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Simulation of streamflow in Glacierized Sunkoshi River Basin, Nepal, using a Glacio Hydrological Model

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Abstract

The Glacio-hydrological Degree-day Model (GDM, Version 2.0) simulates the river runoff and dissects the contribution from different water balance components on simulated stream runoff. GDM has been setup in Sunkoshi river basin and quantifies the various component of river runoff. Initially model is calibrated for the period 2000-2009 and then validated for the period 2010-2020 and demonstrates a satisfactory level of accuracy during both calibration and validation periods, with Nash–Sutcliffe Efficiency (NSE) values 0.79 and 0.77, volume difference (V.D) 8%,9.8% and R2 0.8. In Sunkoshi river basin, of total runoff snowmelt accounts for 9.68% during calibration and 11.38% during validation. Clean ice and debris-covered ice contribute 2.5% and 3%, respectively. Rainfall accounts 50.15% during calibration and 48.26% during validation, while base flow contributes 37.66% during calibration and 37.33% during validation. Runoff contributions by different component is varied, rainfall dominates during the monsoon season (June–September) in river basins, while ice melt peaks from May to October, influenced by temperature and precipitation patterns. The model can be an effective tool for research work on hydrological system dynamics and potential climate change impacts on Himalayan river basins.

Keywords

Climate change, Degree day factor, Glacier modelling, Glacio-Hydrological degree day model, Sunkoshi River Basin

1. Introduction

The Himalayas are distinguished by their numerous glaciers, which serve as a critical, year-round source of water for the rivers that originate from them. Stream are influenced by runoff from precipitation and seasonal snow-ice melting the networks of rivers [1]. The assessment of the water resources and seasonal and yearly variations in the high mountain asia (HMA) region over the course of a century is attracting the interest of an increasing number of scholars from diverse fields [2]. Due to the significant contribution of snow and glacier melt to river discharge in the upper sections of HMA, this area's water supply is particularly vulnerable to climate change [2]. Ever since the 1990s, researchers have used glacio-hydrological models to evaluate river discharge in addition to the role of snow and glacier melt in the HMA [2].Because glacio-hydrological models can be customized to match the features of the data that are currently available, they are being used extensively [3].

The energy balance model and the temperature index model are the two modelling approaches now utilized for determining discharge of river basins that have experienced glaciation. In research [3, 4], temperature index models have been employed in Himalayan basins with sparse data to estimate river discharge at various temporal scales. When taking into consideration sum of energy fluxes inside the atmosphere and glacier border, energy balance approach model melts as remainder in surface energy equilibrium and empirical relation between air temperature and melt drives temperature index model [3, 5].Version 2.0 of the Glacio-hydrological Degree-day Model (GDM) is updated version of distributed and gridded model that can simulate the hydrological components' contribution to the river discharge. GDM models the melting of glacier ice, snow-melt, rainfall, and base-flow at each daily time step as the four distinct run-off components in the overall discharge [3].

GDM is effective for Himalayan catchments where data scarcity is widespread due to impassable terrain and a dearth of weather stations because it can function with little data and few model parameters [4].Different numerous studies has been performed in the sunkoshi river yet the research work on quantifying the various major component of river discharge yet lags so for this study GDM model has been used as the appropriate tool for analysis.

2. Database and Methods

2.1 Study Area

The Sunkoshi is a transboundary river basin situated in eastern portion of Nepal, between Tibet and Nepal, extending from 28.512° to 27.5256° North and 85.43° to 86.312° East in the northern hemisphere, with heights ranging from 564 to 7945 meters above sea level (Figure 1). Covering an area of approximately 4847.0314 km2, with 2847.0314 km2 in Nepal and 2007 km2 in Tibet. The northern portion of the basin is mostly occupied by the Tibet and rest in Nepal covers three districts Sindhupalchowk, Sindhuli and Kavrepalanchowk. The outlet of the basin lies at Purchuwarghat situated in Sindhuli district The basin contains nine lakes, all located in Tibet, including the hazardous Limu Chimi Lake at 5089 m.a.s.l [6].Land use land cover pattern in the Sunkoshi river basin are forest (33.00%), crops (1.00%), grassland (37.00%), Bare lands (19.00%),wet lands (1.00%), settlements (4.00%), debris covered glaciers (1.00%) and clean glaciers (4.00%).

