area and for assessing how resilient the catchment can be to withstand changes in the climate.

Overall, the research plan is divided into four well-defined tasks: (1) to include the storage change and recycled precipitation term within the Budyko framework; (2) validate the update framework in a closed-loop simulation environment; (3) estimate resilience of the catchments against extreme changes in hydrometeorological fluxes, and (4) to separate the relative contribution of climate and human activities. The key steps of the proposed project are illustrated in Fig. 2.

Study Area

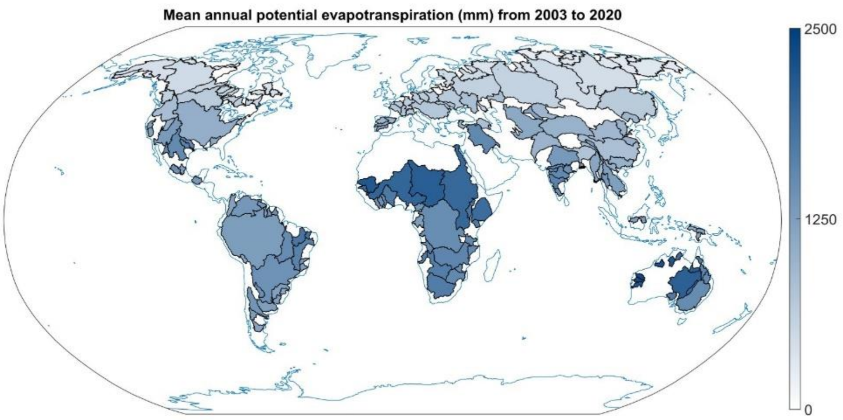

Figure 3: Mean annual potential evapotranspiration) from 2003 to 2020 of the 186 catchments. Hourly from Singer et al. 2021 is converted to annual and finally to basin averaged averaged E_p.

The study area is 186 catchments with area greater than 63000 km^2 over the global land. It covers the Brahmaputra, Kaveri, Ganga, Godavari, Krishna, Mahanadi, Narmada and Tapi basin within India. The study area along with its mean annual potential evapotranspiration is shown in Fig. 3.

Table 1. The project work plan and timeline, divided into four major tasks and quarterly progress over the 24-month project duration.

Task	Year and Months							
	2024				2025			
	3	6	9	12	3	6	9	12
To include the storage change and recycled precipitation term within the Budyko framework								
To validate the update framework in a closed-loop simulation environment								
To estimate the resilience of catchments								
To separate the relative contribution of climate and human activities								
Dissemination of the results								

References

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Singer, M. B., Asfaw, D. T., Rosolem, R., Cuthbert, M. O., Miralles, D. G., MacLeod, D., Quichimbo, E. A., & Michaelides, K. (2021). Hourly potential evapotranspiration at 0.1° resolution for the global land surface from 1981-present. Scientific Data, 8(1). https://doi.org/10.1038/s41597-021-01003-9

Vishwakarma, B. D., Bates, P., Sneeuw, N., Westaway, R. M., & Bamber, J. L. (2021). Re-assessing global water storage trends from GRACE time series. Environmental Research Letters, 16(3). https://doi.org/10.1088/1748-9326/abd4a9

Xing, W., Wang, W., Shao, Q., Yong, B., Liu, C., Feng, X., & Dong, Q. (2018). Estimating monthly evapotranspiration by assimilating remotely sensed water storage data into the extended Budyko framework across different climatic regions. Journal of Hydrology, 567(September), 684–695. https://doi.org/10.1016/j.jhydrol.2018.10.014

Xu, R., Qiu, D., Wu, C., Mu, X., Zhao, G., Sun, W., & Gao, P. (2023). Quantifying climate and anthropogenic impacts on runoff using the SWAT model, a Budyko-based approach and empirical methods. Hydrological Sciences Journal, (just accepted 2023).

<u>**BIO-DATA**</u>

1. **Name and full correspondence address:** Dr. Pushkar Ajaykumar Sharma

   Research Associate, Interdisciplinary Centre for Water Research (ICWaR), Indian Institute of Science (IISc), Bengaluru-560012.

2. **Email(s) and contact number(s):** pushkarsharma2014@gmail.com and +91-9106327724

3. **Institution:** Indian Institute of Science

4. **Date of Birth:** 25th January 1991

5. **Gender (M/F/T):** M (male)

6. **Category Gen/SC/ST/OBC:** Gen

7. **Whether differently abled (Yes/No):** No

8. **Academic Qualification (Undergraduate Onwards)**

	Degree	Year	Subject	University/Institution	% of marks
1.	B.E.	2013	Civil Engineering	Gujarat Technological University	73.80%
2.	M.E.	2016	Hydraulic Structure	The Maharaja Sayajirao University of Baroda	71.16%
3.	Ph.D.	2023	Water Resources Engineering	Indian Institute of Technology Bombay (IITB)	-

9. **Ph.D thesis title:** 'Quantifying Climate and Catchment Effects on Streamflow Using Budyko Framework'
   Guide's Name: Dr. Arpita Mondal, Associate Professor, Department of Civil Engineering, Indian Institute of Technology Bombay (IITB), Mumbai, Maharashtra.
   Institute/Organization/University: Indian Institute of Technology Bombay (IITB), Mumbai, Maharashtra.
   Year of Award: 2023

10. Work experience (in chronological order).

S.No.	Positions held	Name of the Institute	From	To	Pay Scale
1	Assistant Engineer	Mahi Irrigation Circle, Government of Gujarat	21st October 2013	24th August 2014	16500/- R per month
2	Temporary Assistant Professor	The Maharaja Sayajirao University of Baroda	02nd January 2017	06th May 2017	25000/- Rs per month
3	Research Associate	Indian Institute of Science	02nd November 2022	Till date	48000/- Rs per month

11. Professional Recognition/ Award/ Prize/ Certificate, Fellowship received by the applicant. NA

12. Publications *(List of papers published in SCI Journals, in year wise descending order).*

S.No.	Author(s)	Title	Name of Journal	Volume	Page	Year
1.	Sharma P., & Mondal A	Probabilistic Budyko-based Separation of Climate and Catchment Effects on Streamflow	Journal of Hydrology, Elsevier	608, 127665	1-11	2022

13. Detail of patents. NA

14. Books/Reports/Chapters/General articles etc.

S.No	Title	Author's Name	Publisher	Year of Publication
1. (Book Chapter)	Analyzing Rainfall and Reservoir Release Pattern for Ajwa Reservoir: A Case Study	Sharma, P., Mujumdar, S. (2018).	Hydrologic Modeling. Water Science and Technology Library, vol 81. Springer, Singapore.	2018

15. Any other Information (maximum 500 words)

Papers Under Communication to Journals

S.No.	Author(s)	Title	Name of Journal	Volume	Page	Year
1.	Sharma P., & Mondal A	Budyko-based past and future disaggregation of climate and catchment effects on streamflow changes	Hydrological Sciences Journal	Communicated (Under review)	-	-

Conferences, Seminars and Workshops

Sr No.	Particular	Theme	Organized By	Duration
1	International Conference	AGU Fall Meeting	AGU Community	1^{st} -17^{th} December, 2020
2	Refresher Course	Hydrology of Floods	NIH Roorkee, Roorkee, Uttarakhand	08^{th} - 19^{th} Jan, - 2019
3	National Seminar	Climate Change Adaption - Issues and Challenges	The MS University of Baroda, Vadodara	12^{th} Dec, 2016
4	International Conference	International Conference on Water, Environment, Energy and Society (ICWEES-2016)	AISECT University, India & TEXAS A&M University, USA	15^{th} -18^{th} Mar, 2016
5	Workshop	Pre-Conference Workshop on GIS, GPS & Remote Sensing	AISECT University, Bhopal & Center of Excellence in Geo-Informatics MANIT, Bhopal	14^{th} Mar, 2016
6	National Seminar	Recent Scenario in Science and Technology	Faculty of Technology and Engineering, MSU Baroda	27^{th} Feb, 2016
7	Workshop	Advanced Application of MATLAB in Engineering	Malviya National Institute of Technology, Jaipur	23^{rd} -27^{th} Nov, 2016
8	Workshop	Application of Soft Computing Techniques in Civil Engineering	Sardar Vallabhbhai National Institute of Technology, Surat	15^{th}-16^{th} Oct, 2015

Software skills: Python, MATLAB, QGIS, ArcGIS, SWAT, HEC-RAS, HEC-HMS, EPANET (Water Network Design), Allievi (Water Hammer Simulation software), C Language, Microsoft Office.

Academic Projects:

- Worked as a research assistant on a project entitled "Tehri PSP (4 x 250 MW) Hydro Electric Project Model Studies for Orifice of Surge Tank" at The MS University of Baroda (Jan-2017 to Apr-2017).
- Dam Break Analysis Using HEC-RAS and HEC-GeoRAS – A Case Study of Ajwa Reservoir (**M.E-Dissertation**)
  - Analysing the rainfall and release pattern of Ajwa Reservoir
  - To generate hydrograph and recognize severe stations of river passing through area of interest
  - To do the mapping of the floodplains and channel velocity
- Optimization of Trains and Passengers Traffic Flow at Surat Railway Station (**B.E Project**)

Undertaking by the Fellow

I, Dr. Pushkar Ajaykumar Sharma, Son of Shri. Ajaykumar Sharma, resident of D-402, Omkara residency, Chhani road, District: Vadodara, Gujarat 390002 agree to undertake the following, If I am offered the SERB N-PDF.

1. **I shall abide by the rules and regulations of SERB during the entire tenure of the fellowship.**
2. **I shall also abide by the rules, discipline of the institution where I will be implementing my fellowship**
3. **I shall devote full time to research work during the tenure of the fellowship**
4. **I shall prepare the progress report at the end of each year and communicate the same to SERB through the mentor**
5. **I shall send two copies of the consolidated progress report at the end of the fellowship period.**
6. **I further state that I shall have no claim whatsoever for regular/permanent absorption on expiry of the fellowship.**

Date: 07th August 2023

Signature

(Pushkar Sharma)

No.Acad/PC-174040012/2023 Date:03-04-2023

Provisional Certificate

This is to certify that ***Mr.Pushkar Ajaykumar Sharma****, Roll No. 174040012 has qualified for the award of Doctor of Philosophy with thesis entitled*

"Quantifying Climate and Catchment Effects on Streamflow using Budyko Framework."

His defence viva-voce examination was held on 31-03-2023.

The degree will be conferred upon him at the 61st Convocation of IIT Bombay likely to be held on August 19, 2023.

Actg. Deputy Registrar (Academic)

NB: This certificate is valid till the date of convocation as mentioned above.

Undertaking by the Principal Investigator

To

The Secretary
SERB, New Delhi

Sir

I **Dr. Pushkar Ajaykumar Sharma** hereby certify that the research proposal titled **"Understanding the drivers of interannual variability in water cycle in an updated Budyko framework"** submitted for possible funding by SERB, New Delhi is my original idea and has not been copied/taken verbatim from anyone or from any other sources. I further certify that this proposal has been checked for plagiarism through a plagiarism detection tool i.e., **Turnitin** approved by the Institute and the contents are original and not copied/taken from any one or many other sources. I am aware of the UGCs Regulations on prevention of Plagiarism i.e., University Grant Commission (Promotion of Academic Integrity and Prevention of Plagiarism in Higher Educational Institutions) Regulation, 2018. I also declare that there are no plagiarism charges established or pending against me in the last five years. If the funding agency notices any plagiarism or any other discrepancies in the above proposal of mine, I would abide by whatsoever action taken against me by SERB, as deemed necessary.

