SNOW AND VEGETATION CHARACTERIZATION FOR HIMALAYAN RIVER BASINS USING GOOGLE EARTH ENGINE

A DISSERTATION

Submitted in partial fulfillment of the
Requirements for the award of the degree

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INTEGRATED MASTER OF TECHNOLOGY
in
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By
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DECLARATION OF AUTHORSHIP

I hereby solemnly declare that the work presented in this dissertation thesis titled "**Snow and Vegetation characterization of Himalayan River basins using Google Earth Engine**" submitted by me in partial fulfillment of the requirements for award of the degree '**Integrated Master of Technology**' in '**Geophysical Technology**' to the **Department of Earth Sciences, IIT Roorkee**, is an authentic record of my own work carried out during the period May 2018 to April 2019, under the supervision of **Dr. Ajanta Goswami**, Department of Earth Sciences, Indian Institute of Technology, Roorkee. The matter embodied in this dissertation has not been submitted by me for the award of any other degree in any other institute.

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This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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This dissertation is a culmination of support of many individuals, and this is a humble effort to pen my gratitude to them.

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ABSTRACT

Himalayas are one of the largest placeholders for snow and ice outside the Arctic circle and Poles. Geographical settings of the Himalayas, its closeness to the Indian Ocean, along with large mountain ranges and sub-polar settings contribute to an annual cycle of snowing and melt runoffs.

Indus, Ganga and Brahmaputra rivers systems are sustained by this annual cycle of melt runoff in the Himalayas. Approximately 40-50% of the flow from and snow melt runoffs are received by the above river systems. This water sustains the high demand of water use from a large segment of the Indian population, residing in the Indo-Gangetic plains and the Himalayas for various usage requirements such as irrigational, industrial and domestic water use. This water also serves as a source for hydropower generation and for sustaining the Himalayan floral and faunal diversity. Monitoring of Himalayan snow is thus essential, not only for the above stated reasons, but also due to hazard management associated with the many natural hazards occurring in the Himalayas such as avalanches, lake bursts and subsequent flooding, mass wasting and debris flow. Monitoring snow and ice in the Himalayas is thus imperative for its hydrological significance and for mitigating associated hazards in the region.

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1. Introduction

"The importance of snow fields and glaciers of the Himalaya also lies in their interaction with atmosphere. Albedo from snow is one of the important components of the Earth's radiation balance. The difference in temperature between the Himalayan cryosphere and the Indian Ocean pulls SW monsoon towards the Indian landmass during summer (SAC-ISRO's "Monitoring Snow and Glaciers of the Himalayan Region")". Hence, Himalayan snow and glacial landforms control the Indian climatic conditions at regional and global scales. Sensitivity of snow and glaciers to variations in temperature makes them a key indicator of climate change.

Present mindset in the scientific community dictates that increasing concentrations of greenhouse gases, ultimately leading to global warming, has led to significant snowmelt runoff increase in the river systems. In context to water security of the nation, snow fields and glaciers are essential elements which govern climatic changes in the Indian sub-continent. These elements thus need to be constantly monitored and mapped.

Extreme weather conditions, high peaks and rugged terrain contribute to the poor feasibility of conventional methods for studying the Himalayan region. "Satellite data due to its synoptic view, distinct spectral properties of snow and glaciers, high temporal frequency aided by advanced digital image processing and analysis techniques provide accurate and reliable observations (SAC-ISRO's "Monitoring Snow and Glaciers of the Himalayan Region")". Therefore, remote sensing applications along with Geographical Information System (GIS) techniques have become essential tools for fast, reliable observation and analysis of the rugged Himalayan terrain.

Snow is a significant piece of Earth's atmospheric framework. Snow spread controls the temperature of the Earth's surface, and once that snow melts, the water helps fill streams and supplies in numerous districts of the world. Changes in atmosphere can influence how much snow falls and impact the planning of the winter snow season. Between 1990 and 2015, the measure of land and snow that is snow-shrouded every year has diminished over numerous Northern Hemisphere locales, particularly amid the spring snowmelt season. Since changes in snowpack can have sensational ramifications for Earth's condition and for individuals, it is basic to create approaches to consistently quantify the amount of the planet is secured by snow. Over the long haul, this record of snow spread will help in translating environmental and climatic changes.

Observing and recording snow is important for deducing climate changes and study runoffs from various hydrogeological sources. "They can also cause or trigger natural hazards (ice avalanches, glacier lake outburst floods) requiring frequent observation of their changes" (Paul 2004). As snow and ice is distributed globally, with the density of Landsat data increasing by the day, using GEE for the quantification of global snow changes would serve as an essential tool.

Large amounts of carbon dioxide are stored in plants and trees through the process of sequestration. This is an essential component of the process of carbon production and recycling, known as the earth's carbon cycle. Forests are an important aspect in a sense that they buffer some of the carbon dioxide increase which is happening nowadays.

Forests are declining heavily in this new day and age. Burning of wood over deforestation produces large amounts of carbon dioxide which intensifies the Carbon Cycle. Trees have long lives and are immobile, giving them little opportunity to adapt to climate change. Although mobile animals can migrate quickly, trees require the dispersal, germination and growth of trees to adapt to changes in their environment over a longer run. Hence, it is imperative that forests are monitored such that proper track can be kept on sites of carbon production and sinks so as to prepare for the oncoming. Satellite imaging techniques need to be used in tandem with field information about trees images, e.g. type, growth stage, information about land type, so that the magnitude of forest cover in the past and present can be analyzed effectively, with a motive to improve forest health.

1972 marked the launch of National Aeronautics and Space Administration's (NASA) first satellite, and the Landsat program. Landsat sensors can detect and hence be used to record and observe forests. NASA has come a long way since launching more satellites, some of them which even exist in 2017, making Landsat the oldest observation satellite system in history. These satellites incorporate remote sensing, and store data in the form of frequency bands. This data is then processed and analyzed to obtain forest covers.

Applying snowline monitoring on a worldwide scale is conceivable since satellite imagery covers expansive districts of the globe. Prior to that, the application on a worldwide dimension couldn't be sought after because of the extravagant expenses of accessing acquired images and keeping the available databases updated at all times. Despite the fact that in-situ estimations can't be applied to pick up data about the processes on, in and around snow-ridden regions, satellite imagery offers a colossal chance to screen snowline changes at a bigger spatial and temporal scale. Over the previous decades an increasing number of satellite missions have been launched with the intention to review and screen the Earth's surface and near-surface systems.

The accessibility of Landsat Thematic Mapper(TM) to the general public since 1984 (USGS 2008) and the dispatch of the Sentinel satellite mission by the European Space Agency (ESA) inside the Copernicus program in 2014 both element a promising standpoint and speak to significant achievements for observing administrations dependent on satellite imagery. Up to this point, a solitary Landsat satellite crosses each point on earth once every 16 days. This return to recurrence is set to a totally new dimension by the Sentinel satellite mission (Sentinel-2A and Sentinel-2B) which record pictures of an area every 5 days with a three times higher spatial resolution of 10 m. This represents the shear intensity of information which will be available for processing in the future. On one hand, expanding spatial and temporal goals have a positive effect with respect to the density of data accessible for snowline monitoring. But then, it prompts a severe increase in manual workload and computation times on servers and PCs.

Google Earth Engine(GEE) incorporates satellite imagery and is a cloud-computing engine which has the capability to extract useful data from satellite images. GEE can process this data and present it in a visual form, as time series plots and can also be downloaded for further processing as required.

GEE has been very successful and has been utilized extensively for studying global forest cover, in identifying archaeological sites, population study, as well as soil mapping. GEE is not only used by researchers, but also by innumerable regular users of Google Maps, which has been mosaiced over GEE.

Future Global monitoring of snow packs will essentially incorporate self-operating processes for selecting appropriate scenes for snowline mapping. "Until today there have only been a few attempts to automate glacier mapping processes which rely on multi-temporal image processing and use Landsat-type sensors" (Selkowitz & Forster 2016, Winsvold et al. 2016). Shadows, cloud cover and seasonal snow cover are the most main components whether a satellite scene is appropriate or not for snowline mapping applications. The relentless work of analysts to physically peruse through the ever-increasing database of satellite images to all around map snowline, is as of now unsustainable and will be horrendous sooner rather than later if every accessible datum ought to be exploited with respect to the different applications in ecological examinations and glaciology specifically. Our objective is to create an automated process for selecting the most appropriate images for snowline mapping applications, using Google Earth Engine's computational power.

Giving scientifically solid and succinct data is an essential function in this day and age as snow cover changes are among the most noticeable pointers of environmental and climatic changes (WGMS 2008). With the previous section serving as a starting point, complete automation of snowline creation and their areal computation would serve as a fundamental element to monitoring snow cover changes. Thus, a worldwide evaluation at a high spatial and temporal goals could be sought after with significantly reduced effort. Aside from image selection, the creation of snowline and the consequent snow cover regional area estimation, there are different extra applications which can profit from the potential outcomes of computerized automation preparing giving improved access to significant data and information.

Research Objectives

The objective of this research are as follows:

1. To automate the process of data extraction and pre-processing.
2. To study the changes in snow and tree line for different period within a year.
3. To study the changes in a range of year.
4. To study the effect of movement of tree line on snow line.

2. Literature Review

In this Chapter the scientific background is given and the data for the computations are described. GEE's essential functionalities have been described as most of the computations are done with GEE itself, employing autonomous computations on a cloud-networking platform to achieve scientific research goals. This Chapter serves as a basis for the next chapter which discusses the methodologies used.

2.1 Google Earth Engine

Open-sourcing of Landsat archives have opened new doors for the scientific community. The density of the images available to the public has rapidly improved from when they weren't available for free to current scenario. This sea of images which is now available to the researchers is being exploited, for good reason.

Google takes this a step further and combines the access to around 10 petabytes of publicly available satellite data ranging from Landsat 4-8, Sentinel 1-2, MODIS to Aster, with climate, land cover and topography data. GEE has an inbuilt JavaScript and Python API where the data acquired above can be analyzed and manipulated. GEE code editor is an integrated development environment which allows access to all GEE function in a single place. GEE uses parallel computing to handle datasets and perform operations efficiently through cloud computing. The result is that the computational power offered by GEE far exceeds any other PC and allows unfunded scientists to use extremely powerful supercomputers to conduct planetary scale research using GIS-based operation involving satellite imagery, available with nothing but the internet. GEE is free to use and only requires registration to be approved for usage.