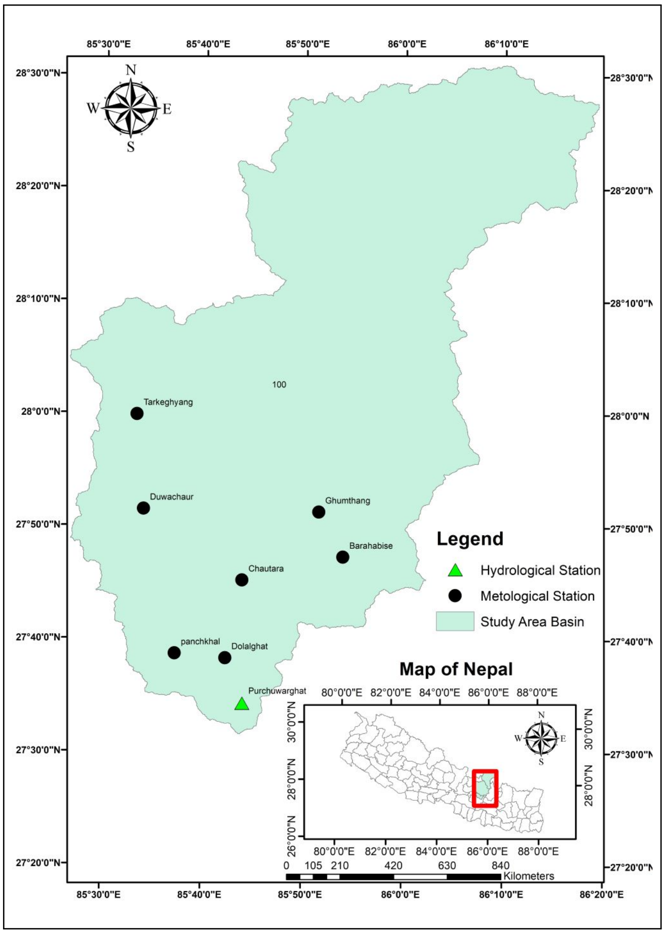

Figure 1: Study area map of Sunkoshi river basin, Nepal

2.2 Input Data

Hydrological and metrological daily observed data set of air temperature, precipitation and stream-flow data are obtained from Department of Hydrology and Meteorology (DHM), Nepal. The hydrological meteorological stations in the basin is also shown in (Figure 1). The Purchuwarghat hydrological station (Station no. 630) was selected as the outlet point for the study. Daily observed data obtained from DHM were available for the period 1964 to 2020 for the Purchuwarghat station. In this research work, IDW is used to calculate and fill missing daily precipitation values. Temperature data from Panchkhal, within the Sunkoshi River Basin was collected, encompassing the period between 1990 and 2022. Missing temperature data at each station posed a challenge, and to address this, the temperature lapse rate method was employed

For geo-spatial data set Grid elevation data in GDM is calculated using the Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) v3, having resolution 30 meters, available from Earthdata (https://www.earthdata.nasa.gov/). Land use/land cover data of 10 m resolution from Sentinel-2 was acquired from ESRI. The inventory of clean and debris-covered ice glaciers was sourced from the RGI Consortium (2017). The reclassification of land use and land cover using the LULC is in Figures 2 and 3.