07th August 2023
Pushkar Sharma,
Research Associate, ICWaR, IISc,
Bengaluru - 560012

Signature of PI with date

Name/designation

ફોર્મ - ૫ FORM - 5

सत्यमेव जयते

ગુજરાત સરકાર

GOVERNMENT OF GUJARAT

આરોગ્ય અને પરિવાર કલ્યાણ વિભાગ

DEPARTMENT OF HEALTH AND FAMILY WELFARE

જન્મ પ્રમાણપત્ર

BIRTH CERTIFICATE

(જન્મ અને મરણ નોંધણી અધિનિયમ, ૧૯૬૯ની કલમ ૧૨/૧૭ અને
ગુજરાત જન્મ-મરણ નોંધણી નિયમો, ૨૦૦૪ના નિયમ - ૮/૧૩ મુજબ)

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૧. નામ / 1. Name : પુષ્કર

૨. જાતિ (પુ./સ્ત્રી) / 2. Sex (M/F) : પુરૂષ

૩. જન્મ તારીખ / 3. Date of Birth : ૨૫/૦૧/૧૯૯૧ (પચ્ચીસમી જાન્યુઆરી ઓગણીસો એકાંણુ)

૪. જન્મ સ્થળ / 4. Place of Birth : મોબીનકોલોની અંકલેશ્વર

૫. માતાનું નામ / 5. Name of Mother : મીરાશર્માં

૬. પિતાનું નામ / 6. Name of Father : અજયકુમાર શર્માં

૭ બાળકના જન્મ સમયે માતા-પિતાનું સરનામુ / 7. Address of parents at the time of Birth of child :

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૯. નોંધણી ક્રમાંક / 9. Registration No. : ૨૯૦૮

૧૦. નોંધણીની તારીખ / 10. Date of Registration : 30/09/૨૦૧૪

૧૧. રીમાર્કસ (વિશેષ નોંધ) / 11. Remarks (if any) : એડી ચીફ જયુ.મેજી. કોર્ટ અંકલેશ્વર ના હુકમ તા.૨૯/૦૯/૨૦૧૪ થી જન્મ નોંધ કરેલ છે.ક્રિ.પ.અન ૧૦૫/૨૦૧૪

પ્રમાણપત્ર કાઢી આપનાર સત્તાધિકારીની સહી
Signature of the issuing authority

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જન્મ / મરણ નોંધણી કલાર્ક
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17/10/2014

પ્રમાણપત્ર કાઢી આપ્યાની તારીખ / Date of issue : 17 OCT 2014

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સ.મુ. ભા.–(વાય)-૨૬૫-૧૬,૩૦,૦૦૦-૨-૨૦૧૪.(૩)

ROSARY HIGH SCHOOL, BARODA

(HIGHER SECONDARY SCIENCE STREAM)
(GUJARATI / ENGLISH MEDIUM)

Leaving Certificate

G. Reg. No. 4852 Serial № 4438

Name of the pupil in full: Sharma Pushkar Ajaykumar

Cast with Sub-Caste: Hindu Brahmin

Place of Birth: Ankleshwar

Date, month & year (in words) of birth according to the Christian Era: 25-01-1991 Twenty fifth Jan. N.H. Ninety one

Last School Attended: S.V. Eng. med. School, Ankleshwar

Date of admission: 18-6-07

Progress: Good

Conduct: Good

Date of Leaving School: 31-5-09

Class in which studying and since when: Std XII (Twelfth) Since June'08

Reason for leaving School: Sent up for H.S. Exam. of March'09

Attendance (No. of days) in Class during School year – out of –

Remarks: APPEARED FOR HSC EXAMINATION HELD IN MARCH 2009 VIDE SEAT NO. B 060668 AND PASSED/FAILED

Certified that the above information is in accordance with the School Register.

PRINCIPAL
ROSARY HIGH SCHOOL
BARODA-2
Principal

Date 28 MAY 2009

No change in any entry in this certificate shall be made except by the authority issuing it.
Any infringement of the rule is liable to be dealt with by rustication or by other suitable punishment.

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Research papers

Probabilistic Budyko-based Separation of Climate and Catchment Effects on Streamflow

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ABSTRACT

Streamflow variability is affected by both climate change and direct human impacts within the catchment. Quantification of the role of these two factors have significant implications for water resources. In recent years, Budyko-based analytical methods have been widely used for such quantification due to their simplicity and efficacy. This paper presents a comparison of such methods to attribute changes in streamflow in four Model Parameter Estimation Experiment (MOPEX) catchments in the contiguous United States. Further, a new, improved Two-stage Decomposition method to separate the role of climate and catchment changes on streamflow is proposed, considering the uncertainty in the catchment parameter that further leads to a range of evaporative index values within a catchment. We find that climate and catchment effects are sensitive to the choice of Budyko equation, disaggregation algorithm and approximation technique. Further, the catchment parameter can be expressed probabilistically, to account for the uncertainty because of limited hydrometeorological records. The proposed approach employs a bootstrap analysis to obtain the stochastic range of the catchment parameter, considering different choices of Budyko equations. We argue that rather than relying on a single Budyko-based approach for separation of climate and catchment effects on streamflow, the proposed method offers a more robust way by considering the entire range of uncertainty of the catchment parameter.

1. Introduction

Hydrologic processes in river basins are primarily governed by atmospheric mechanisms—both large-scale and regional, the local topography, and land use characteristics in the catchment (Acharya et al. 2012; Houghton 1996; Werth and Avissar 2002). The change in streamflow due to changes in precipitation and/or temperature is classified as the climate change effect, while that due to changes in catchment activities such as human settlements, construction of barriers, regulations of flow and vegetation changes that impact the streamflow directly constitute the catchment change effect on streamflow. Disaggregating the influence of climate and catchment effects on streamflow is necessary for answering important questions on regional environmental changes and subsequent impacts on present and future water availability (Dey and Mishra 2017; Ma et al. 2008; Wang et al. 2013; Zhang et al. 2008).

Several methods are available for separating the individual impacts of climate change and catchment activities on streamflow variability. These techniques can be broadly classified as methods based on physical processes such as hydrologic modeling (Arnell 1999; Li et al. 2009; Liu et al. 2013; Ma et al. 2009), field experiments such as paired catchment methods (Huang et al. 2003; Liu et al. 2004), and conceptual reasoning such as climate elasticity (Roderick and Farquhar 2011; Sankarasubramanian et al. 2001) and decomposition methods (Liang et al. 2013; Wang and Hejazi 2011). Hydrologic modeling follows a bottom-up approach for capturing physical processes taking place within the hydrological cycle, but this approach requires a large amount of data (Vieux 2001). Paired catchment methods, on the other hand, identify impacts on flow characteristics by comparing two catchments with similar physical properties such as catchment area, soil type, and vegetation cover (Loon et al. 2019). However, this approach is limited to the availability of an ideal reference catchment for comparison (Liu et al. 2004).

Unlike these approaches, methods based on conceptual reasoning have the potential advantage of capturing the hydrological processes without focussing individually on the different physical mechanisms. They follow a top-down approach that attempts to model catchment properties as a function of observed data (Wang et al., 2016). Many

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Table 1
Details of the four single parameter Budyko equations. The generating function for any equation is given in terms of the aridity index ($\varnothing = E_p/P$) and the catchment parameter. Though the catchment parameter is represented here using different notations for the different equations in their original form, for the rest of the present paper, we use 'm' to denote the catchment parameter to maintain uniformity.

Name of the equation	Functional form	References
Budyko-Fu	$f(\varnothing) = 1 + \varnothing - [1 + (\varnothing)^m]^{\frac{1}{m}}$	Fu (1981)
Budyko-CY	$f(\varnothing) = \frac{\varnothing}{(1+\varnothing^n)^{1/n}}$	Choudhury (1999), Yang et al. (2008)
Budyko-WT	$f(\varnothing) = \frac{1+\varnothing-\sqrt{(1+\varnothing)^2 - 4\varepsilon(2-\varepsilon)\varnothing}}{2\varepsilon(2-\varepsilon)}$	Wang and Tang (2014)
Budyko-Zh	$f(\varnothing) = \frac{1+w\varnothing}{1+w\varnothing+(\varnothing)^{-1}}$	Zhang et al. (2001)

conceptual reasoning-based techniques rely on the simple proportionality between streamflow and precipitation, modelled either as ratios or via regression, without physically accounting for the water balance (Gao et al. 2011; Sankarasubramanian et al. 2001; Zhao et al. 2014; Zheng et al. 2009). Conceptual methods based on Budyko framework overcome this limitation and model the link between supply (precipitation) and demand (potential evapotranspiration) using a class of equations known as the Budyko-based equations. This framework is widely preferred for its simplicity and effectiveness (Jiang et al. 2015; Liang et al. 2015; Ning et al. 2018; Wang and Hejazi 2011; Wang and Tang 2014; Xin et al. 2019; Yang and Yang 2011).

The Budyko framework assumes that the ratio of actual evapotranspiration (E) to precipitation (P) is a function of the aridity index, that is the ratio of potential evapotranspiration (E_p) to precipitation, while also assuming the net storage change to be zero (Budyko 1974; Ol'Dekop, 1911; Pike 1964; Schreiber 1904; Turc 1954).

$$\frac{E}{P} = f\left(\frac{E_P}{P}\right) \tag{1}$$

This relationship was later appended to include a catchment parameter (denoted by $c, m, n, w or \varepsilon$ in different studies, viz. Choudhury 1999; Fu (Chinese), 1981; Wang and Tang 2014; Yang et al. 2008; Zhang et al. 2004). Table 1 presents the different Budyko equations based on the different generating functions. The catchment parameter is represented in Table 1 using different notations for the different equations in their original form, for the rest of the present paper, we use 'm' to denote the catchment parameter to maintain uniformity. The parametric Budyko-based equations can be written as follows.

$$\frac{E}{P} = f\left(\frac{E_P}{P}, m\right) \tag{2}$$

Budyko-based approaches for disaggregation of climate and catchment change contributions to streamflow change are broadly classified under sensitivity and decomposition methods. While the sensitivity method involves obtaining the total differential of streamflow as a sum of its partial derivatives (Roderick & Farquhar 2011), the decomposition method (Wang and Hejazi 2011) uses the relative positions of the watershed on the Budyko curve in the pre- and post-change periods to quantify individual effects of climate and catchment changes on streamflow. Previous studies have used a single type of decomposition method and validated the results with a single type of elasticity method (Gao et al. 2016; Jiang et al. 2015; Liang et al. 2015; Ning et al. 2018; Wang and Hejazi 2011). Several studies have also assessed climate/catchment change contributions by using different Budyko equations in a single type of climate elasticity method (Jiang et al. 2015; Wu et al. 2017). Considering the fact that these different Budyko-based disaggregation methods have their individual strengths and limitations, it is important that a comprehensive comparative analysis be taken up and the uncertainty, arising from the choice of a method, approximation technique or Budyko equation, be quantified. Further, all the studies listed above consider the catchment parameter *m* as a deterministic quantity, fixed for a catchment, for a particular period. Though the catchment parameter has no a priori physical meaning associated to it, it has been shown to be affected by changing climate and catchment properties (Greve et al. 2014, Greve et al. 2015) leading to a range of evaporative index values (Gudmundsson et al. 2016). In addition, the estimation of the catchment parameter *m* is uncertain because of limited hydro-meteorological record length (Guo et al. 2019). Further, the parametric Budyko equations are non-equivalent functional forms of each other and thus may contradict each other in terms of evaporative index values while following a constant parameter trajectory (Reaver et al. 2020). Effects of uncertainty on disaggregating climate and catchment effects on streamflow change within the Budyko framework, arising due to non-uniqueness nature of catchment parameter while following constant parameter trajectory, has not been explored in past studies. Also, the procedural advantages and limitations arising from each method has to be understood, for obtaining reliable estimates of climate and catchment changes. Therefore, in the present study, each of the method has been classified individually based on the type of approximation and disaggregation technique. The study alleviates a new probabilistic approach to quantify uncertainty arising from different Budyko equations, choice of disaggregation, and approximation techniques.