"The Google Earth Engine is a platform combining a multi-petabyte catalogue of satellite imagery and geospatial datasets with planetary-scale analysis capabilities and is available for everyone to detect changes, map trends, and quantify differences on the Earth’s surface (Google Earth Engine Team)." It is hence a tool for analyzing geospatial and temporal data with a JS and Python API.

2.1.1 Background

The prospect of mapping glaciers autonomously on a global scale is truly revolutionary for climate change studies. Google Earth Engine has the capability to operate on an extensive amount of data and deduce spatial-temporal aspects of glacial extent with a time period. To achieve this, it is essential to understand important functions and verify their existence with the GEE, and if not, whether they can be acquired through other methods.

Terminology of data types

The following terms and expressions are used here as they exist within the GEE (Google Earth Engine Team).

`Image`
: `Images` are composed of one or more bands and each band has its own name, data type, pixel resolution and projection. In addition, each `Image` has metadata stored as a set of properties.

`ImageCollection`
: An `ImageCollection` is a stack or time series of Images.

`Feature`
: A `Feature` is defined as a GeoJSON feature and includes geometry properties which can be added to a map in the GEE or outside of it when exported.

`FeatureCollection`
: A `FeatureCollection` is a collection of `Features`. Imported *.shp*-files are saved as `FeatureCollection` within GEE containing single glacier polygons as single `Features`.

Data availability

GEE sources its data from a variety of satellite systems. A user gets access to various images from systems such as MODIS, LANDSAT, SENTINEL or SRTM. In addition to that, the GEE data catalog includes satellite data in raw format, orthorectified imagery, top-of-atmosphere- and surface reflectance data.

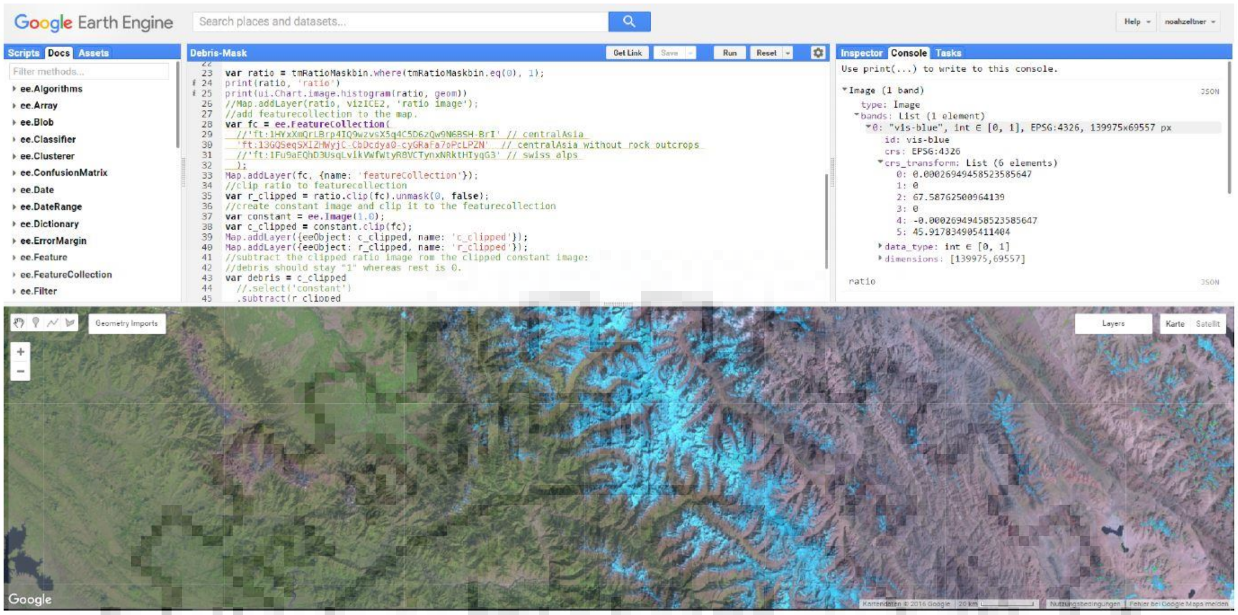


Figure 1: GEE's API with the documentation tab, the code editor, the output tab and map view

This data catalog serves as a fundamental element for computations inside the GEE environment. Additional data can be imported but have limited use as they compromise the use of in-built functions, which are designed to work on data within the GEE catalog.

Limits and restrictions

An integral component of algorithm building is testing of its various fragments to ensure that usage limits on Google's servers is not reached. Google has a query limit of 3 queries per second allocated to GEE so as to ensure that it these algorithms do not affect the availability of GEE's services.

Additionally, computations on the client's side time-out after three minutes, whereas exports time out after ten minutes per feature.

Optimizing ImageCollection and FeatureCollection sizes, the above limits and standards are achievable. Data and its parameters can be modified to bypass some of these limits. For e.g., at an expense of precision, the calculation times can be reduced using the scale parameter. Google offers additional computational power to bright and promising projects, but only a few of these exist.

2.1.2 Methodical feasibility: basic functionalities

Access satellite raw data

One can extract particular spectral band data by calling that band in any image with the GEE. A band normally consists of Digital Number(DN) values.

Sub-setting

GEE has inbuilt sorting features (by row, column and true/false operators) to filter a list. Sub settings are made by adding items to exclusions from more operations using filters. Filters play an essential role to downsize processing, by reducing the amount of data in pre-processing.

Masking

Masks are used to hide particular value and ranges. It is often applied as a filter.

Cloud detection

GEE provides a mechanism for scoring pixels by cloudiness, a scoring algorithm and also provides other methods to create a single combined image from singular pixel chosen by their cloudiness index.

Ratio images

Simple operations on pixel size are done to create ratio images.

Pixel counting

Areal calculations for snow and ice regions are made possible using a pixel counting algorithm, which are used in tandem with other internal functions in GEE.

2.1.3 Export and further calculations

Images, tables and FeatureCollections, which exist in the form of multi-band GeoTIFF, .csv-, .kml- and GeoJSON-files are the only exportable ones and are saved to one's own Google Drive, from where they can be downloaded for additional operations.

2.2 General Background on Snow and Ice monitoring

Snow as crystalline ice precipitates from the cloud in the form of a snowflakes. It is made of tiny granules made up of ice. This process of precipitation is known as snowfall. Density of snow varies with the time it has been present on the earth. Fresh snow density is around 30-50 kg/m3. After surviving for at least one summer, snow becomes fern and has a density of about 400-800 kg/m3. After surviving for multiple years, snow becomes glacier and has a density of 830-900 kg/m3. This noted density increase due to remelting and recrystallization accompanied with air pore reduction within the ice crystals.

Atmospheric conditions for snowfall are achieved at higher altitudes and latitudes. Snow cover can be divided into three major classes, which are:

i. Temporary
ii. Seasonal
iii. Permanent

Temporary and seasonal snow cover happens majorly in winters, whereas permanent snow covers are season independent and are retained for many years. Some regions with permanent snow cover are Greenland, Antarctica and the permanent snow line in hilly and mountainous regions. It is essential to monitor seasonal snow cover as it has various applications and directly impacts melt runoff.

Snow cover is the second largest component of the Cryosphere when its areal extent is considered, covering about 40-50% of the total land on Earth during winters (Hall et al., 1995; Pepe et al.,2005). Areal snow cover extent is an essential aspect for various hydrological and climatological uses.

Older research shows that the Earth's radiation budget is kept in balance by reflection from snow surface, which keeps the insolation in check (Foster and Chang, 1993; Klein et al., 2000; Jain et al, 2008; Zhao et al., 2009). "The thermal insulation provided by snow protects plants from low winter temperatures" (Rees, 2006). "Several fundamental physical properties of snow modulate energy exchanges between the snow surface and the atmosphere (Armstrong and Brun, 2008)".

"The surface reflection of incoming solar radiation is important for the surface energy balance" (Wiscombe and Warren, 1981).

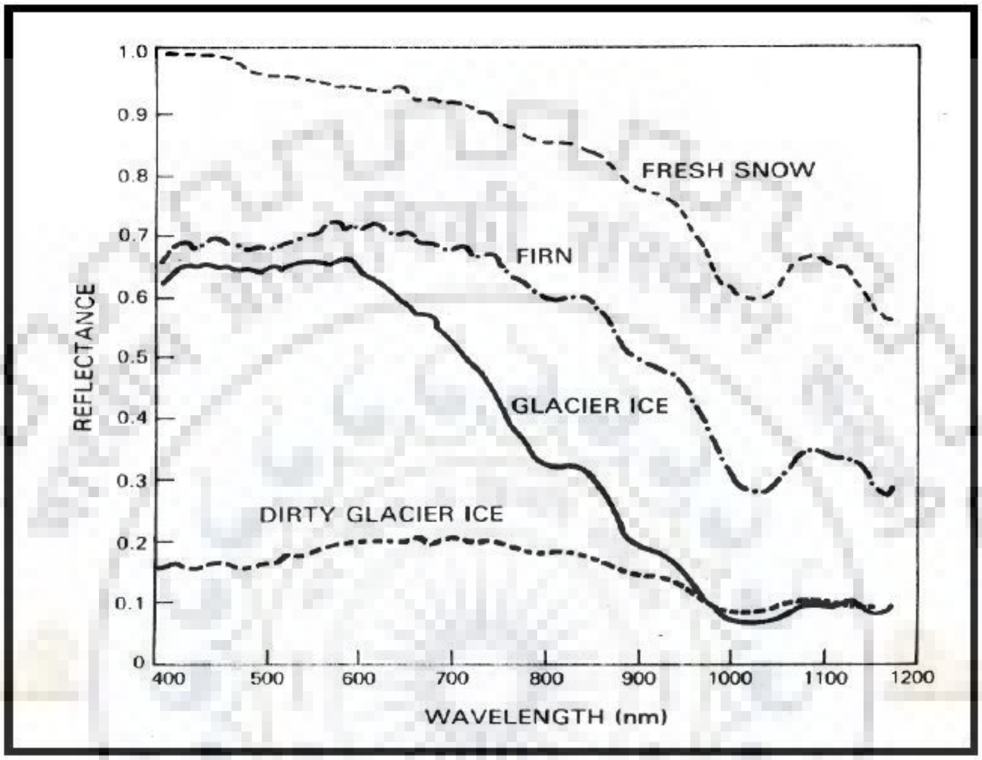
Increasing albedo for snow causes rapid changes in reflectivity in autumn and spring seasons in portions of the hemispheres further away from the equator. Positive feedback to surface air temperature is provided through the high surface reflectivity of the snow. This influence is most profound during the spring season when incoming Solar radiation is greatest over snow cover.