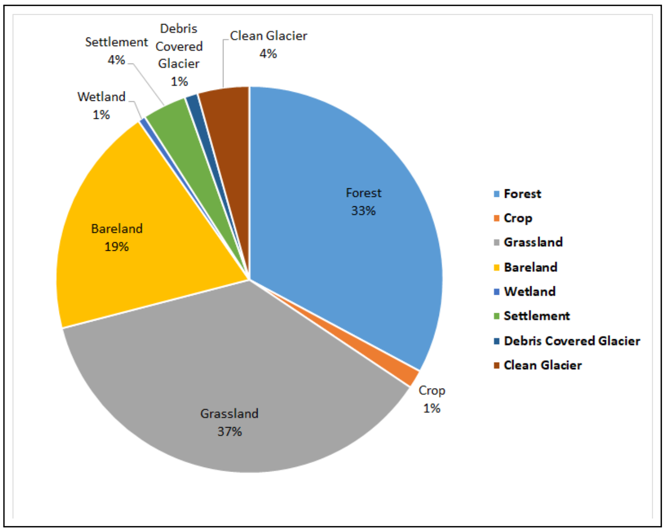

Figure 2: Reclassification of land use land cover according to the area coverage

2.3 Model Setup

According to Kayastha et al on [2, 3], the GDM v2.0 is a distributed and gridded Glacio-hydrological model that simulates the daily river discharge and calculates the contribution from snow-melt, ice-melt, rain, and base-flow on river discharge The model's discharge simulation is driven by daily extrapolated temperature and precipitation data, which are extended from the reference station to each grid. The distinction between snow and rain within each grid and time step is determined by the threshold temperature (TT), as follows:

$$\text{Precipitation} = \begin{cases} \text{rain, if } T \geq TT \\ \text{snow, if } T < TT \end{cases} \qquad [3]$$

The model separately estimates melt for snow, clean ice and ice under debris based on the degree-day approach [4, 7, 8] as:

$$M = \begin{cases} \{(ks, kb, kd) \times T\}, & \text{if } T > 0 \\ \{0\}, & \text{if } T \leq 0 \end{cases} \qquad [4]$$

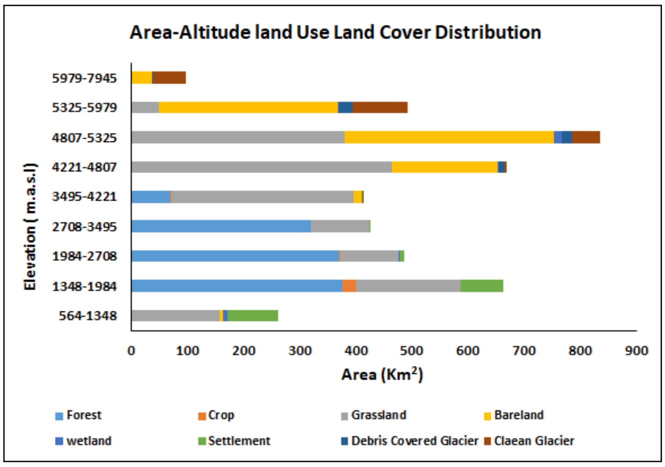

Figure 3: Classification of LULC according to the elevation

where, M is the snow or ice melt in mm d-1 in each grid, T is the daily air temperature in °C and ks, kb and kd are the degree-day factors in mm °C^{-1} d^{-1} for snow, clean ice and debris-covered ice, respectively [4]

The simulated discharge accounts summation of runoff from base-flow, rain, snow-melt and ice-melt from each grid. Summation of discharge at every grid is routed towards the outlet point which gives the final simulated discharge. For base flow calculation, a simulation approach similar to SWAT is employed. This involves utilizing a two-aquifer system concept—shallow and deep aquifer systems—to simulate base flow in a basin dominated by glacier and snow melt [3, 9, 10].Advantage of employing a two-reservoir system against single-reservoir system lies in its ability to release discharge during the recession period, ensuring a closer alignment between simulated and observed discharge levels. Figure 4. illustrates the overall framework that were carried out to analyze and evaluate the Impacts of climate change on the study area.