To address these gaps, this study aims at the following objectives: 1) a comparative assessment of Budyko-based methods for disaggregation of climate and catchment effects on streamflow change, and their sensitivity to the choice of different Budyko equations and approximation techniques, 2) to understand the effect of the stochastic uncertainty of the catchment parameter on disaggregation of climate and catchment effects on streamflow using a bootstrap algorithm, 3) to propose a new, robust method for such disaggregation based on the entire uncertainty range of the evaporative index – this method finds an optimized non-parametric Budyko curve for the pre- and post-change period of the catchment, and finally, 4) to compare the performance of the proposed method with respect to existing Budyko-based methods for disaggregation of climate and catchment effects on streamflow change. Four Model Parameter Estimation Experiment (MOPEX) catchments in the contiguous United States are chosen for this analysis.

2. Methodologies

2.1. Model description

Fig. 1 shows an overall schematic of the study. The first step towards segregating climate and catchment effects on streamflow is to determine a changepoint in the long-term streamflow time-series. Streamflow measured at the outlet of a catchment is obtained after all the major abstractions post precipitation. Therefore, the streamflow is inherent to the catchment and climate effects. Thus, the studies on the Budyko framework focuses on finding the change point based on streamflow, following which the rank-based non-parametric Pettitt's changepoint test (Pettitt 1979) is performed on the long-term streamflow series (Gao et al., 2016; Guo et al., 2019; Liang et al., 2015; Wang & Hejazi, 2011; Zhao et al., 2014; Zhang et al. 2008) to split the series into pre-change (Period-1) and post-change (Period-2) time periods. The change point detection test is done for the four catchments for a significance level of 0.05, and it is observed that all the four catchments show significant change points. We have used three budyko-based equations, namely, Budyko-Fu, Budyko-CY, and Budyko-WT. The Budyko-Zh equation is not used in this study since it is not able to satisfy the Budyko state space for the energy limit condition for catchment lying in humid regions (Yang et al. 2008). The catchment parameter *'m'* is estimated from the known values of potential evapotranspiration (E_p), precipitation (P), and

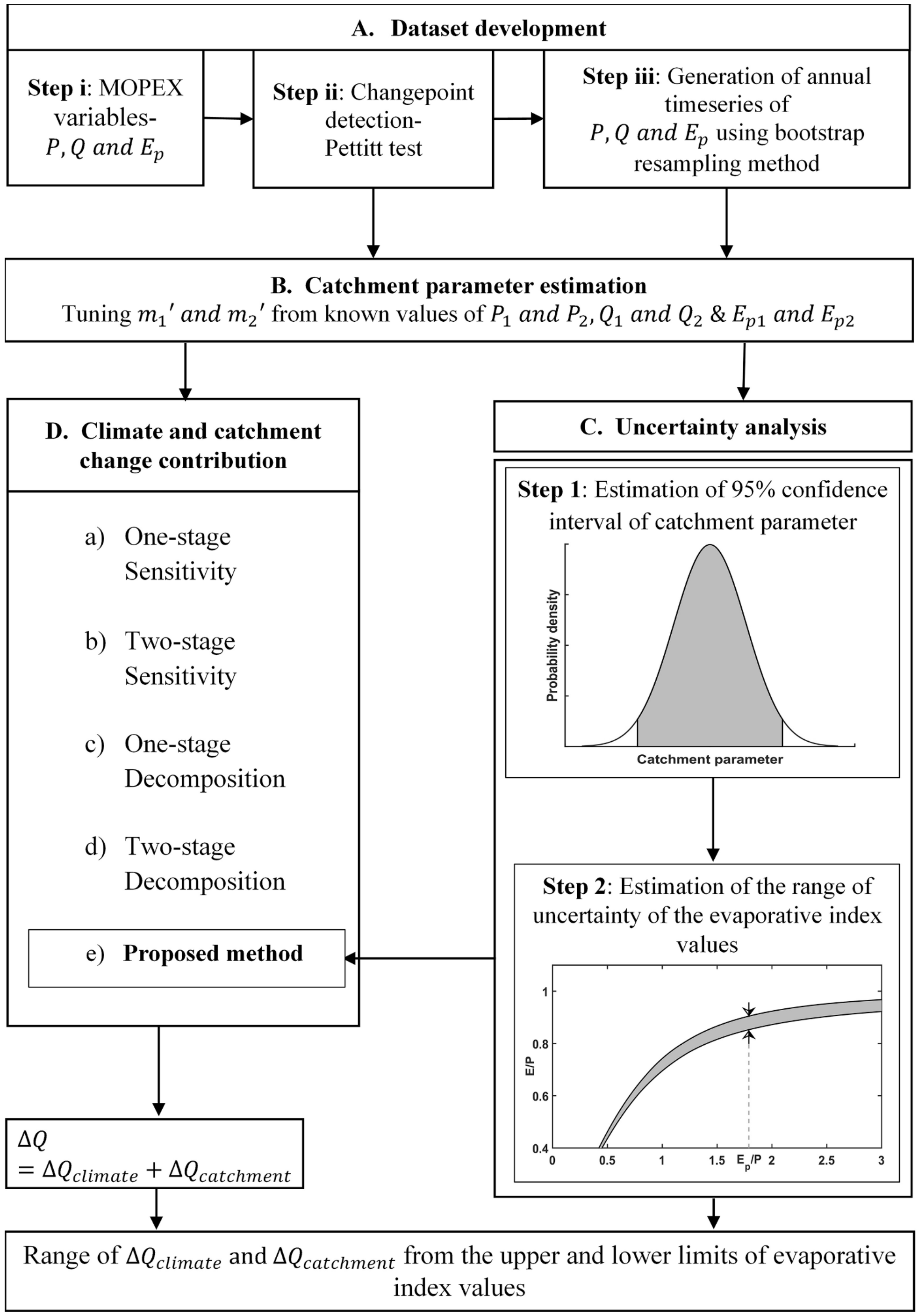

Fig. 1. Schematic of the Budyko-based framework for separation of climate and catchment change contributions to streamflow, and quantification and propagation of associated uncertainties. Based on the uncertainty analysis, the present study proposes a new method to segregate climate and catchment change impacts on streamflow.

streamflow (Q), averaged over Period-1 and Period-2. The influence of climate and catchment change activities on streamflow are quantified using different disaggregation methods – the One-stage (Roderick and Farquhar 2011) and Two-stage (Jiang et al. 2015) Sensitivity methods, and the One-stage (Yang et al. 2014) and Two-stage (Patterson et al. 2013; Wang and Hejazi 2011) Decomposition methods. Uncertainty in the catchment parameter is assessed by applying the bootstrap resampling technique to sets of values of E_p, P and Q for Period-1 and Period-2. This uncertainty due to the stochastic nature of the catchment parameter, as well as due to the choice of Budyko equations lead to a range of uncertainty in the evaporative index for each catchment, for Period-1 and Period-2. Based on this range of uncertainty in the evaporative index, the upper and lower limits of climate and catchment contributions to streamflow are obtained. Further, we propose a new, improved Two-stage Decomposition method considering the median of the ensemble of evaporative index values.

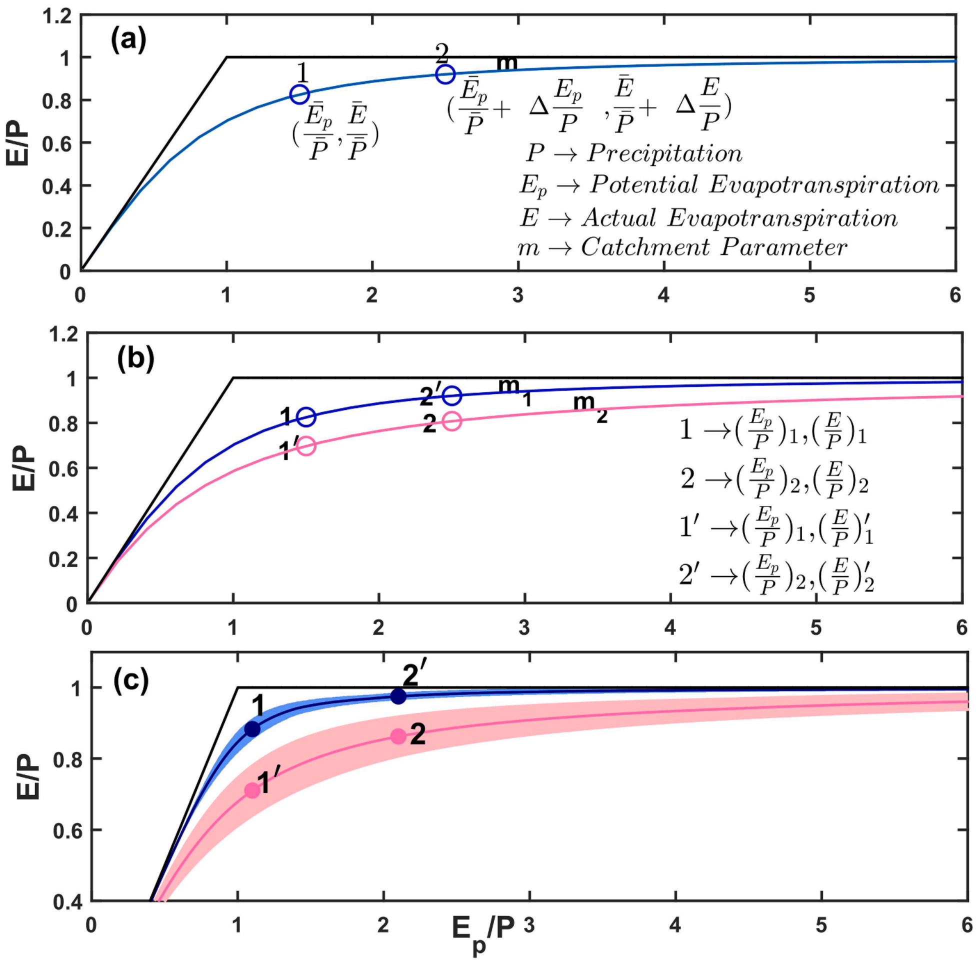

Fig. 2. Depiction of movement of watershed from pre-change condition (denoted by 1) to post-change condition (denoted by 2) on the Budyko curve by (a) One-stage Decomposition method, via path 1 → 2, for a catchment with catchment parameter m (blue), (b) Two-stage Decomposition method, via path 1 → 2′→2 & path 1 → 1′→2. Here, 1′ and 2′ denote the apparent positions of the catchment in the pre-change and post-change conditions, with parameters m_1 and m_2, respectively, (c) proposed method to quantify climate and catchment effects on streamflow change, considering uncertainty in the catchment parameter, m. Here, 1 → 2′ and 1′→2 represent the pre-change and post-change paths, respectively, based on the median of the ensemble of evaporative index values. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