Another important aspect to be considered in snow precipitation is the role it plays in forming glaciers. Snowfall annually feeds the accumulation zone and is an essential factor in glacial studies which involve mass balance. The third role of snow is in glacial melt runoff. Snowmelt is a source of freshwater required for essential human and ecological sustenance, which other important industrial and agricultural applications in middle and high latitudes (Jain et al., 2008)

Himalayas are covered in snow and have a massive glacial extent. These mountains are drained by three major rivers, Ganga, Brahmaputra and Indus. Regions in upper altitudes of these river's paths receive heavy snowfall and subsequent melting leads to runoff to lower regions. The snowfall feeds glaciers of Himalayas and annual flow of all the rivers originating from higher Himalayas (Agarwal et al., 1983; Jain et al., 2010). Atmospheric temperature increase influences snowmelt and subsequent runoff pattern which is essential for hydropower generation (Kulkarni et al, 2002a; Kulkarni et al., 2011; Rathore et al., 2009; Rathore et al., 2011). Snow Cover data is also a requirement to strategically deploy plans as snowfall can significantly hinder human and machine mobility.

2.3 Snow Cover

Seasonal snow cover observation and analysis using conventional methods is difficult in the rugged terrains of the Himalayas primarily due to its harsh climatic conditions. Weather stations in large numbers are required for in situ analysis which is a tear some task. Moreover, the rugged terrains and harsh climate do not allow ground instruments to survive for long. Therefore, mapping and monitoring snow cover using remote sensing techniques is best suited because the areal extent is large, data is acquired at high temporal frequencies and snow can be distinctly recognized through its reflectance (Figure 2.1).



<u>Figure 2</u>: Spectral reflectance of fresh snow, firn, glacier ice and dirty glacier ice. Note changes in reflectance as fresh snow changes into glacier ice (Source: Hall and Martinec, 1985)

2.4 Normalized Difference Snow Index

One encounters difficulties in snow cover mapping under the influence of mountain shadows, making it difficult and time consuming. Normalized Difference Snow Index (NDSI) has been developed for this very reason. Snow appears to have higher reflectance as compared to other features and appears white, whereas this order reverses in SWIR region and snow appears darker than other land features. This characteristic has been exploited to develop NDSI for snow cover mapping. It is a useful application and can be used under mountain shadows. It also overcomes the issue of differentiating cloud and snow under mountain shadows.

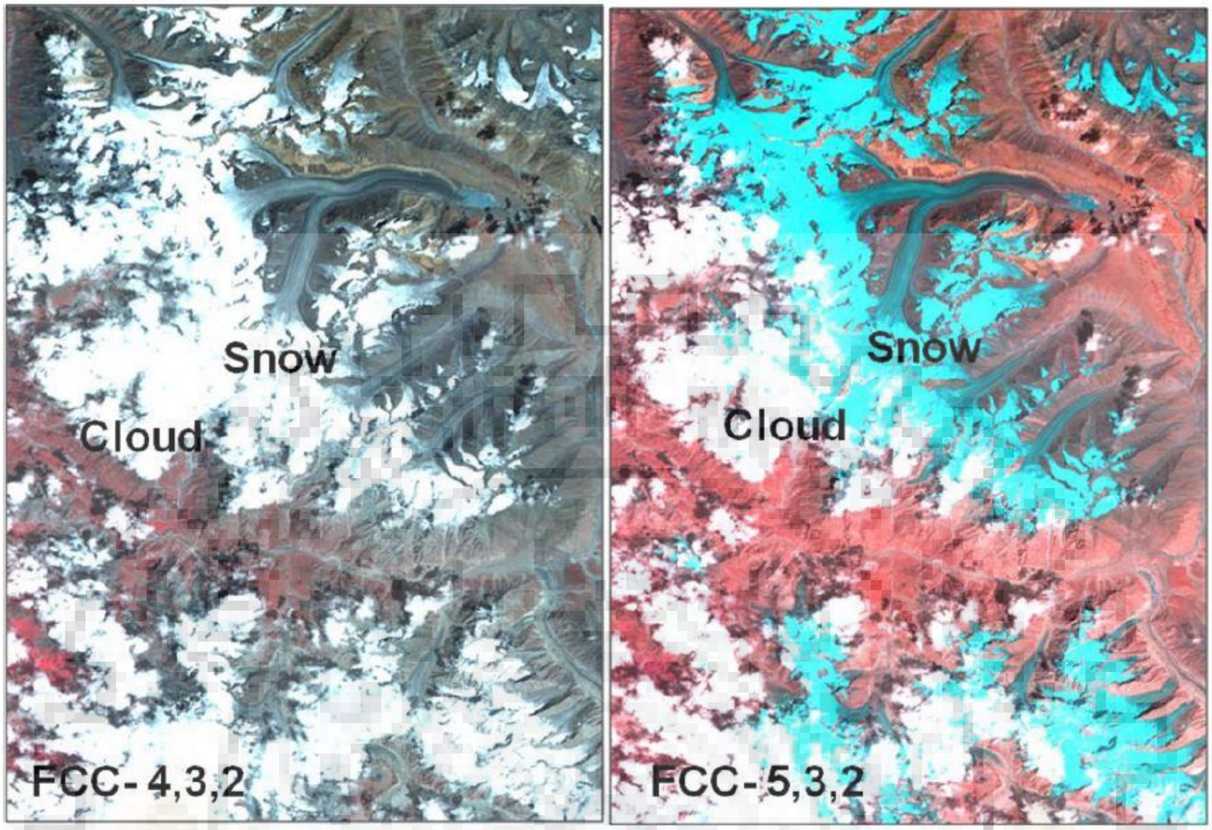
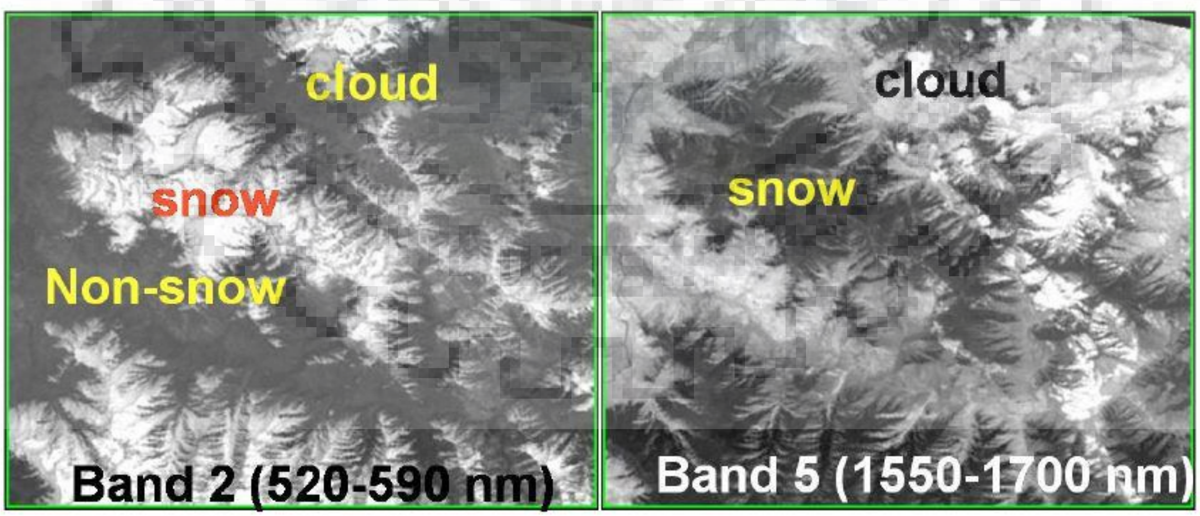


Figure 3: Snow and cloud differentiation using FCC with SWIR channel (1.55 – 1.75 μm) of AWiFS



<u>Figure 4</u>: Snow and cloud differentiation using SWIR channel (1.55 – 1.75 μm) of AWiFS. Band 2 shows snow and cloud as bright white and rest as grey to black whereas Band 5 shows snow in dark tone and cloud in white tone

As snow reflects strongly in visible region and absorbs in SWIR, an NDSI image is prepared to delineate snow and non-snow features with the help of difference ratio of visible and SWIR channel, as given below

$$\text{NDSI} = \frac{\text{Green Reflectance (B2)} - \text{SWIR Reflectance (B5)}}{\text{Green Reflectance (B2)} + \text{SWIR Reflectance (B5)}}$$

The above formula is applicable for B2 and B5 bands and can be rewritten for B1 and B2 bands as

Polar orbiting sensors such as MODIS, AWiFS etc. have been routinely used to map and monitor snow cover at regular interval (Hall et al., 1995; Kulkarni et al., 2006b; SAC, 2011; Singh et al., 2014; Rathore et al., 2015a). Snow being very dynamic in nature, high temporal frequency is an essential requirement in snow cover monitoring.

2.5 Essential components of Snow mapping

2.5.1 Satellite imagery

The focus lies on optical rather than on microwave sensors and especially on Landsat TM/ETM+ type sensors which are most frequently used for snow and ice mapping (Paul, 2014). All algorithms employed in upcoming chapters have been developed using Landsat TM/ETM+ type sensor data but work as well with the Operational Land Imager (OLI) sensor from Landsat 8 or Sentinel 2 Multispectral Image (MSI) sensor imagery (Paul et al. 2016). Other sensor types have not been tested but will work similarly if the sensor has individual bands recording in similar spectral ranges (Zeltner 2016: "Using the Google Earth Engine for Global Glacier Change Assessment").