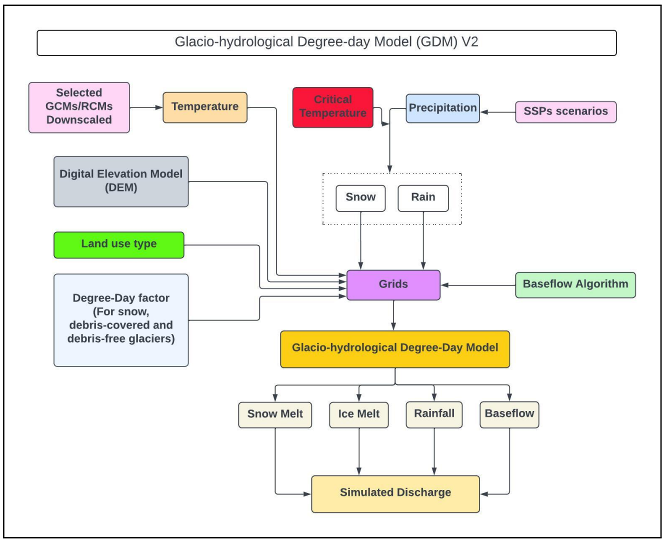

Figure 4: Flow Chart showing the methodology of the GDM v.2

2.4 Hydrological Simulation

2.4.1 Simulation Experiment

The GDM undergoes calibration for its performance over a span of ten years (2000–2009) and is then subjected to evaluation for the subsequent eleven years (2010–2020) by comparing its simulated discharge results with the actual data from the Purchuwarghat hydrological station in sunkoshi river basin. Range of values for degree-day factors for snow-melt and ice-melt in melt module parameter have their foundations from field observations conducted in the Nepalese Himalayas [2]. It is postulated that the degree-day factor for ice-melt beneath debris strata approximates half of the rate for clean ice melt, drawing insights from field observations carried out on the Khumbu and Luring Glaciers in the Nepalese Himalayas

2.4.2 Performance Index

Model's accuracy is evaluated through two method :The Nash-Sutcliffe Efficiency (NSE) index [11] as shown in Equation i

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Q_i - Q'_i)^2}{\sum_{i=1}^{n}(Q_i - \overline{Q})^2} \tag{1}$$

Where Qi represents daily observed discharge, Q'i daily simulated discharge, and $\bar{Q}$is average observed discharge. Additionally, model accuracy has been assessed through volume difference (VD) [2], calculated as:

$$VD(\%) = \frac{(VR - V'R)}{VR} * 100 \tag{2}$$

Here, VR represents the measured discharge, and V'R represents the simulated discharge

3. Result and Discussions

3.1 Model Calibration and Validation

In GDM, to optimize model's performance, various positive degree-day factors are applied, each specific to different months falling inside estimated ranges of values based upon observed values on various glaciers in the Nepalese Himalayas. Also, the model undergoes calibration for snow and ice coefficients, as well as recession coefficients. All the parameters and coefficient after model's calibration and its successful validation are shown in Table 1.

The model's performance is evaluated using the optimal parameters for the basin. In Sunkoshi river basins, Nash-Sutcliffe Efficiency (NSE) [11] values are 0.79 and 0.77, volume difference remains within 8 %. and 9.8% and coefficient of determination (R^2) reaches 0.83 and 0.77 for calibration and validation periods. Hence, model's performance during the basin's calibration and validation periods is very good [12]

Daily simulated discharge is compared with the observed discharge hydrograph of Sunkoshi river basin at Purchuwarghat for the both calibration and validation period (Figure 5). Simulated discharge by the model is consistent with both the high and low observed discharge at the Purchuwarghat. A slight overestimation in the pre-monsoon or low-flow period by the model could be attributed to the way precipitation is distributed. The intricate topography of the high Himalayan region within the basin can impact the spatial and temporal distribution of precipitation, posing challenges in representing precipitation patterns [3].

However, even with these restrictions, the model accurately predicts daily discharge, obtaining favorable NSE and R^2 values and keeping a volume difference within 10%, even with a small amount of input data.Figure 5.C, D shows an (R^2) of 0.8371 and 0.7705 between simulated discharge and observed discharge indicates that approximately 83.71% and 77.05% of the variability in the observed discharge in calibration and validation can be explained by the variability in the simulated discharge using this model. It also indicates a better fit of the model to the observed data.