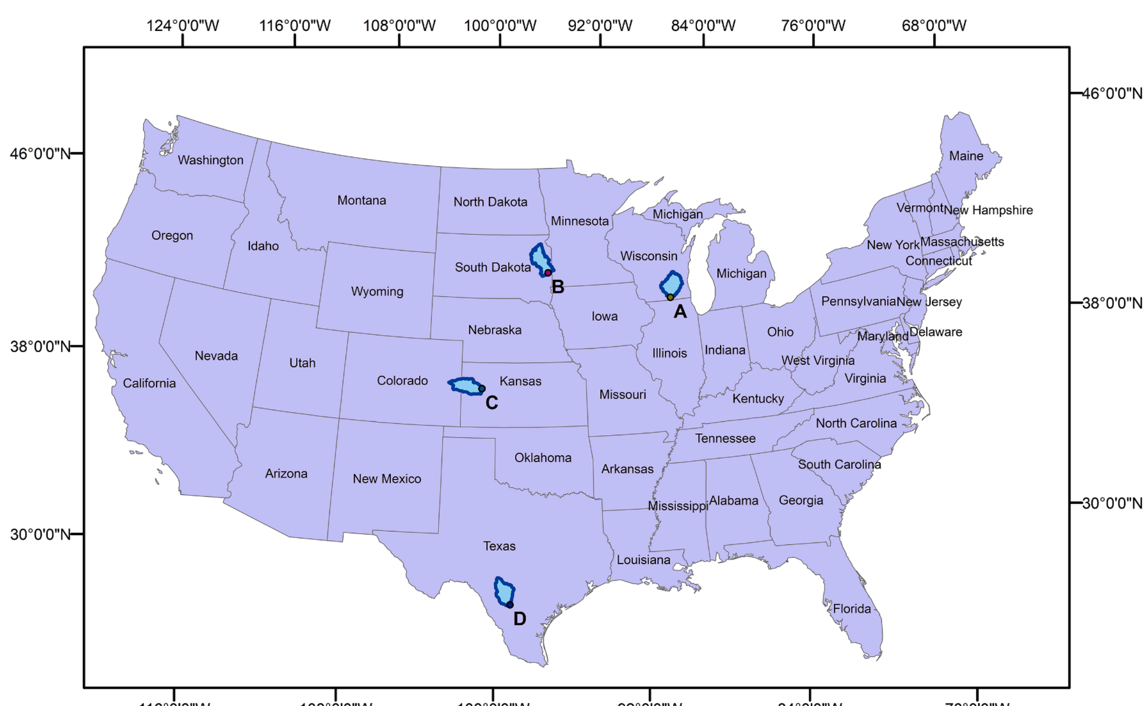

Fig. 3. Geographic locations of the four MOPEX catchments.

2.2. Budyko-based disaggregation techniques to separate climate and catchment effects on streamflow

The sensitivity method of separation of climate and catchment effects on streamflow follows the concept of obtaining the total differential of a variable (streamflow, in this case) as a sum of its partial derivatives (Roderick & Farquhar 2011). The concept of decomposition method was introduced by Wang and Hejazi (2011). In this method, the contribution of climate and catchment change activities on streamflow is estimated based upon the relative positions of the watershed on the Budyko curve from position 1 to position 2 as shown in Fig. 2. (See Fig. 3)

2.2.1. One-stage Sensitivity method

In this approach, the partial rate of change of streamflow (Q) with respect to each of the drivers namely, precipitation (P), potential evapotranspiration (E_p), and catchment parameter (m) yields the streamflow sensitivities to the respective drivers (Roderick & Farquhar 2011), which are then separately quantified into climate ($\Delta Q_{climate}$) and catchment change components ($\Delta Q_{catchment}$).

$$Q = P\left(1 - \frac{E}{P}\right) \tag{3}$$

Using Eq. (2),$Q = P(1 - f(\varnothing, n))$ (4)

The first-order approximation of the total differential of equation (4) gives

$$dQ = \frac{\partial Q}{\partial P}dP + \frac{\partial Q}{\partial E_P}dE_P + \frac{\partial Q}{\partial n}dn \tag{5}$$

Following previous studies, the infinitesimal changes dQ, dP, dE_Panddn are replaced by their respective absolute changes $\Delta Q, \Delta P$, ΔE_PandΔn (Gudmundsson et al. 2016; Renner and Bernhofer 2012). From Eq. (5), the separate contributions of climate ($\Delta Q_{climate}$) and catchment ($\Delta Q_{catchment}$) effects to change in streamflow are estimated as,

$$\Delta Q_{climate} = \frac{\partial Q}{\partial P}\Delta P + \frac{\partial Q}{\partial E_P}\Delta E_p \tag{6}$$

$$\Delta Q_{catchment} = \frac{\partial Q}{\partial n}\Delta n \tag{7}$$

where, $\Delta Q = Q_2 - Q_1, \Delta P = P_2 - P_1, \Delta E_p = E_{p2} - E_{p1}$ and $\Delta Q = \Delta Q_{climate} + \Delta Q_{catchment}$.Here, subscripts 1 and 2 refer to Period-1 and Period-2, respectively.

It has been reported that using the Taylor series expansion up to first order as in Eq. (5) can yield results that are slightly different from the actual estimates (Yang et al. 2014), with larger errors for catchment effects ($\frac{\partial Q}{\partial n}$), as compared to the climate effects $\left(\frac{\partial Q}{\partial P}, \frac{\partial Q}{\partial E_P}\right)$. Therefore, the catchment contributions to streamflow change is calculated as the difference between the total streamflow change and the climate contribution, given as (Gao et al. 2016; Liang et al. 2015),

$$\Delta Q_{catchment} = \Delta Q - \left(\frac{\partial Q}{\partial P}\Delta P + \frac{\partial Q}{\partial E_P}\Delta E_p\right) \tag{8}$$

The intervals of ΔP and ΔE_p can sometimes be large leading to erroneous climate contributions to streamflow (Jiang et al. 2015; Yang et al. 2014). This limitation is overcome in the Two-stage Sensitivity method described below.

2.2.2. Two-stage sensitivity method

The Two-stage Sensitivity method follows the same principle as that of the One-stage Sensitivity method, but instead of the rate of change in Q with respect to P and E_p over the entire period, the average rate of change for Period-1 and Period-2 is used (Jiang et al. 2015) for the computations.

$$\Delta Q_{climate} = \frac{1}{2}*\left[\left(\frac{\partial Q}{\partial P}\right)_1 + \left(\frac{\partial Q}{\partial P}\right)_2\right]\Delta P + \frac{1}{2}*\left[\left(\frac{\partial Q}{\partial E_p}\right)_1 + \left(\frac{\partial Q}{\partial E_p}\right)_2\right]\Delta E_p \tag{9}$$

and, $\Delta Q_{catchment} = \Delta Q - \Delta Q_{climate}$ (10)

The Two-stage Sensitivity method can also be used to get the lower and upper limits of the climate/catchment change impact on streamflow by using only one rate of change i.e. $\left(\frac{\partial Q}{\partial P}\right)_1$ or $\left(\frac{\partial Q}{\partial P}\right)_2$ at a time in Eq. (9). It has also been shown that using first-order approximation techniques for estimating the catchment contribution to streamflow, relative to climate change, as given by Eq. (10), yield results that are comparable to that of the complementary approach of estimating catchment and climate change contributions separately (Zhou et al. 2016), thus justifying the suitability of the Two-stage Sensitivity method for estimation of the lower and upper limit of climate/catchment change contribution to streamflow. However, the Two-stage Sensitivity method is limited by the first-order approximation error (Yang et al. 2014) which may be overcome by the Decomposition methods.

2.2.3. One-stage decomposition method

The One-stage Decomposition method involves quantifying the climate contributions to streamflow based on the relative positions of the catchment on the Budyko curve, as shown in Fig. 2a. Accordingly, from known values of the long-term mean aridity index (E_p/P) and the average streamflow (Q) of the catchment, the catchment parameter is tuned to fit each of the Budyko equations given in Table 1. Thereafter, the Budyko curve is plotted for the obtained catchment parameter for the mean value of E_p/P (Fig. 2a). Here, E_p and P represent the climate variables. Therefore, any change in aridity index of the catchment is only due to climate change activities, and the catchment follows the Budyko curve while moving in the horizontal direction. On the other hand, the divergence of the catchment from the Budyko curve will denote the change in streamflow due to catchment activities. This is because of the change in actual evapotranspiration caused by catchment activities.

To separate the climate and catchment change impact on streamflow, Yang et al. (2014) proposed a modified decomposition approach, as shown in Fig. 2a. In this method, the catchment parameter is determined by considering the mean values of aridity and evaporative index for the entire data period. Position-1 of the catchment is determined by aridity value of the catchment for the entire data period used in the study, while Position-2 of the catchment is determined by adding the change in the aridity value to the long term mean aridity value determined for Position-1. Climate and catchment contributions to streamflow are estimated as follows:

$$Q = P\left(1 - \frac{E}{P}\right) \tag{11}$$

$$Q = P\left(1 - f(E_p, P, n)\right) \tag{12}$$

Since, the catchment is assumed to move on a single path the catchment parameter n is fixed and climate variables E_p and P is allowed to vary.

$$\Delta Q_{climate} = f\left(\overline{E_p} + \Delta E_p, \overline{P} + \Delta P\right) - f\left(\overline{E_p}, \overline{P}\right) \tag{13}$$

$$\Delta Q_{catchment} = \Delta Q - \Delta Q_{climate} \tag{14}$$

This method assumed the catchment to move along a single Budyko curve, not accounting for all possible changes in the catchment parameter, and may thus result in misleading magnitudes of $\Delta Q_{climate}$. Using separate Budyko curves for the pre- and post-change periods, as used in the Two-stage Decomposition method can overcome this limitation.

2.2.4. Two-stage decomposition method

The Two-stage Decomposition method (Fig. 2b) involves estimation

Table 2
Summary of the hydro-climatic variables of the four MOPEX catchments. Subscripts 1 and 2 denote the pre-change and post-change periods, respectively. The change point is determined by the Pettitt change point analysis using a level of significance = 0.05.

Catch-ment (∅)	Period	Change point	Area (km^2)	Mean			Period-1 (mean)			Period-2 (mean)		
				Q (mm)	P (mm)	E_p (mm)	Q_1 (mm)	P_1 (mm)	E_{p1} (mm)	Q_2 (mm)	P_2 (mm)	E_{p2} (mm)
A (1.1)	1948–2001	1971	8650	211.5	808.2	895.4	167.5	760.4	895.4	246.7	846.3	895.4
B (1.78)	1954–2001	1982	10,095	30.88	584.0	1042.5	15.2	553.5	1042.5	54.7	630.4	1042.5
C (3.44)	1948–2001	1969	9207	2.15	438.6	1512.4	4.4	418.7	1512.4	0.5	452.2	1512.4
D (2.27)	1948–2001	1970	8881	13.19	675.4	1536.6	7.2	616.3	1536.6	17.5	719.3	1536.6

of the catchment parameter for the pre- and post-change conditions separately (Patterson et al. 2013). The mean aridity index-evaporative index pair for the pre-change state of the catchment is plotted at Position-1 and that of the post-change state is plotted at Position-2. Both the paths, i.e., $1\to2^{'}\to2$ and $1\to1^{'}\to2$ are feasible for a catchment to traverse in Two-stage Decomposition method as shown in Fig. 2b. The average change in streamflow from these paths give the catchment contributions to change in streamflow as shown below:

$$\Delta Q_{catchment(1\to2^{'}\to2)} = P_2\left(\frac{E^{'}_2}{P_2}-\frac{E_2}{P_2}\right), \Delta Q_{catchment(1\to1^{'}\to2)} = P_1\left(\frac{E_1}{P_1}-\frac{E^{'}_1}{P_1}\right) \tag{15}$$

$$\Delta Q_{catchment} = \frac{\Delta Q_{1\to2^{'}\to2}+\Delta Q_{1\to1^{'}\to2}}{2} \tag{16}$$

Finally,

$$\Delta Q_{climate(1\to2^{'}\to2)} = P_2\left(1-\frac{E^{'}_2}{P_2}\right)-Q_1, \Delta Q_{climate(1\to1^{'}\to2)}P_1\left(1-\frac{E^{'}_1}{P_1}\right)-Q_2 \tag{17}$$

$$\Delta Q_{climate} = \frac{\Delta Q_{1\to2^{'}\to2}+\Delta Q_{1\to1^{'}\to2}}{2} \tag{18}$$

2.3. Uncertainty in the evaporative index value

Here, the nonparametric bootstrap resampling method (Kybic and Nieuwenhuis 2011, Guo et al. 2019) is used to obtain the uncertainty in the catchment parameter for the pre-change period. We generate 10,000 sets of *P, Q,* and E_p values from the pre-change period annual records. For each such set, average *P, Q,* and E_p values are obtained for the pre-change period. Then, each set is used to generate a catchment parameter for each of the three Budyko equations. Then, for each Budyko equation, we fit an empirical distribution to the generated catchment parameter values, and use the 5th and 95th percentile values of that distribution to obtain the limits of evaporative index. For each possible aridity index values (theoretically, zero to infinity), the minimum and maximum values of the evaporative index obtained based on the different Budyko equations give the range of uncertainty of evaporative index values, as shown in Fig. 2c. Similar procedure is followed to obtain the range of uncertainty of evaporative index values for the post-change period. Then, the Two-stage Decomposition method is applied using the lower and upper limits of the evaporative index values, at the aridity index values of Period-1 and Period-2 for that catchment.