2.5.2 Scene selection

Three factors/requirements for optimal image selection are (Paul 2004):

1. cloud-free conditions
2. timing of images near the end of the ablation period
3. minimum extent of seasonal snow

Prerequisite (1) can be evaluated using a cloud-score algorithm which sorts pixels by their relative cloudiness including various indicators of a pixel to be cloudy. By filtering the dates using built-in functions prerequisite (2) is considered.

Since most snow lain areas are rarely images in decent standard conditions and hence prove to be very challenging when the above requirements are implemented. Finding good images in a particular region does not guarantee its viability for further calculations and analyses.

2.5.3 Classification of snow and ice area

Segmentation of ratio images

Classification of snow and ice involve different methods, which have been investigated in older studies. One of the most promising methods still is the segmentation of ratio images which already has been used extensively until today (Carturan et al. 2013, Gardent et al. 2014). Near infrared and shortwave infrared bands have been, in combination with red light bands (corresponding to TM4, TM5 and TM3 respectively), been implemented successfully so as to acquire better performance in zones of shadows (Rott & Markl 1989, Paul & Kääb 2005).

Sources of error

Seasonal snow heavily impacts the are occupied by snow, as it appears larger than it actually is. Water bodies are also sometimes classified as glaciers and require removal through manual visual interpretations or by using more commonality in the datasets or by using classifiers. "Evaluating the result of the classification in the other direction is the case for shadow being cast on parts of the glacier which usually occurs near steep mountainsides (Paul 2000)."

2.5.4 Automation processes

Essential experience and expert technical knowledge is a critical component in creating high quality inventory of snow and ice images from aerial photographs and satellite imagery. All parameters need to judged equally to ensure proper quality is maintained throughout the database. "Additionally, every satellite scene should be analyzed individually as atmospheric conditions are changing from scene to scene and even within a single scene. This knowledge is still applicable when working with semi-automated methods as has been done in other studies before (Selkowitz & Forster 2016, Robson et al. 2016, Winsvold et al. 2016, Zeltner 2016: "Using the Google Earth Engine for Global Glacier Change Assessment")".
Automations often are not flexible in approach to the above parameters. Improving the intuitiveness of an algorithm so that the computer works in a way an actual expert would in processing the data. An inherent component of this is taking actions on whether processing should further based on current results. Attaining this intuitiveness and reliability is a monstrous task. Accuracy depends upon the spatial and temporal resolution of the images, which might not be suitable for particular applications. Any simplifications done to the algorithm contribute to errors.

Automation in itself is a boon. Although it is difficult to automate the process of selecting appropriate images based on different climatic and atmospheric conditions in different regions of the world with highly varying parameters such as cloudiness, snow and shadows, working towards automation has a lot of positives. Ever increasing workload and processing times on servers and PCs requires alternate methods to handle this endless, humongous data flow. Automation enables true powers of computer-based processing to come in play and can introduce new dimensions in geospatial calculations. Automation can be done with the GEE itself, where it incorporates cloud computing to handle all queries on its own servers, leading to faster processing speeds on the user's PC. This PC is given the final results of the data enquiry. This hence makes snowline and ice change monitoring a viable option.

2.6 Normalized Difference Vegetation Index

Normalized Difference Vegetation index gives an estimation of the quality of plant life and their density at a particular pixel in an image based on the principle that intensities of reflected sunlight vary according to vitality and density in visible (0.4-0.7 um) and near-infrared (0.7-1.1 um) spectrum when picked up by satellite sensors. Healthy leaves absorb light in the range of red (0.63-0.69 um), their cell walls reflect light from the NIR spectrum. If an observation is made where VIS is less than NIR collected, it is likely that the pixel is populated with healthy plants as they absorb most of the red. Hence, NDVI can also serve as a photosynthetic capability indicator. Monitoring NDVI can be used to detect changes in land usage and cover, can be used to identify anomalies in changing seasons and is useful for identification of areas of likely desertedness and drought.

The index ranges from -1 to +1 and is calculated by

$$NDVI = (NIR - VIS)/(NIR + VIS)$$

from the satellite frequency bands, while NDVI-values itself range from 0.1 (stone, sand and snow), 0.3 (sparse vegetation) and 0.6 (temperate forests) to 0.8 - 1.0 (highest possible density of vegetation/leaves, e.g. rainforests). Water presence is indicated by an NDVI value below zero. Cloud cover and aerosols play an important role in NDVI analysis as these cause distortions in the data and these pixels should be filtered out to maintain a high-quality data.

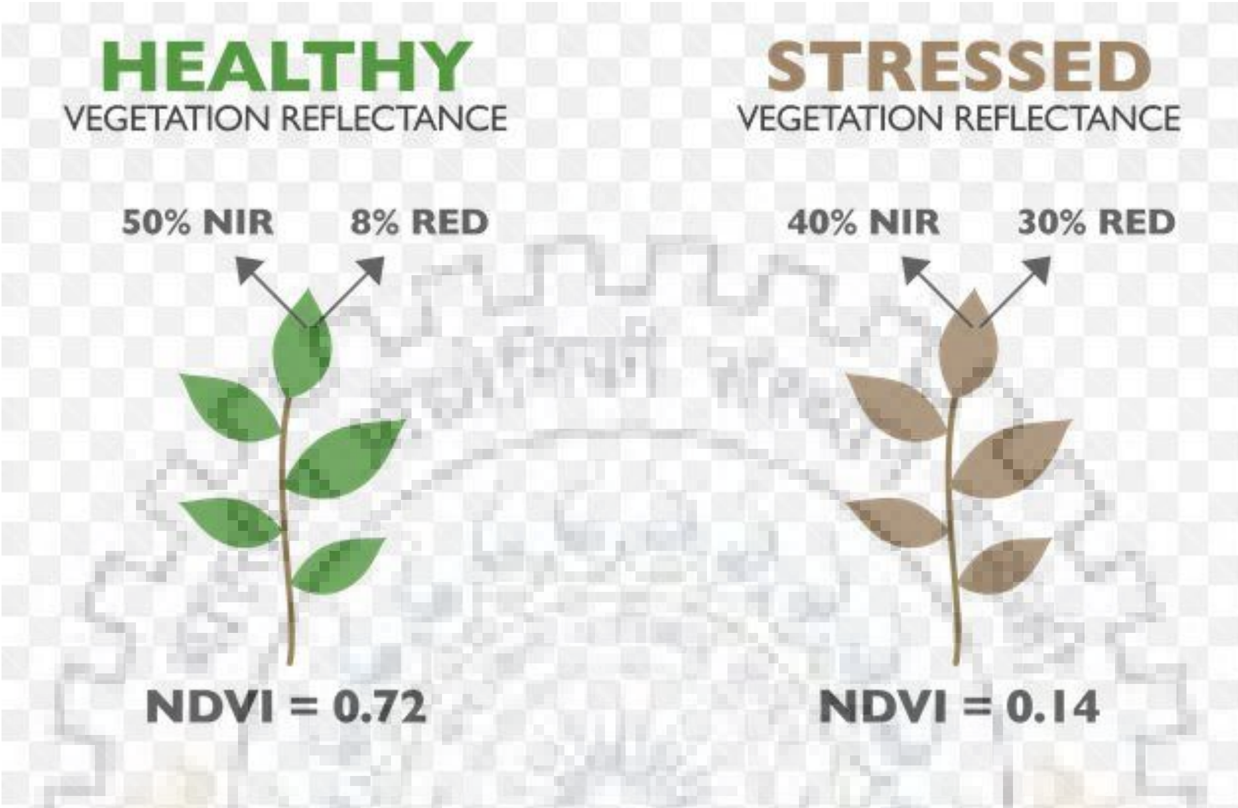


Figure 5: Average NDVI differences between a healthy and a stressed plant

3. Study Area

Brahmaputra, Indus and the Ganges are the three most important river basins which are supported by the annual melt runoffs from Himalayan snow. These three river systems are of extensive utility to the Indian subcontinent as a whole, serving as sources for freshwater required for different domestic, agricultural and industrial uses, whilst also serving as an important aspect governing Indian climatic changes and is also a definite indicator of global warming. Even minute disruptions in these melt runoff patterns can lead to extensive adversities, disrupting the ecology of that region, which is one of the essential reasons why these three river systems need to be analyzed.