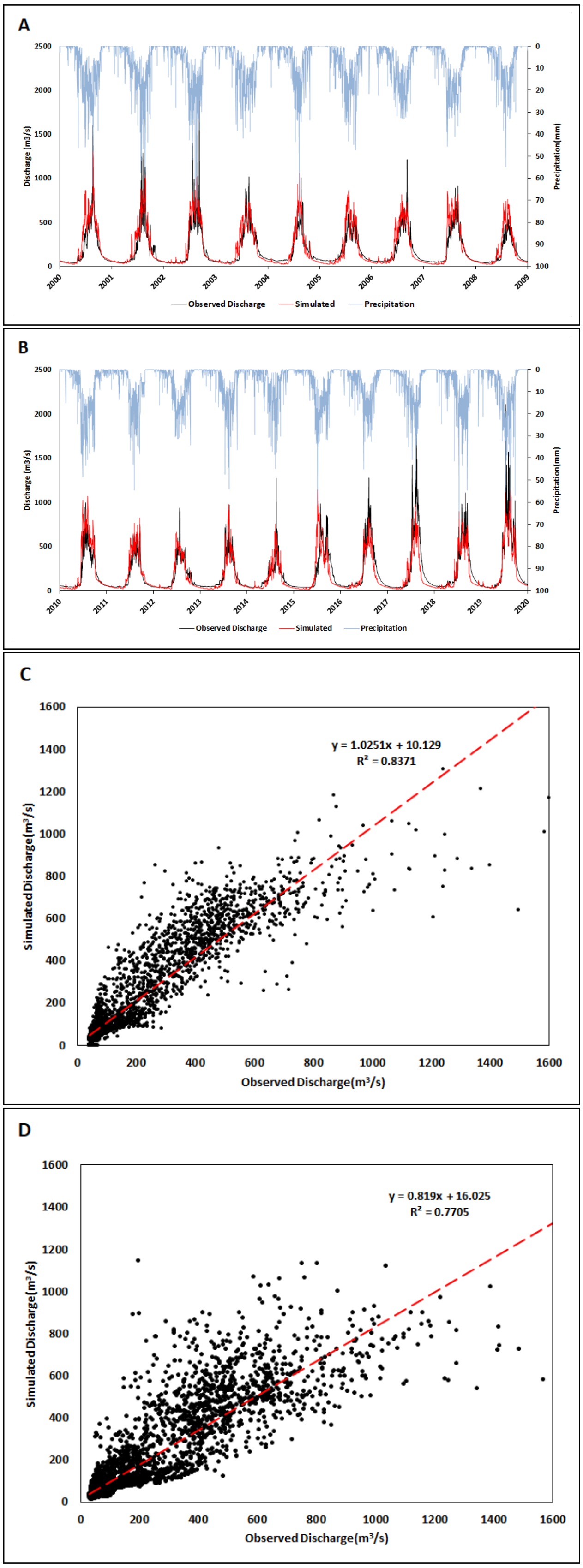

Figure 5: (A) Precipitation distribution and observed vs Simulated discharge for calibration (2000-2009),
(B) Precipitation distribution and observed vs Simulated discharge for validation (2010-2020),
(C)Scatter plots of observed and simulated discharge for the calibration period (2000-2009) and
(D) Scatter plots of observed and simulated discharge for the validation periods (2010-20200)

3.2 Contribution of Snow-melt, Ice-melt, Rain and Base-flow

Sunkoshi river basin's snow-melt accounts 9.68% during calibration and 11.38% during validation. Clean ice and debris-covered ice contribute 2.5% and 3%, respectively. Rainfall represents 50.15% during calibration and 48.26% during validation, while base flow constitutes 37.66% during calibration and 37.33% during validation (Figure 6).

Comparing our findings against research on Koshi river basin reveals differences. In their study, snow-melt contributed 16%, ice melt varied between 11-14%, rainfall constituted 25-26%, and base flow was at 45-47%. [4] Our results show a bit similar snow-melt contribution, varying ice melt, different rainfall percentages, and similar base flow contributions.Research by Khanal et al [13, 14] in Narayani river basin using SPHY model the contribution of rain runoff is 63%-65%, snow-melt 9%-12% , ice-melt is 3%-4% , and base flow is 21%. This research intently matches contribution from snow-melt and ice-melt, besides the contribution of rain and base-flow is varied this may be due to the area coverage of the basin i.e. the Narayani basin is about 37 times bigger than our study area river basin. Hence the runoff contributions by different component is varied Rainfall dominates during the monsoon season (June–September) in river basins, while ice melt peaks from May to October, influenced by temperature and precipitation patterns.