2.4. Proposed method

Based on the above discussion, it is clear that the Two-stage Decomposition method is the most robust against errors and approximations. However, the non-uniqueness of the Budyko equations and the stochastic nature of the catchment parameter lead to a range of uncertainty in the evaporative index that must be considered in this method for a reliable quantification of climate and catchment contributions to streamflow change.

In the proposed method, we consider this range of uncertainty in the evaporative index values, estimated as explained above in Section 2.3. The range of evaporative index values corresponding to all possible aridity index values, as shown in Fig. 2c, are derived from any one of the Budyko equations; therefore, each trajectory in the ensemble shown in Fig. 2c for Period-1 or Period-2 automatically follows the water and energy limits in the Budyko state space. The movement of catchment from upper limit of evaporative index in Period-1 to upper limit in Period-2 is estimated using Two-stage Decomposition method to obtain the upper bound of climate/catchment change. Similarly, the lower bound is estimated and the probabilistic range for change in climate/catchment contribution is shown in Table 3. Since each trajectory within this uncertainty range is a possible representation of the catchment in Period-1 or Period-2, the median of the band for each period is considered to determine the location of the catchment in Period-1 and Period-2. This ensures a realistic movement of the catchment along feasible trajectories in the Budyko space, resulting in reasonable changes in the evaporative index value, $(\Delta\frac{E}{P})_{2-1}$. The median is a choice of representative behaviour of the uncertainty band of possible trajectories. The trajectories defined by the different Budyko equations are non-unique (Reaver et al. 2020). This implies that for catchments where the range of uncertainties in evaporative index for Period-1 overlap with that of Period-2, with any alternate representative measure such the mean, the computed trajectories for Period-1 and Period-2 might cross each other. The median avoids such non-uniqueness. Thus, the catchment is located along the median curve for Period-1 and Period-2 based on the pairs of its aridity and evaporative index values for the two periods, respectively. Since the decomposition method is a graphical concept of the Budyko framework, one can apply this process without the use of any equation, provided the trajectory is defined. The Two-stage Decomposition method is applied to the relative positions of the catchment along these median curves, to obtain the climate and catchment change effects on streamflow, as follows:

$$\left(\frac{E}{P}\right)_{50^{th}percentile} = f\left(\frac{E_P}{P}\right) \tag{19}$$

$$Q = P\left(1-\left(\frac{E}{P}\right)_{50^{th}percentile}\right) \tag{20}$$

3. Study area and dataset

Four large MOPEX catchments in the contiguous United States of America (Duan et al. 2006; available at ftp://hydrology.nws.noaa.gov/), with aridity indices ranging from 1 to 4, and a minimum catchment area of 8500 sqkm, are chosen for this study. These catchments are denoted as non-referenced catchments in the Geospatial Attributes of Gages for Evaluating Streamflow (GAGES-II) dataset by Falcone (2011), which substantiates the presence of human intervention. The catchment details are provided in Table 2. Catchment#5430500 (A) – Rock River at Rock County, Wisconsin State and Catchment#6480000 (B) – Big Sioux River at Brookings County, South Dakota State have hydroelectric power plants and urban settlements on the upstreams, while Catchment#6860000 (C) – Smoky Hill River at Logan County, Kansas State is characterized by irrigated agriculture. Catchment#8205500 (D) – Frio River at Frio County, Texas State is noted to have oil fields, along with proximal irrigation (Falcone 2011).

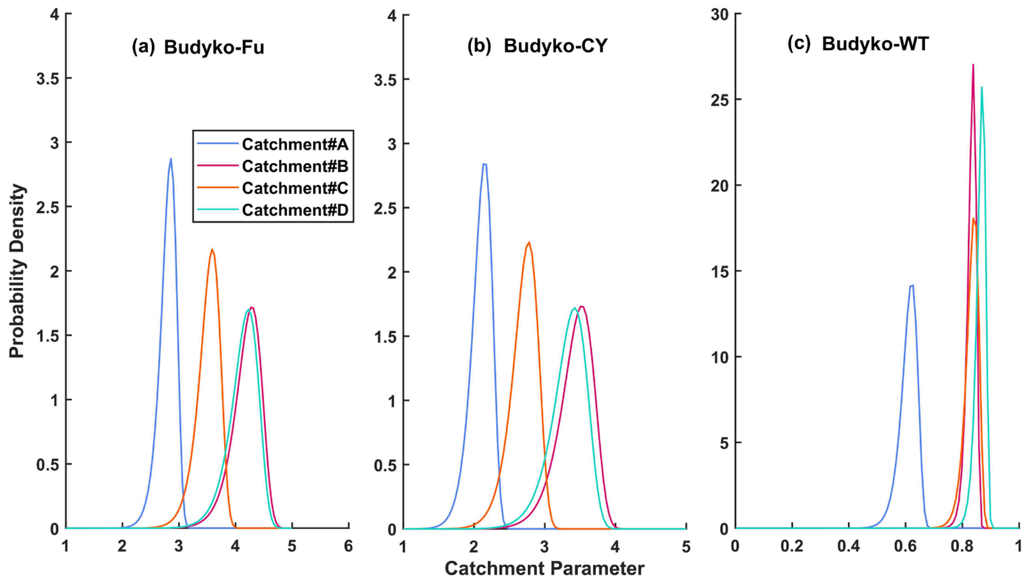

Fig. 4. Probability density plots of the bootstrap estimates of the catchment parameter, for the four MOPEX catchments for Period-1 for (a) Budyko-Fu, (b) Budyko-CY and (c) Budyko-WT equations.

4. Results and discussions

Streamflow is found to increase from Period-1 to Period-2 in all catchments, except Catchment# C, while precipitation increases in all the four catchments, as shown in Table 2. The potential evapotranspiration, on the other hand, is observed to remain unchanged; thus, it may be inferred that the climatic contribution to change in streamflow is entirely due to change in precipitation. In this regard, if an increase (decrease) in streamflow (Q) due to climate change ($\Delta Q_{climate}$) is reflected as an increase (decrease) in the observed streamflow (ΔQ) as well, it is referred to as a positive effect by climate change on streamflow. On the other hand, if the increase (decrease) in streamflow (Q) by climate change corresponds to a decrease (increase) in the observed streamflow (ΔQ), it is referred to as negative effect by climate change ($\Delta Q_{climate}$) on streamflow and is reported accordingly with a negative sign. The contribution of climate and catchment change effects on streamflow change calculated using the proposed method and the four sensitivity and decomposition methods for the three Budyko-based equations. The catchment change impacts here are estimated relative to the climate change estimates ($\Delta Q_{catchment} = \Delta Q - \Delta Q_{climate}$), except for

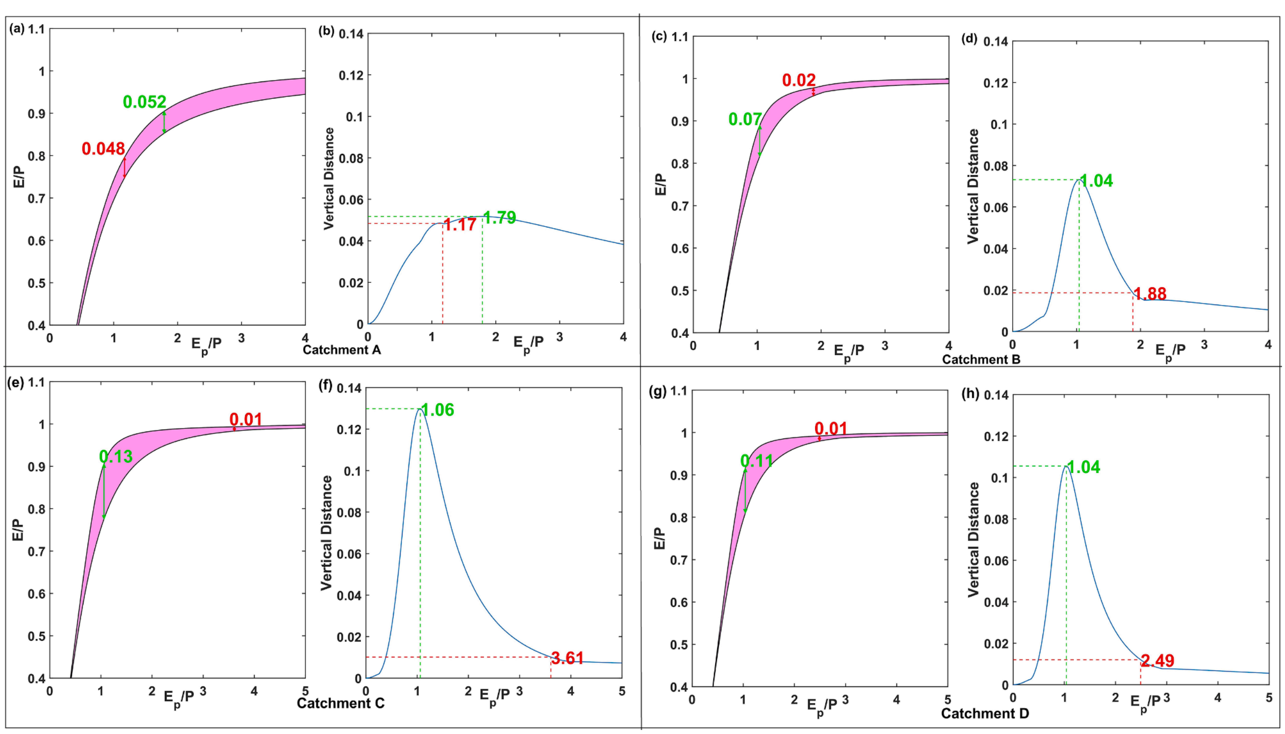

Fig. 5. (a), (c), (e), and (g) The upper and lower bounds of the uncertainty in Budyko curve for the four MOPEX catchments, based on the 5–95% range of the bootstrap catchment parameter, using different Budyko equations, for Period-1. (b), (d), (f) and (h) Vertical distance between the upper and lower bounds of the evaporative index. The maximum vertical distance (green), and the vertical distance at the aridity index of each catchment (red), are also shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