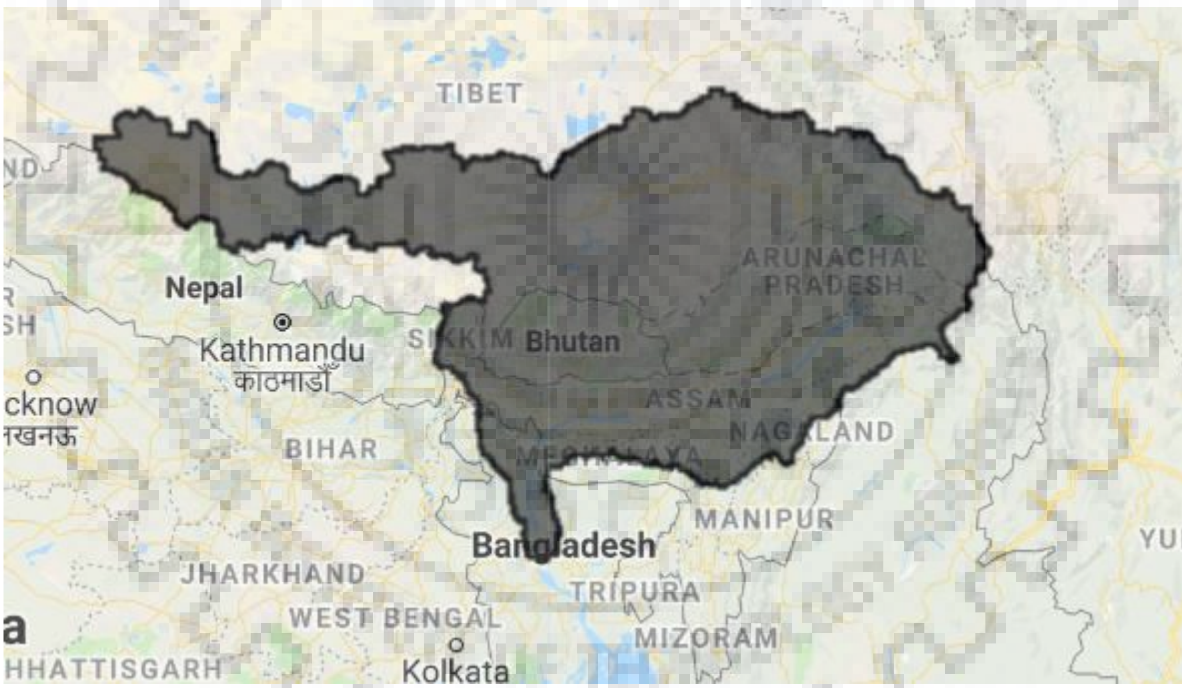


Figure 6: Brahmaputra Basin generated using GEE

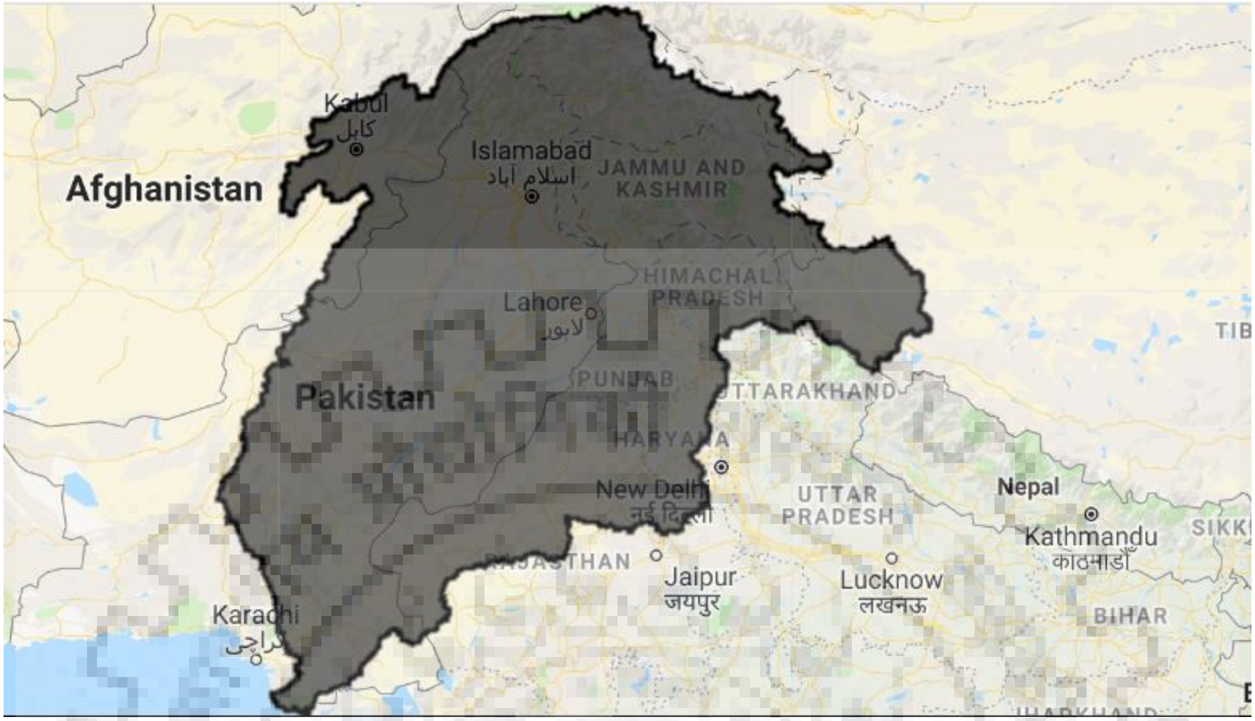


Figure 7: Indus Basin generated using GEE

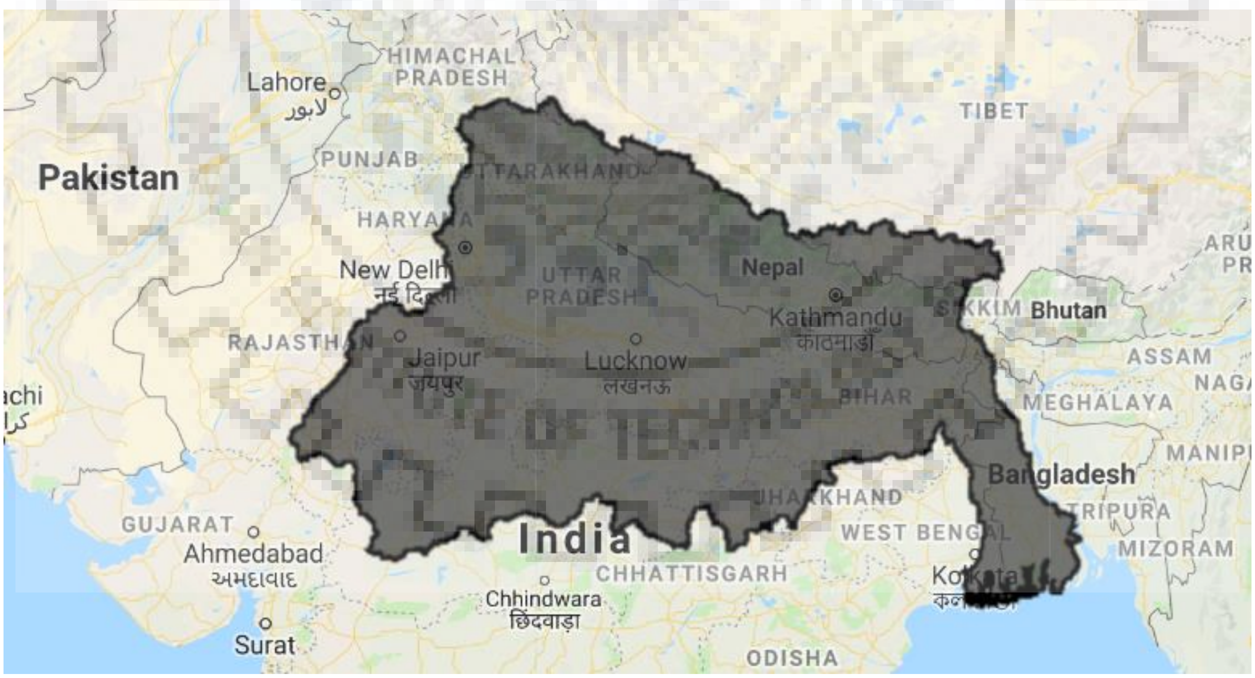


Figure 8: Ganga Basin generated using GEE

4. Data used

MODIS data

MODIS is an imaging sensor onboard the NASA Terra satellite. It has 36 bands out of which 2 bands were selected for analysis.

MOD13A1, which corresponds to vegetation data, and gives us NDVI

MOD10A2, which corresponds to snow cover data and gives us maximum snow extent.

SRTM-DEM

Contains high resolution elevation data which was used to create elevation-count-time plots

5. Methodology

Google Earth Engine plays a very essential role in remote sensing application such as satellite imagery. Automation is an important aspect of this as it reduced mind labor for the various glaciologists around the world. Here we discuss the methodology followed in this study. The methods of this study in GEE, in chronological order of the functions required, is as follows:

5.1 Importing ".shp" files

Ganga, Brahmaputra and Indus basins have been evaluated for snow and vegetation analysis, so as to observe trends in snowline and treeline changes.

```
Imports (3 entries)
▸ var table: Table users/ashishchopra375/ganga
▸ var table2: Table users/ashishchopra375/Brahmaputra
▸ var table3: Table users/ashishchopra375/indus
```

Figure 9: GEE- Imported tables

The most fundamental and basic step in achieving this is importing the required data in its specific format, which in our case is Shape or .shp file format. These files contain the areal extent of the above river basins in the form of area polygons.

5.2 Creating Feature Collection

After importing the data, we extract essential features such as the overall shape, corners and geometry of the basin. For this, we use the FeatureCollection aspect, where we can simply change the name of the river basin in the function to acquire features for different river basins.

```
var area= ee.FeatureCollection('users/ashishchopra375/Brahmaputra').geometry();

Map.addLayer({eeObject: area, name: 'area'});
Map.centerObject(area);
```

Figure 10: GEE- Feature Selection

Next step is highlighting the required area, i.e. the area covered by our three river basins by using a layer over the map as shown in the code snippet above.

5.3 Extracting Satellite Data

This study requires two different types of data to be extracted, one pertaining to snow and the other to vegetation. We collect images from MODIS satellite series, with data corresponding to two different aspects. MOD13A1.006 Terra Vegetation indices, which have a spatial and temporal resolution of 500m and 16 days respectively, which is used for calculating NDVI. The other, MOD10A2.006 Terra Snow Cover indices, having the same spatial resolution as the MOD13A1 but a temporal frequency of 8 days, and it gives maximum snow extent.

```
var imgcolfun = function(start, end){
  var imgColl = ee.ImageCollection("MODIS/006/MOD13A1")
    .filter(ee.Filter.calendarRange(1, 356, 'day_of_year'))
    .filter(ee.Filter.calendarRange(ee.Number(start), ee. Number(end), 'year'))
    .filterBounds(area)
  ;
  return imgColl;
};
```

Figure 11: GEE- Extracting MODIS Data

By changing the name in the ImageCollection function (MOD13A1 to MOD10A2), we can extract the required data sets.

Filter Calendar Range selects the time period in a year for which data needs to be extracted.

(Start, End) is used to specify the range of years for which data needs to be extracted.

Filter Bounds limits the area of extraction to our study area.

5.4 Normalization of the extracted data

In order to bring the extracted MOD13A1 data to NDVI range, each pixel value in the image is multiplied by a factor of 0.0001, which is the scale.

Name	Units	Min	Max	Scale	Wavelength	Description
NDVI		-2000	10000	0.0001		Normalized Difference Vegetation Index
EVI		-2000	10000	0.0001		Enhanced Vegetation Index
DetailedQA						VI quality indicators

Figure 12: GEE- MOD13A1 Data Properties (Earth Engine Data Catalogue)

MOD10A2 data requires no such normalization.