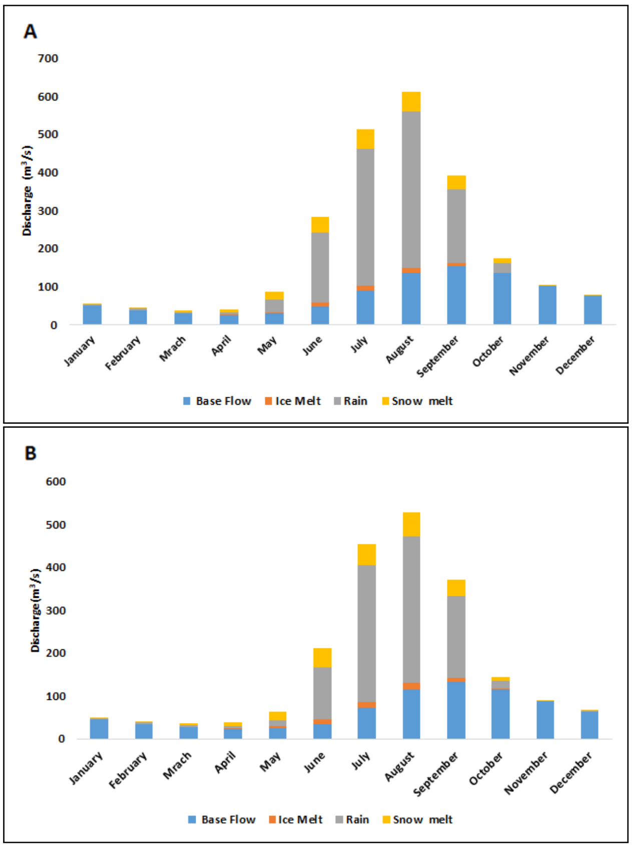

Figure 6: (A) Contribution of base-flow, rain, snow melt, and ice melt for the calibration period (2000-2009)
(B) Contribution of base-flow, rain, snow melt, and ice melt for the calibration period (2010-2020)

Table 1: Calibration parameters and values in Sunkoshi river basin

Parameters	Symbol	Units	Values
Critical Temperature		°C	2
Temperature Lapse Rate		°C/m	0.006
Recession coefficient			0.70
Latitude : Geographical centroid			28.05
Runoff coefficient (Land Use Land Cover Type)			
1. Forest			0.3 to 0.6
2. Crops			0.5 to 0.7
3. Grassland			0.5 to 0.6
4. bare land			0.3 to 0.6
5.Flooded Vegetation			0.95
6. Settlement			0.95
7. Debris covered glacier			1
8. clean glacier			1
Interception Threshold			1 to 6
Degree Day Factor			
	Snow (Ks)t	mm/(°C*d)	7 to 8.5
	Bare ice (Kb)	mm/(°C*d)	8 to 10.5
	Debris covered ice (Kd)	mm/(°C*d)	3
Time delay (shallow aquifer geologic formations)	δ gw,sh		20 days
Recession constant (shallow aquifer)	α gw,sh		0.5
Time delay (deep aquifer geologic formations)	δ gw,dp		100 days
Recession constant (deep aquifer.)	α gw,dp		0.5
coefficient of shallow aquifer percolation to deep aquifer	β dp		0.80

4. Conclusion and Recommendations

Glacio-hydrological Degree-day Model (GDM) has been effectively set up to estimate discharge in Himalayan river basins with glaciers highlighting its ability to account for snow-melt, ice-melt, rain, and base-flow valuable contribution on basin's hydro-logical system. Notably, model demonstrates a satisfactory level of accuracy with values of R^2 0.83 ,0.77, volume difference 8% and 9.8% and Nash-Sutcliffe Efficiency (NSE) [11]values 0.79 and 0.77 during both calibration and validation duration. Based on our investigation, snow and glacier melting barely affects the total stream flow during winter and reaches its highest point during the monsoon season. In contrast, rainfall predominantly influences the stream flow during the monsoon period, followed by the consistent contribution of base flow throughout the entire year. As a result, it's crucial for project planners and developers to consider the seasonal fluctuations in water supply and their impact on sustainable development

Acknowledgments

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