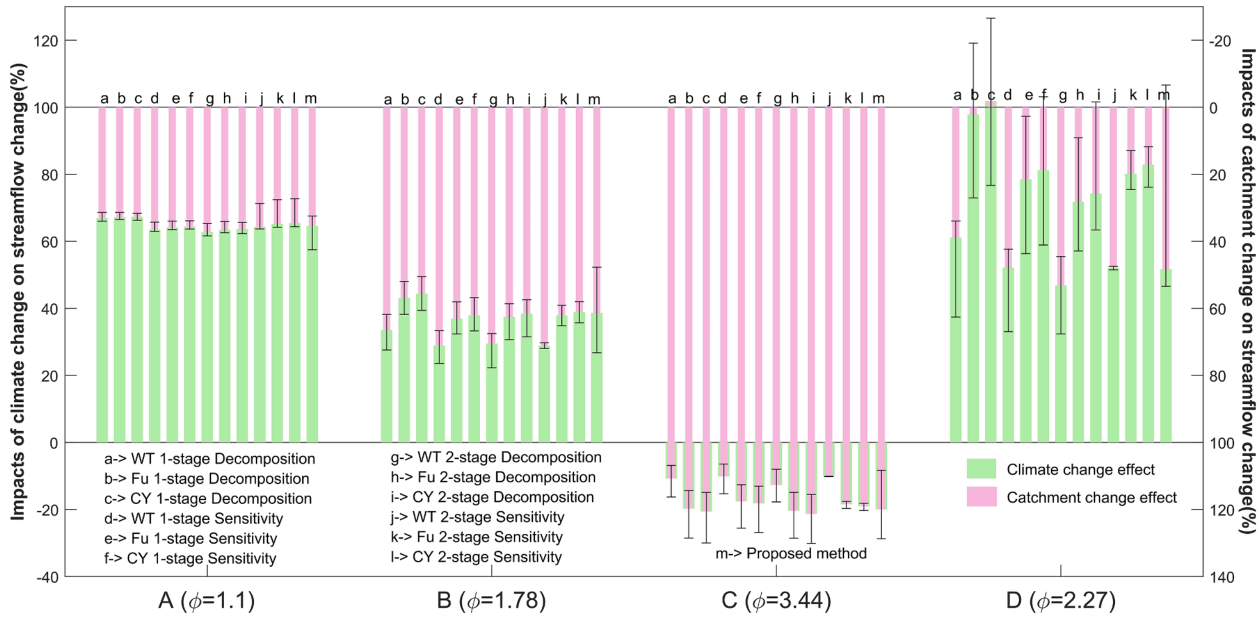

Fig. 6. Contribution of climate and catchment effects on changes in streamflow using existing methods (a through l) and the proposed method (m) for the four MOPEX catchments. Each of a through l represents plausible segregation of climate and catchment change contribution to streamflow (uncertainty for each method is shown by whiskers). The proposed method, on the other hand, summarizes the uncertainty not only in the form of Budyko equation, but also considers the probabilistic nature of the catchment parameter.

the Two-stage Decomposition method where the catchment changes are also estimated from the Budyko curve (Wang and Hejazi 2011).

4.1. Uncertainty in the Budyko parameter

The empirical distributions fitted to the generated catchment parameter values from the bootstrap resampling technique, for each of the four catchments and, for the three Budyko equations, are shown in Fig. 4. The figure shows the range of catchment parameter values spanned for different Budyko equations for different state of each catchment in Period-1. The range is obtained from the pairs of annual average values of *P, Q,* and E_p. More diverse the combination, more uncertainty will be seen in the catchment parameter values. For a given catchment, the value of the Budyko parameter is determined from a fixed pair of values of aridity index and evaporative index. From the range of generated pairs of aridity and evaporative indexes, the range of the Budyko parameter is obtained. The catchment parameters can overlap each other (as seen in Fig. 4), because these equations contradict each other while following a constant trajectory in each of their formulation (Reaver et al. 2020). Furthermore, the width of uncertainty band depends upon the variability in the range of annual hydroclimatic variables that are used to derive the Budyko parameters. It is observed that the span of Budyko-WT catchment parameter is concentrated for catchments B, C and D, and more widespread for Catchment#A. This is because of the smaller range of the Budyko-WT catchment parameter [0,1], as compared to Budyko-Fu (1,∞) and Budyko-CY (0,∞) and its smaller sensitivity towards the water limit. Catchment#A being more humid as compared to the other catchments, lie towards the energy limit, thereby showing a wider band in the probability density of the Budyko-WT parameter (Fig. 4c).

The ensemble of trajectories in the Budyko state space, arising from the uncertainty in evaporative index values, for the four catchments are shown in Fig. 5(a, c, e, g). The range of evaporative index at each aridity index value is denoted as the vertical distance. Fig. 5(b, d, f, h) shows the value for the vertical distance at each aridity index value. The figure also shows the maximum vertical distance and the vertical distance at the aridity index of the catchment marked in green and red, respectively, for Period-1. It is observed from Fig. 5f and h that for arid catchments, the uncertainty in evaporative index values initially increases and decreases sharply (Catchment#C and Catchment#D). On the other hand, the uncertainty range in wetter catchments – Catchment#A and Catchment#B that have aridity index 1.1 and 1.88, respectively, continue to remain wide. These results imply a greater significance of the uncertainty in evaporative index values in wetter catchments. Further, the choice of Budyko equation leads to largest sensitivity in the transition from wet to dry states (Yang et al. 2008; Zhou et al. 2015), leading to largest uncertainty in the range of aridity index values of 1.4 to 2.4. The Budyko parameter range depends upon the state of the catchment. Catchments A, B, C and D have runoff coefficients (Q/P = 1-E/P) as 0.22, 0.03, 0.01 and 0.01, respectively, in Period-1. The catchments with lower runoff coefficient will exhibit more uncertainty in the transition zone of Budyko curve from humid to dry state, as compared to catchment having higher runoff coefficient. This is due to the asymptotic nature of the Budyko curve. The catchments with higher runoff coefficient are characterized by lower evaporative index values lying far from the horizontal line of water limit. The catchments with higher runoff coefficient values will exhibit less uncertainty since the departure between the Budyko curves arising from different parameter ranges would be low due to smooth transitioning from humid to dry state, after which they eventually become asymptotic to the Budyko limits. On the other hand, the catchments with lower runoff coefficient show a steep rise and fall in the uncertainty band due to quick transitioning from the humid to dry state. Accordingly, the highest uncertainty in the catchments A, B, C and D are 0.052, 0.07, 0.13 and 0.11 respectively.

4.2. Climate and catchment effects on streamflow

The contribution of climate and catchment effects on streamflow change, obtained using the proposed method and the four sensitivity and decomposition methods for the three Budyko-based equations are shown in Fig. 6. The range of uncertainty of the catchment and climate change contributions shown in Fig. 6 is derived from the range of evaporative index values based on the 5th and 95th percentile values of the Budyko paramater for each catchment. In general, results are sensitive to the aridity state of catchment, the adopted disaggregation and approximation technique, and the Budyko equation used. In Catchment#A and

Table 3
Quantification of uncertainty in separation of climate and catchment effects on streamflow.

Catchment	Maximum elasticity of streamflow to precipitation	Maximum elasticity of streamflow to potential evapotranspiration	Range of contribution of climate change (%)	Range of contribution of catchment change (%)
A	2.4	1.21	57.51–67.55	32.45–42.49
B	4.1	0.12	26.77–52.29	47.71–73.23
C	3.5	1.24	(-28.75) – (-8.33)	108.33–128.75
D	4.3	0.02	46.59–106.64	(-6.64) – 53.41

Catchment#B, the rainfall and the streamflow are found to increase from the pre-change period to the post-change period, suggestive of a positive effect from climate change on streamflow. The relative contributions from the catchment change i.e., 35.3% and 65.7% in Catchment#A and Catchment#B respectively (the numbers used from hereon for discussion are from the proposed method), suggest an increase in streamflow majorly driven by climate change in Catchment#A while due to catchment characteristics in catchment B. However, the catchment change has certainly contributed for the increase in streamflow, in both the catchments. This increase is presumably due to urbanization and releases in river flows caused by hydroelectric power generation upstream of the catchment. On the other hand, for Catchment#C, the decrease in streamflow from Period-1 to Period-2 along with a simultaneous increase in rainfall, implies that the effects of climate and catchment change on streamflow act in opposite directions. The percentage contribution to streamflow from climate change for Catchment#C is −18%. For this catchment, climate change has increased the streamflow, although the observed streamflow is seen to decrease from Period-1 to Period-2. This observed decrease can be largely attributed to increased evapotranspiration on account of the irrigation activities in this catchment. Moreover, the aridity index of this catchment is 3.44, indicating a dry catchment. In such catchments, the dependence of the catchment on climate variables is found to decrease, and the catchment becomes more sensitive to catchment changes (Liang et al. 2015), explaining the high catchment change contribution of 118% in streamflow for such catchment. Catchment#D also shows a positive effect of climate change on streamflow. This catchment has the largest variability in the contribution from climate/catchment change on streamflow as compared to other catchments. In addition to the resident land use characteristics, this divergence is largely explained by a careful analysis of the position of the catchment on the Budyko curve, which in turn is governed by the aridity index of the catchment and the choice of the generating function (Zhou et al. 2016). The aridity index of this catchment ($\varnothing \approx 2.27$; Table 2) implies that the catchment is in the transition phase, between wet and dry states, where the change in streamflow are highly sensitive to m and ϕ (Yang et al. 2008; Zhou et al. 2016).

The ranges of climate and catchment change effects on streamflow obtained by the probabilistic framework are shown in Table 3. With a few exceptions for Catchment#D, the different disaggregation methods agree with each other. For this catchment, climate change effects, for Budyko-Fu One-stage and Budyko-CY One-stage Decomposition method are 98% and 101%, respectively, much higher as compared to other methods. This may happen in One-Stage methods where the elasticity of streamflow is high for a particular Budyko equation and the change in magnitude of aridity index between Period-2 and Period-1 is also considerably large. With the different parameter range values for every equation, the uncertainty range of evaporative index at each aridity index keeps changing. Generally, the elasticity of precipitation to streamflow for the Budyko-WT equation remains lower than the other two equations. Therefore, the climate change contribution from the Budyko-WT equation remains lower as compared to other equations. The probabilistic approach to separate the climate and catchment change effects on streamflow gives a range of values for each catchment (Table 3). The range of values shown in Table 3 is calculated from the upper and lower bound of the trajectories, obtained from different equations and ranges of Budyko parameters. Further, these ranges are able to capture the contribution values obtained by other disaggregation methods shown in Fig. 6.

5. Summary and conclusions

Climate and catchment change activities are major factors that can significantly alter streamflow in a catchment. It is important to quantify the changes in streamflow due to these individual factors, while formulating any development or restoration strategies for the catchment of interest. The Budyko-based approaches are widely preferred to other alternatives for such quantification on account of their simplicity and effectiveness (Chang et al. 2016; Jiang et al. 2015; Liang et al. 2015; Xin et al. 2019). In this study, four Budyko-based disaggregation algorithms: One-stage Sensitivity, Two-stage Sensitivity, One-stage Decomposition, and Two-stage Decomposition methods are applied on four MOPEX catchments in the contiguous United States, their performances are compared and their advantages and limitations are discussed. Three types of single-parameter Budyko equations are used for each disaggregating method. The Two-stage Decomposition method is noted to be the most robust disaggregation technique.

Earlier studies focussing on separating the roles of climate and catchment changes on streamflow do not take into account the probabilistic nature of the catchment parameter, neither consider the effect of the choice of Budyko equation. In this study, we present a framework to quantify the uncertainty in evaporative index values arising from the stochasticity of the catchment parameter and from the choice of Budyko-equation, and also propose an improved Two-stage Decomposition method based on this uncertainty range. A bootstrap resampling technique is used to arrive at the uncertainty range of evaporative index values. The theoretical justification behind consideration of this uncertainty stems from the fact that the catchment can move along many possible paths from a pre-change to a post-change location in the Budyko state space.