Maximum_Snow_Extent	The maximum snow extent during the eight-day period plus other values. Cells with snow on any day during the period are mapped as snow. Clouds are only reported if all eight days were obscured by clouds. Cells with no snow are filled with the observation that occurred most often. Possible values are: 0: missing data 1: no decision 11: night 25: no snow 37: lake 39: ocean 50: cloud 100: lake ice 200: snow 254: detector saturated 255: fill

Figure 13: GEE- MOD10A2 Data Properties (Earth Engine Data Catalogue)

5.5 Classification using threshold values

For classifying the extracted data, we use a mask which differentiates data based on a threshold value. The above code snippet is applicable for MOD13A1 dataset, which gives us NDVI. Here, for putting sparse vegetation as a threshold, we get gte_ndvi value as 0.3, and all other values are classified as ones and zeroes whether they are more or less than this gte_ndvi value.

```
var fnSnowcount = function(img){
  var classification_masked = img.updateMask(ndvi.gte(gte_ndvi));
  var count = classification_masked.reduceRegion({
    reducer: ee.Reducer.count(),
    maxPixels: 34e9
  });
```

Figure 14: GEE- Classification of Data

Similarly, for MOD10A2 dataset, we use a threshold value of 200. All pixel values of 200 are classified as snow or ones, else as zeroes.

5.6 Tree and Snow Count

After pixel value classification, we count the number of pixels with values of one.

```
var fnLimit = function(img){
  var count = ee.Number(img.get('treecount'));
  var mean = ee.Number(img.get('mean_tc'));

}
```

Figure 15: GEE- Code for count

In the MOD10A2 dataset, we count to number of pixel with values of one to get the tree count. Similarly, repeating the same procedure for MOD13A1 dataset, we get the snow count.

5.7 SRTM-DEM and further operations

Above filtered images are exported and elevation-count modelling is done at elevation increments of 500m. This essentially gives us an idea of tree and snow distribution at various elevations. This combination of SRTM-DEM and count data gives us zonal count, which can be multiplied with the pixel area (250000 m2 or 0.25 km2) to give us the area covered by any particular feature.

We apply this procedure to snow and vegetation count data so as to obtain areas covered by snow and vegetation respectively. This has been done for data from the months of March and September of a year because seasonal snow cover is least during these months.

For each year, we average out the data for the months of March and September, respectively, and arrive at single values for these months.

6. Results

PART 1

In Figures 16 to 21,

X-axis in the diagrams represents Months, from January to December;

Y-axis represents snow/tree cover area in km^2.

6.1 Vegetation in Ganga Basin, 2001-2016

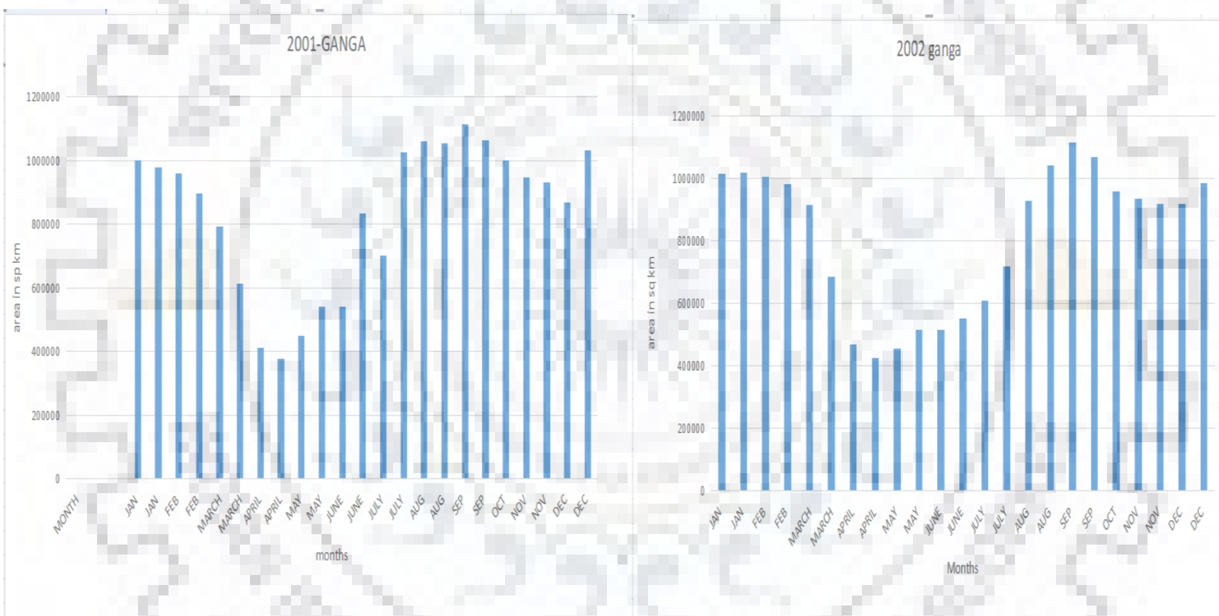
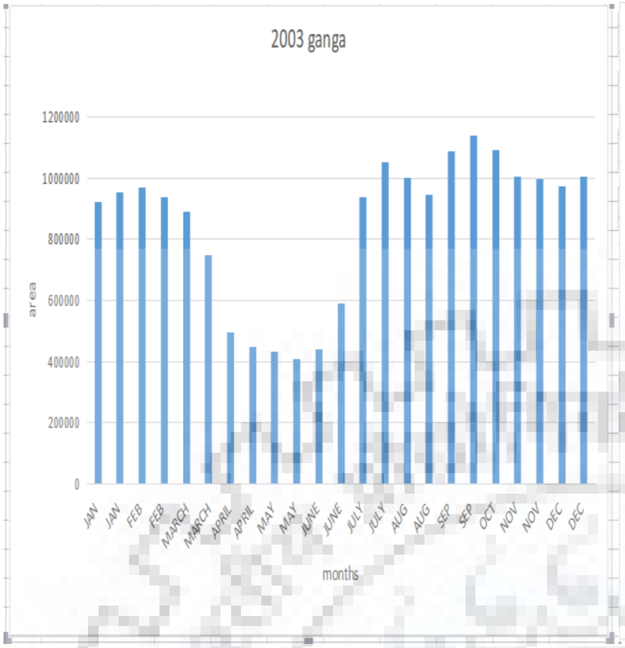
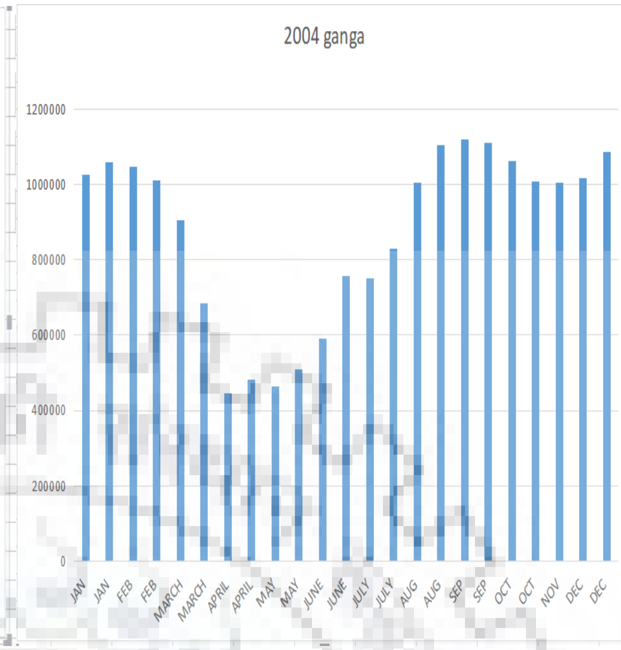
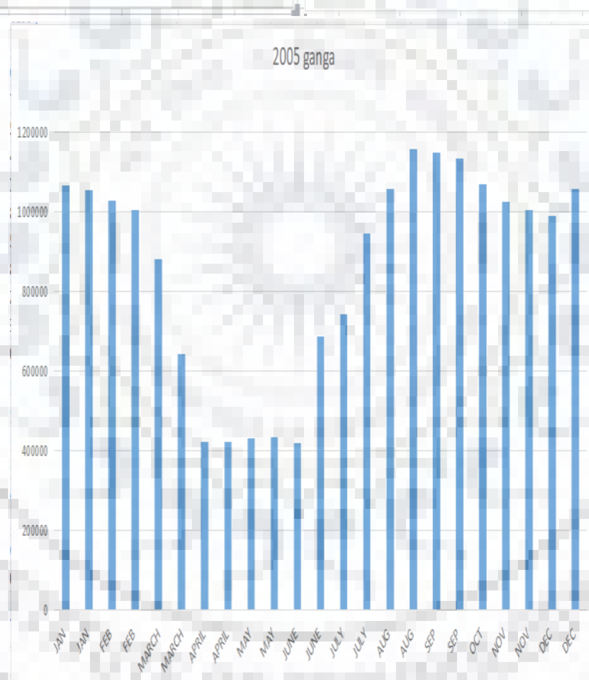
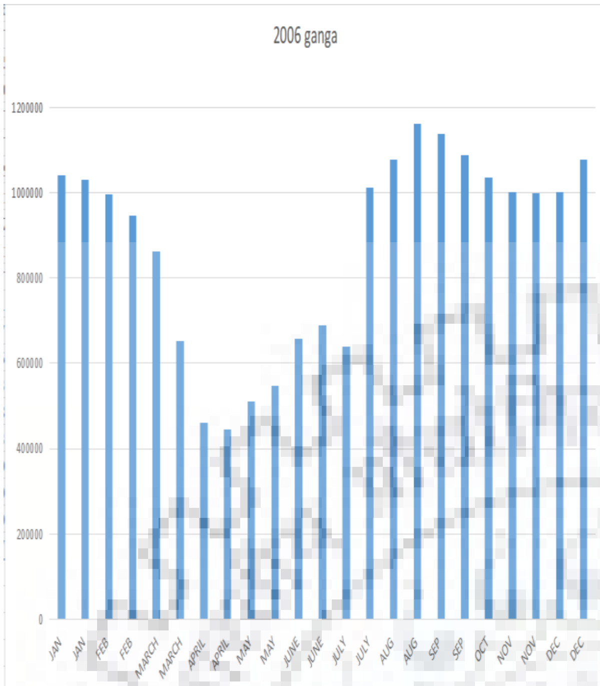


Figure 16: Ganga Vegetation area 2001-16 (Monthly)