Our results show that climate or catchment contributions to streamflow change may vary across a wide range, depending on the aridity index and the elasticity of the catchment. Also, wetter catchments are observed to be more prone to larger ranges of uncertainty in the evaporative index, as compared to arid catchments. In general, we observe that climate or catchment effects are sensitive to the choice of disaggregation algorithms or of the Budyko equation. Therefore, the proposed method is more robust since it considers the range of uncertainty in the trajectory of the catchment, rather than relying on a single method.

CRediT authorship contribution statement

Pushkar Sharma: Conceptualization, Methodology, Software, Data curation, Writing – original draft. **Arpita Mondal:** Visualization, Investigation, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Wang, D., 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. https://doi.org/10.1002/2014GL060509.

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Zhang, X., Zhang, L., Zhao, J., Rustomji, P., Hairsine, P., 2008. Responses of streamflow to changes in climate and land use/cover in the Loess Plateau. China. Water Resources Research 44 (7). https://doi.org/10.1029/2007WR006711.

Zhao, G., Tian, P., Mu, X., Jiao, J., Wang, F., Gao, P., 2014. Quantifying the impact of climate variability and human activities on streamflow in the middle reaches of the Yellow River basin. China. Journal of Hydrology 519 (PA), 387–398. https://doi.org/10.1016/j.jhydrol.2014.07.014.

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भारतीय विज्ञान संस्थान
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Email: registrar@iisc.ac.in

Regr/(CE)/59/2023 07 August 2023

CERTIFICATE FROM THE HEAD OF THE INSTITUTION OF THE PRINCIPAL COLLABORATOR FROM INDIA

This is to certify that:

I. The applicant, Dr. Pushkar Ajaykumar Sharma, will assume full responsibility for implementing the project.

II. The fellowship will start from the date on which the fellow joins University/Institute where he/she implements the fellowship. The mentor willsend the joining report to the SERB. SERB will release the funds on receipt of the joining report.

III. The applicant, if selected as SERB-N PDF, will be governed by the rules and regulations of the University/ Institute and will be under administrative control of the University/ Institute for the duration of the Fellowship.

IV. The grant-in-aid by the Science & Engineering Research Board (SERB) will be used to meet the expenditure on the project and for the period for which theproject has been sanctioned as indicated in the sanction letter/ order.

V. No administrative or other liability will be attached to the Science & Engineering Research Board (SERB) at the end of the Fellowship.

VI. The University/ Institute will provide basic infrastructure and other required facilities to the fellow for undertaking the research objectives.

VII. The University/ Institute will take into its books all assets received under this sanction and its disposal would be at the discretion of Science & Engineering Research Board (SERB).

VIII. University/ Institute assume to undertake the financial and other management responsibilities of the project.

IX. The University/ Institute shall settle the financial accounts to the SERB as per the prescribed guidelines within three months from the date of termination of the Fellowship.

Dated: 02 Aug 2023
Signature of the Mentor:
Dr. Bramha Dutt Vishwakarma
Assistant Professor, ICWaR, IISc

Capt Sridhar Warrier (Retd) (Aug 7, 2023 16:06 GMT+5.5)

Date : 07 August 2023

Place : IISc Bengaluru

Name & Signature of the Head of the Institution

Indian Institute of Science Bangalore-560 012

ಕ್ಯಾಪ್ಟನ್ ಶ್ರೀಧರ್ ವಾರಿಯರ್ (ನಿವೃತ್ತ)/कप्तान श्रीधर वारियर (सेवानिवृत्त)
Capt. Sridhar Warrier (Retd.)
ಕುಲಸಚಿವರು/कुलसचिव/REGISTRAR
ಭಾರತೀಯ ವಿಜ್ಞಾನ ಸಂಸ್ಥೆ/भारतीय विज्ञान संस्थान/INDIAN INSTITUTE OF SCIENCE
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Bramha Dutt Vishwakarma

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Work Experience

Assistant Professor Aug 2021–ongoing
Interdisciplinary Centre for Water Research, Indian Institute of Science
Centre for Earth Sciences, Indian Institute of Science

Honorary Research Fellow Aug 2021–Nov 2022
Bristol Glaciology Center, School of Geographical Sciences, University of Bristol

Marie Curie Research Fellow Jul 2019–Jul 2021
Bristol Glaciology Center, School of Geographical Sciences, University of Bristol

- CLOSeR: an EU Horizon 2020 project investigating contribution of land water storage change to the sea level rise.

Research Associate Mar 2018–June 2019
Bristol Glaciology Center, School of Geographical Sciences, University of Bristol

- GlobalMass project: studying the sea level budget.

Research Assistant May 2017–Oct 2017
Institute of Geodesy, University of Stuttgart

- ESA-ADDCON project, GRACE satellite gravimetry products for global hydrological application

Asst. Professor (Lecturer) Jul 2012–Feb 2013
College of Engineering Roorkee, India

- Teaching: Land surveying, An Introduction to GPS, Digital signal processing.

Research Interest

Physical Geodesy, Hydrology, ice-mass balance, sea level rise, climate change, Solid Earth Geophysics, GRACE products, signal processing, data-driven algorithms, data assimilation.

Education

PhD, Geodesy (*Magna cum laude*) 2013–2017
Institute of Geodesy, University of Stuttgart, Germany

Masters', Geomatics Engineering (CGPA: 9/10) 2010–2012
Indian Institute of Technology Roorkee, India

Bachelors', Electronics and Communication Engineering (Distinction) 2006–2010
Uttar Pradesh Technical University, India

Supervision

1. Mr. Chethan Ram, PhD Thesis, "A Bayesian approach to estimate groundwater and soil moisture from remote sensing data ", at ICWaR, IISc (Aug 2023 – ongoing).

2. Ms. Vandana S., PhD Thesis, "Estimating coastal sea level rise from satellite data and modeling", at ICWaR, IISc (Aug 2023 – ongoing).

3. Ms. Samira Sadri (from Iran), PhD Thesis, “Geodetic data assimilation for understanding surface hydrology”, at ICWaR, IISc (Aug 2023 – ongoing).
4. Mr. Chitavan singh, Summer Intern, “Developing Fourier Neural Networks for solving PDEs”, at ICWaR, IISc (May 2023 – July 2023).
5. Ms. Jasmine Sultana, Visiting Master student for research thesis, “Flood modelling of Bengaluru Lakes”, at ICWaR, IISc (Jan 2023 – June 2023).
6. Dr. Maya Suryawanshi’s under the IISc-ISRO STC project, “Improving the spatial resolution of GRACE TWS for India using remote sensing datasets and modeling approach” at ICWaR, IISc (Jan 2023 – ongoing)
7. Dr. Retinder Kour’s Postdoc Work, “Impact of future climate projections on the streamflow of Himalayan River Basins” at ICWaR, IISc (Dec 2022 – March 2023)
8. Dr. Abhishek’s C V Raman Postdoc Fellowship work on, “Disentangling Human and climate signals in hydrological observations”, at ICWaR, IISc (Dec 2022 – Mar 2023)
9. Dr. Pushkar Sharma’s postdoc work, “Modifying Budyko framework to better characterize climate change” at ICWaR, IISc (Nov 2022 – ongoing).
10. Ms. Vandana S for her research under the SERB funded project, “MApping Terrestrial wateR resources from spAce (MATRA)” at ICWaR, IISc (Oct 2022 – July 2023).
11. Mr. Balaram Shaw, PhD Thesis, “Using Budyko framework and hydrogeodetic observations for hydrology”, at ICWaR, IISc (July 2022 – ongoing).
12. Ms. Tsungrojungla Walling: a Cargill International award winner, for summer internship at IISc (Summer 2022).
13. Mr. Amin Shakya under the IISc-ISRO STC project, “Improving the spatial resolution of GRACE TWS for India using remote sensing datasets and modeling approach” at ICWaR, IISc (June 2022 – Feb 2023).
14. Dr. Arindan Mandal’s NPDF postdoc work, “Establishing an in-situ glacier monitoring network in Leh” at ICWaR, IISc (Mar 2022 – ongoing).
15. Ms. Vandana S., Visiting Master student for research thesis, “Validating coastal altimetry products against tide gauge data along the Indian coast”, at ICWaR, IISc (Mar 2022 – Aug 2022).
16. Mr. Vivek Kumar Yadav, PhD Thesis, “Hindcasting GRACE data for understanding climate change impact on TWS changes” at ICWaR, IISc (July 2021 – ongoing).
17. Co-supervisor of Ms. Fanny Lehmann, Master thesis “Mapping secular changes in regional water budget components” (Sep 2020 – Sep 2021).
18. Co-supervisor of Mr. Iongel Dúran Lacer, PhD thesis “Depletion of groundwater and its relation to agriculture and dependent ecosystems in watershed of North Central’s Chile” (2018 - 2022).
19. Co-advisor of Ms. Farideh Sabzehee, PhD thesis “Monitoring hydrology of Iran by using remote sensing methods” (2017 – 2023).
20. Co-advisor of Laura Balangé, BSc thesis “Validation of GRACE products by closing the water budget” (2016).

Awards, Recognition, and Grants (since 2010)

- 2022: Awarded IISc-Imperial joint fund for initiating research exchange.
- 2022: A 2 year SERB **research grant** for ”Mapping Terrestrial Water Resources from Space”.
- 2022: A 3 year STC **research grant** for ”Improving the spatial resolution of GRACE TWS for India using remote sensing datasets and modeling approach”.
- 2022: Best presentation award in Department of Science and Technology sponsored Geo-Innovation Challenge (Geo-Health) at Chandigarh Engineering College, Mohali from 2 - 4 Feb, 2022.

- 2021: Invited as an external expert in the review panel for proposals received by National Science Centre, Poland.
- 2021: Awarded startup Grant of approx. INR 50,00,000 to start a group at IISc.
- 2019-2021: Marie Skłodowska-Curie Actions Individual **fellowship** under EU Horizon 2020 program.
- 2020: UKIERI-DST **seed grant** for organizing a Workshop on *Water Security assessment of rivers originating from Himalayas*, PI: Prof. J. L. Bamber and Prof. RAAJ Ramsankaran. (I led proposal writing and team building)
- 2019: Invited as an external expert in the peer review panel for proposals received by NASA for "GRACE-FO Science Team".
- 2013-2017: DAAD (Deutscher Akademischer Austauschdienst) **scholarship** for PhD.
- 2015: Travel Grant for young scientists, to attend IUGG 2015, held in Prague, from June 22-July 02, 2015.
- 2014: Won first place in Science Slam (Geodetic week 2014, Berlin, October 07-09, 2014).
- 2010-2012: MHRD (Ministry of Human Resource Development, Govt. of India) **scholarship** for pursuing Master of Technology at Indian Institute of Technology Roorkee.
- 2011: DAAD **scholarship** for master thesis under "Sandwich-Stipendien für Master-Studierende der Indian Institutes of Technology (IITs)" program (from September 01, 2011 to May 31,2012) at Institute of Geodesy, University of Stuttgart.