2003 ganga
area
months


2004 ganga


2005 ganga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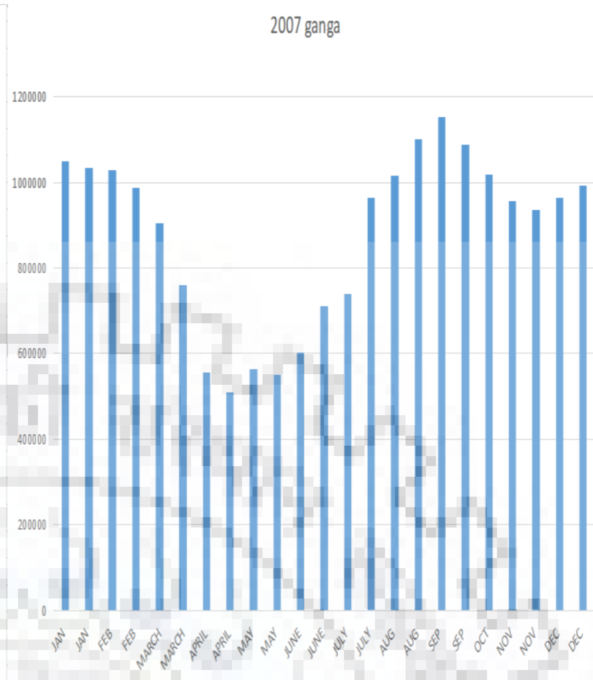
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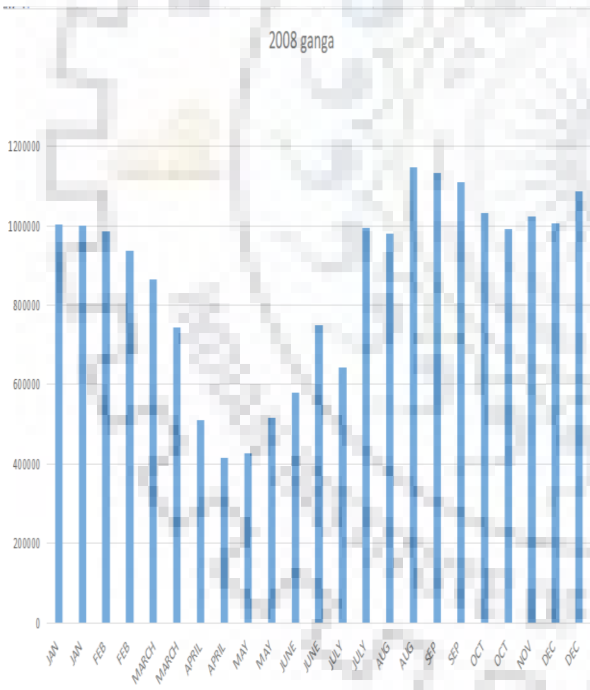
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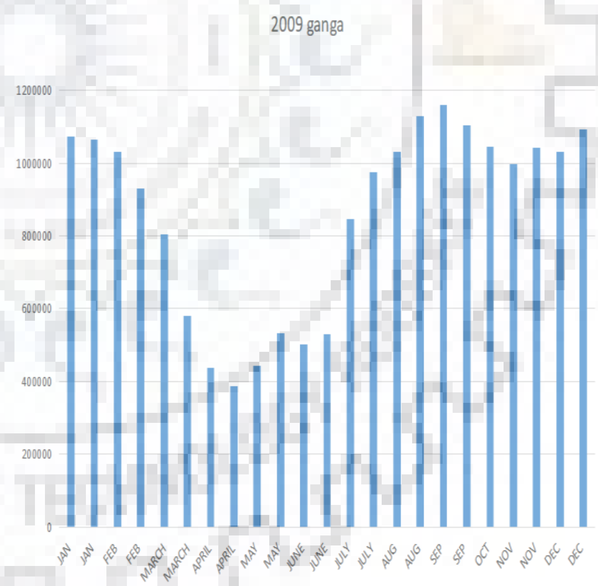
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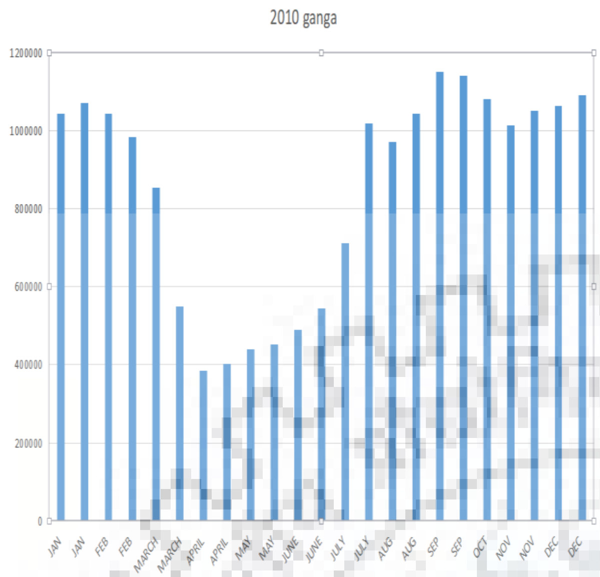
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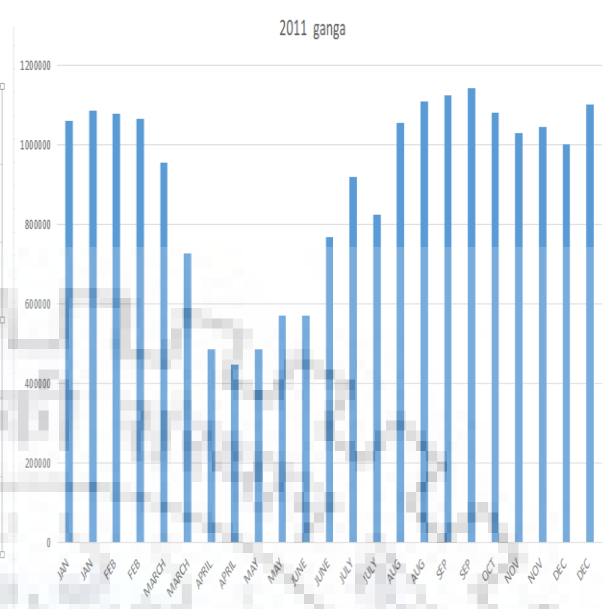
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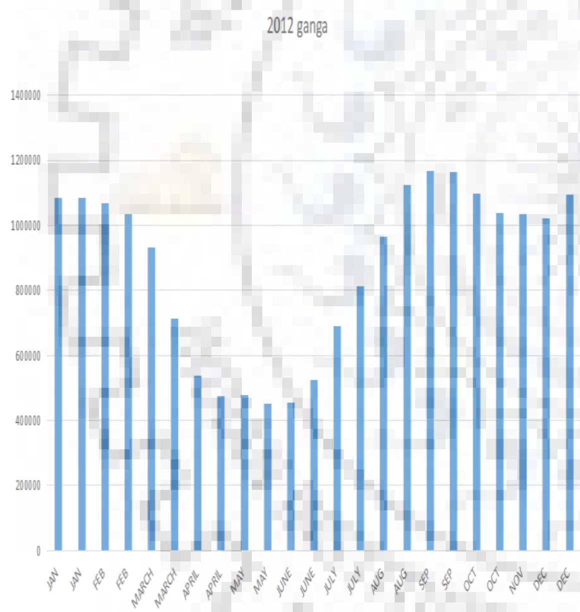
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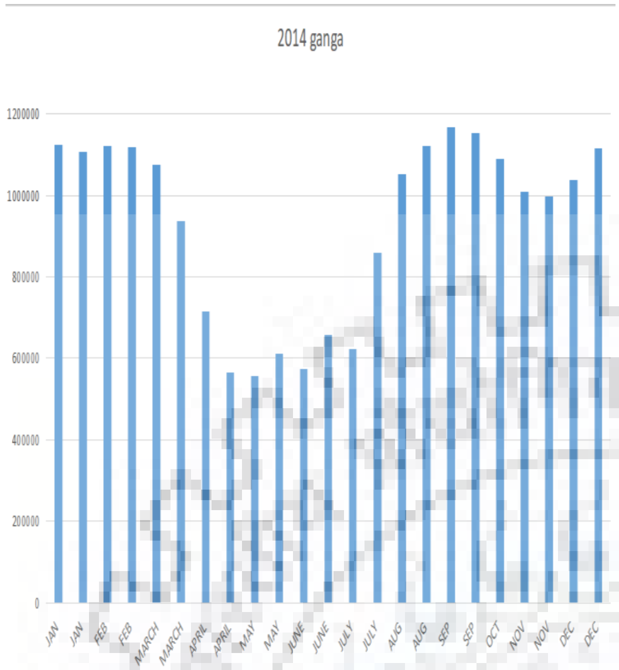
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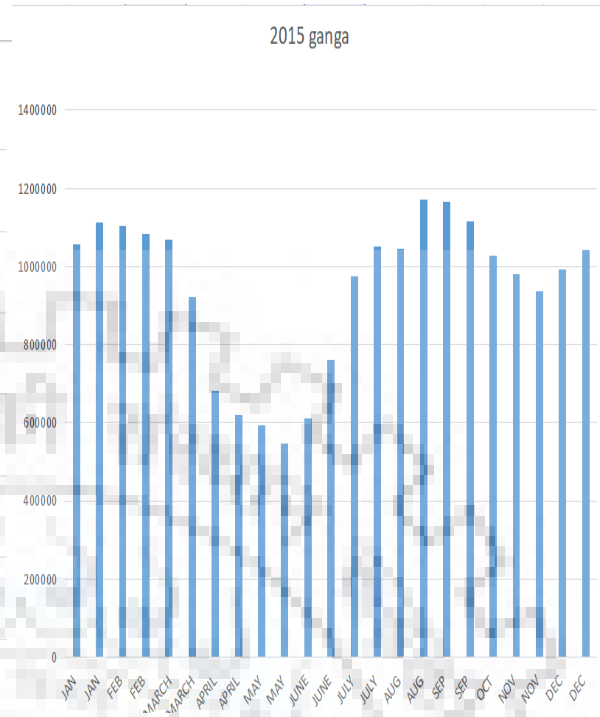
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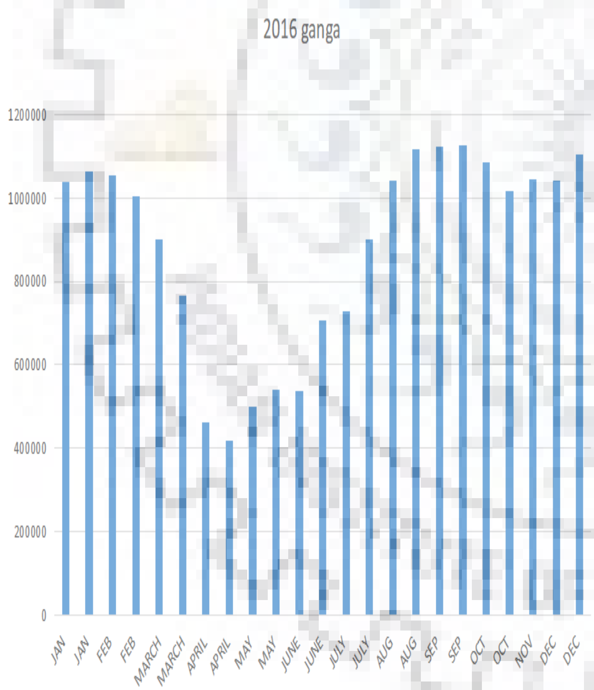
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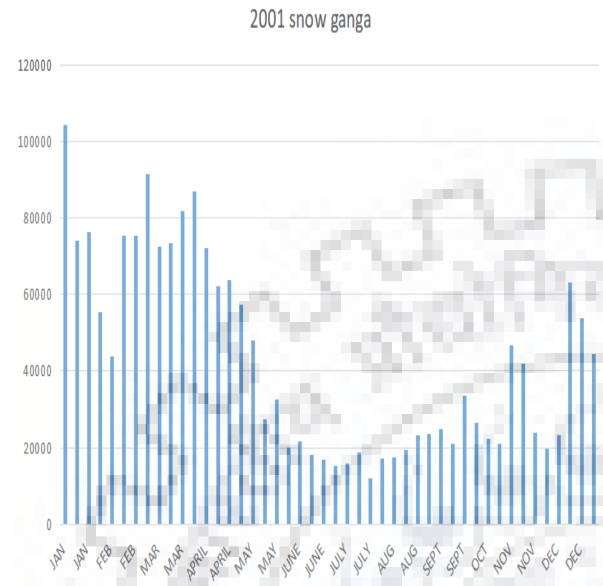
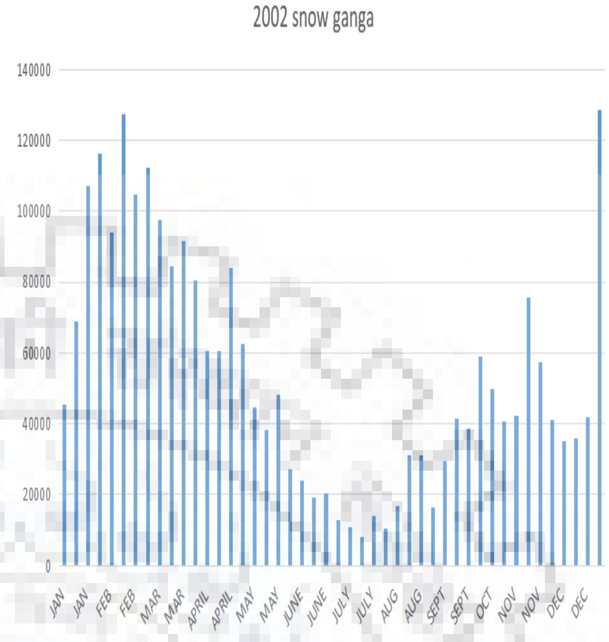
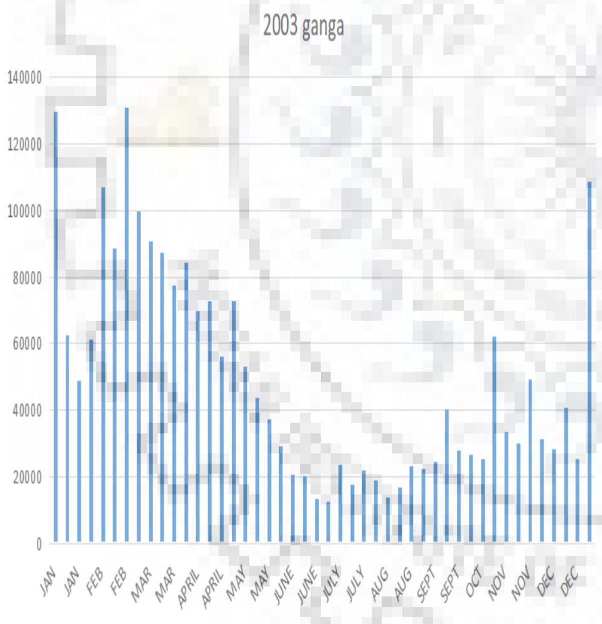
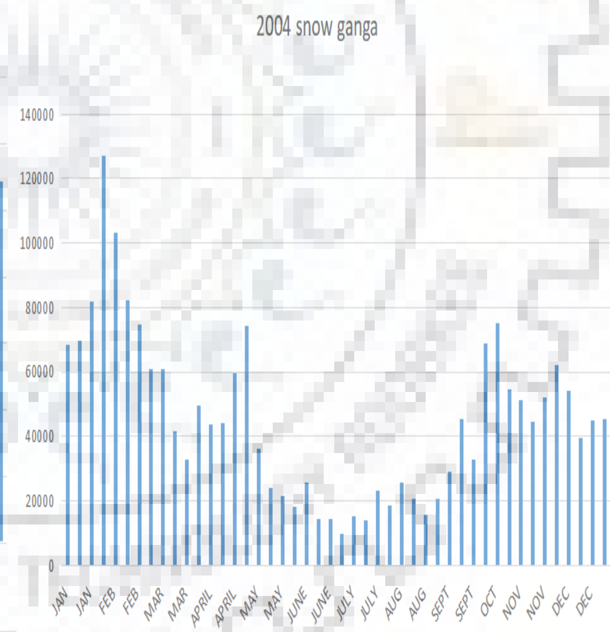
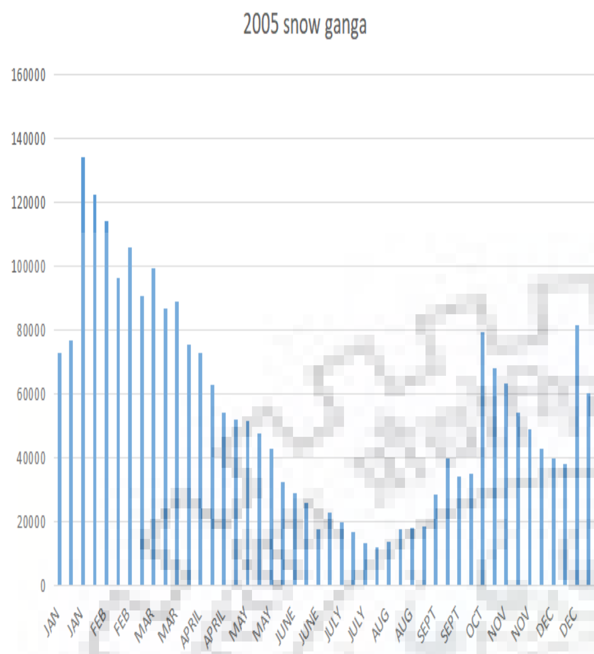
6.2 Snow in Ganga Basin, 2001-2016