Peer-Reviewed publication

27. I. N. Otosaka, A. Shepherd, E. Ivins, ... **B. D. Vishwakarma**, ... and B. Wouters "Mass balance of the Greenland and Antarctic Ice Sheets from 1992 to 2020", (2020), **Earth System Science Data,** *15(4)*, 1597–1616, doi: 10.5194/essd-15-1597-2023.
26. F. Sabzehee, A. R. Amiri-Simkooei, S. Iran-Pour, **B. D. Vishwakarma**, R Kerachian "Enhancing spatial resolution of GRACE-derived groundwater storage anomalies in Urmia catchment using machine learning downscaling methods", (2023), **Journal of Environmental Management,** *330*, 117180, doi: 10.1016/j.jenvman.2022.117180.
25. Y. Ziegler, **B. D. Vishwakarma**, A. Brady, S. Chuter, S. Royston, J. Rougier, R. Westaway and J.L. Bamber "Can GPS and GRACE data be used to separate past and present-day surface loading in a data-driven approach", (2023), **Geophysical Journal International,** *232*, 884-901, doi: 10.1093/gji/ggac365.
24. **B. D. Vishwakarma**, Y. Ziegler, J. L. Bamber, S. Royston "Separating GIA signal from surface mass change using GPS and GRACE data", (2023), **Geophysical Journal International,** *232*, 537-547, doi: 10.1093/gji/ggac336.
23. J. Rougier, A. Brady, J.L. Bamber, S. Chuter, S. Royston, **B. D. Vishwakarma**, R. Westaway and Y. Ziegler "The scope of the Kalman filter for spatio-temporal applications in environmental science", (2022), **Environmetrics,** *34*, 1, e.
22. D. M. Mitchell, E. J. Stone, O. D. Andrews, J. L. Bamber, R. J. Bingham, J. Browse, ... **B. D. Vishwakarma**, ... M. Taylor, R. Tunnicliffe "The Bristol CMIP6 data hackathon", (2022), **Weather,** *77*, 6, doi.org/10.1002/wea.4161.
21. **B. D. Vishwakarma**, RAAJ Ramsankaran, M. F. Azam, T. Bolch, A. Mandal, S. Srivastava, P. Kumar, R. Sahu, P. J. Navinkumar, S. R. Tanniru, A. Javed, M. Soheb, A. P. Dimri, M. Yadav, B. Devaraju, P. Chinnasamy, M. J. Reddy, G. P. Murugesan, M. Arora, S. K. Jain, C. S. P. Ojha, S. Harrison and J. L. Bamber "Challenges in understanding the variability of the cryosphere in the Himalaya and its impact on the regional water resources ", (2022), **Frontiers in water** *4:909246*, , doi: 10.3389/frwa.2022.909246.
20. F. Lehmann, **B. D. Vishwakarma**, J. L. Bamber "How well are we able to close the water budget at the global scale?", (2022), **HESS,** *26(1)*, , doi: 10.5194/hess-26-35-2022.
19. **B. D. Vishwakarma**, M. Horwath, A. Groh, J. L. Bamber "Accounting for GIA signal in GRACE products", (2022), **Geophysical Journal International,** *228(3)*, 2056-2060, doi: 10.1093/gji/ggab464.
18. A. Tiwari, Arun G., **B. D. Vishwakarma** "Parameter importance assessment improves efficacy of machine learning methods for predicting snow avalanche sites in Leh-Manali Highway, India", (2021), **Science of the Total Environment,** *794*, 148738 , doi: 10.1016/j.scitotenv.2021.148738.

17. **B. D. Vishwakarma**, J. Zhang, and N. Sneeuw "Downscaling GRACE total water storage change using partial least squares regression", (2021), **Scientific Data,** *8*, 95, doi: 10.1038/s41597-021-00862-6.

16. **B. D. Vishwakarma**, P. Bates, N. Sneeuw, R. M. Westaway, J. L. Bamber "Re-assessing global water storage trends from GRACE time series", (2021), **Env. Res. Letters,** *16(3)*, 034005, doi: 10.1088/1748-9326/abd4a9.

15. **B. D. Vishwakarma** "Monitoring Droughts from GRACE", (2020), **Frontiers in Environmental Sciences,** *8*, 274, doi: 10.1016/j.rsase.2020.100361.

14. A. Balha, **B. D. Vishwakarma**, C. Singh, S. Pandey "Predicting impact of urbanization on water resources in megacity, Delhi", (2020), **Remote Sensing Applications: Society and Environment,** *20*, 100361, doi: 10.1016/j.rsase.2020.100361.

13. P. Saemian, O. Elmi, **B. D. Vishwakarma**, M. J. Tourian, S. Roohi, M. Dashtabadi, and N. Sneeuw "Analysing the Lake Urmia restoration progress using ground-based and spaceborne observations", (2020), **Science of the Total Environment,** *721*, 139857, doi: 10.1016/j.scitotenv.2020.139857.

12. **B. D. Vishwakarma**, S. Royston, R. E. M. Riva, R. M. Westaway, J. L. Bamber "Sea level budgets should account for ocean bottom deformation", (2020), **Geophysical Research Letters,** *47*, e2019GL086492, doi: 10.1029/2019GL086492.

11. S. Royston, **B. D. Vishwakarma**, R. M. Westaway, J. Rougier, Z. Sha, and J. L. Bamber "Can we resolve the basin scale sea level budget from GRACE ocean mass", (2020), **JGR Oceans,** *125*, e2019JC015535, doi: 10.1029/2019JC015535.

10. A. Shepherd, E. Ivins, ... **B. D. Vishwakarma**, ... and J. Wuite "Mass balance of the Greenland Ice Sheet from 1992 to 2018", (2020), **Nature,** *579*, 233–239, doi: 10.1038/s41586-019-1855-2.

9. A. Tiwari, A. Ahuja, **B. D. Vishwakarma**, and K. Jain "Groundwater Potential Zone (GWPZ) for Urban Development Site Suitability Analysis in Bhopal, India", (2019), **Journal of the Indian Society of Remote Sensing,** *47*, 1793-1815, doi: 10.1007/s12524-019-01027-0.

8. F. Sabzehee, V. Nafisi, S. Iran Pour, and **B. D. Vishwakarma** "Analysis of the precipitation climate signal using empirical mode decomposition (EMD) over the Caspian catchment area", (2019), **The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences,** *XLII-4/W18*, 923–929, doi:10.5194/isprs-archives-XLII-4-W18-923-2019.(proceedings)

7. F. Sabzehee, V. Nafisi, S. Iran Pour, and **B. D. Vishwakarma** "Investigation of the correlation between GRACE TWS and soil moisture in Sarakhs catchment", (2019), **The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences,** *XLII-4/W18*, 931–934, doi:10.5194/isprs-archives-XLII-4-W18-931-2019.(proceedings)

6. N. Bhattarai, K. Mallick, J. Stuart, **B. D. Vishwakarma**, R. Niraula, S. Sen, and M. Jain "An automated multi-model evapotranspiration mapping framework using remotely sensed and reanalysis data", (2019), **Remote Sensing of Environment,** *229*, 69–92, doi: 10.1016/j.rse.2019.04.026.

5. A. Shepherd, E. Ivins, ... **B. D. Vishwakarma**, D. Wiese, and B. Wouters "Mass balance of the Antarctic Ice Sheet from 1992 to 2017", (2018), **Nature,** *558*, 219-222, doi: 10.1038/s41586-018-0179-y.

4. **B. D. Vishwakarma**, B. Devaraju, and N. Sneeuw "What is the spatial resolution of GRACE products for hydrology?", (2018), **Remote Sensing,** *10*, 582, doi: 10.3390/rs10060852.

3. **B. D. Vishwakarma**, M. Horwath, B. Devaraju, A. Groh, and N. Sneeuw "A data-driven approach for repairing the hydrological catchment signal damage due to filtering of GRACE products", (2017), **Water Resources Research,** *53*, 9824– 9844, doi:10.1002/2017WR021150.

2. **B. D. Vishwakarma**, B. Devaraju, and N. Sneeuw "Minimizing the effects of filtering on catchment scale GRACE solutions", (2016), **Water Resources Research,** *52*, 5868–5890, doi:10.1002/2016WR018960.

1. **B. D. Vishwakarma**, K. Jain, N. Sneeuw, and B. Devaraju "Mumbai 2005, Bihar 2008 Flood Reflected in Mass Changes Seen by GRACE Satellites", (2013), **Journal of Indian Society of Remote Sensing,** *41(3)*, 687–695, doi:10.1007/s12524-012-0256-x.

Professional Services

Reviewer NASA-NSPIRES grant review panel, grant reviewer for National Science centre Poland, IPCC AR6, Nature Climate change, Nature Water, Water Resources Research, Journal of Geodesy, Journal of Hydrology, HESS, Remote sensing of Env., Scientific Data, Geophysical Research Letters, Remote sensing, Water, Computer and Geosciences, Hydrological Sciences, Journal of hydrometeorology, Sensors, Env. Res. Letters, Science of the Total Env. ...

Member EGU, AGU, IAG-ICCC working groups, GRACE Science Team

Leadership
1. Session Convener - European Geoscience Union meeting 2023, Vienna.
2. Co-chair of the IAG-ICCC working group on GRACE signal leakage.
3. European Geoscience Union Climate division ECS outreach team (2019 – 2021).
4. AOGS 2021 session co-convener.
5. Organizing committee member - UKIERI-DST workshop, WEIGH, September 2020.
6. Organizing committee member - Geodetic Week 2016, Stuttgart.

Invited or Plenary Lectures

11. Using Geodesy for Earth and climate sciences, **IISER Pune**, May 2023.
10. Using GRACE for hydrogeodetic applications, **IIT Roorkee**, Nov 2021, Nov 2022.
9. Geodesy for Earth System Science, Geospatial analytics workshop at **JSS academy of Technical education, Bangalore**, Sep 26th, 2022.
8. Understanding ground water anomalies using geophysical signals captured by GRACE, **Space Application Centre, ISRO**, May 26th, 2022.
7. Dealing with the signal leakage in GRACE, 2021 and 2022 edition of GRACE Hackweek at **Indian Institute of Technology Kanpur.**,
6. Using satellite gravimetry to understand extremes of water availability, Geoinformatics for Extreme Events GEE 2020, *held online*, Nov 24, 2020.
5. Using GRACE satellite data in Earth sciences: advantages and limitations, **Indian Institute of Technology Kanpur**, Oct 04, 2019.
4. Mapping global water stress from GRACE satellite data, Plenary lecture in the Drought Conference held in the **Oxford University, UK**, Mar 20, 2019.
3. Repairing the damage in GRACE recorded catchment scale hydrological signal due to filtering: a comprehensive data-driven approach, **GeoForschungZentrum (GFZ), Oberpfaffenhofen, Wessling**, May 18, 2017.
2. Repairing the damage in GRACE products due to filtering, Institute für Erdmessung, **Leibniz Universität Hannover**, Dec 2, 2016.
1. Minimizing impact of filtering on GRACE signal at catchment scale, Institute of Planetary Geodesy, **Technical University of Dresden**, Aug 8, 2016.

Conferences and Meetings

44 contributions in international conferences and meetings, latest five are:

5. B. D. Vishwakarma, Y. Ziegler, S. Royston, and J. L. Bamber, "A data-driven framework for estimating GIA from GPS and GRACE data" The General Assembly 2023 of the European Geosciences Union (EGU), from April 23–28, 2023 (oral presentation).
4. V. Tripathi, B. D. Vishwakarma, M. Horwath, "Data-Driven and Scaling Factor methods of GRACE leakage correction: Can they be reconciled?" The General Assembly 2023 of the European Geosciences Union (EGU), from April 23–28, 2023 (oral presentation).

3. A. Mandal, B. D. Vishwakarma, T. Angchuk, M. F. Azam, P. K. Garg, M. Soheb, "Glacier mass balance and its climatic and non-climatic drivers in the Ladakh region during 2000-2021 from remote sensing data" The General Assembly 2023 of the European Geosciences Union (EGU), from April 23–28, 2023 (Poster presentation).

2. M. Weigelt, A. Jäggi, U. Meyer, D. Arnold, T. Mayer-Gürr, B. D. Vishwakarma, B. Devaraju, H. Steffen, K. Sośnica, S. Ebadi, "Bridging the gap between GRACE and GRACE-Follow On by the combination of hlSST and SLR" The General Assembly 2022 of the European Geosciences Union (EGU), from May 23–27, 2022 (oral presentation).

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