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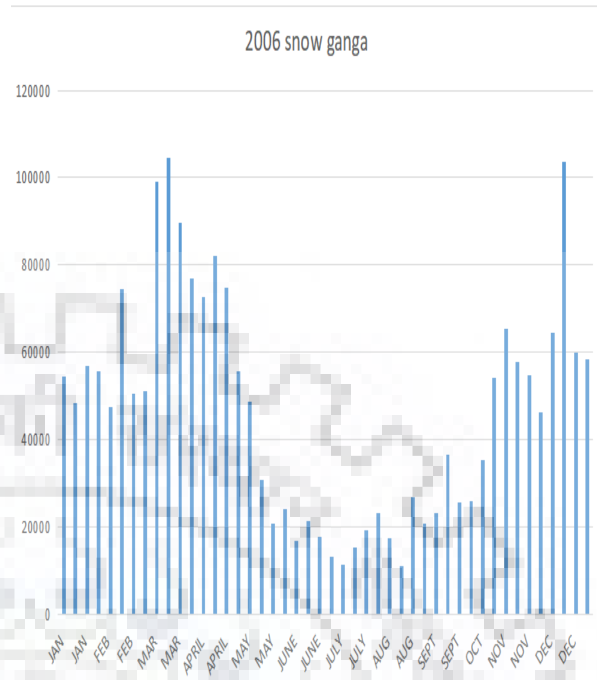
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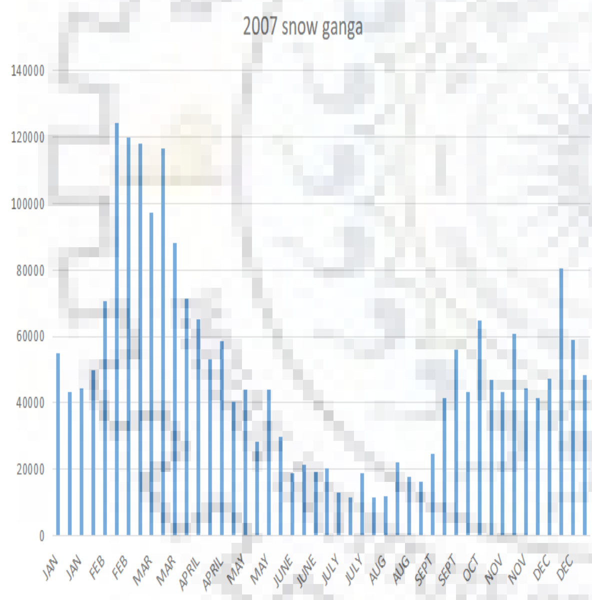
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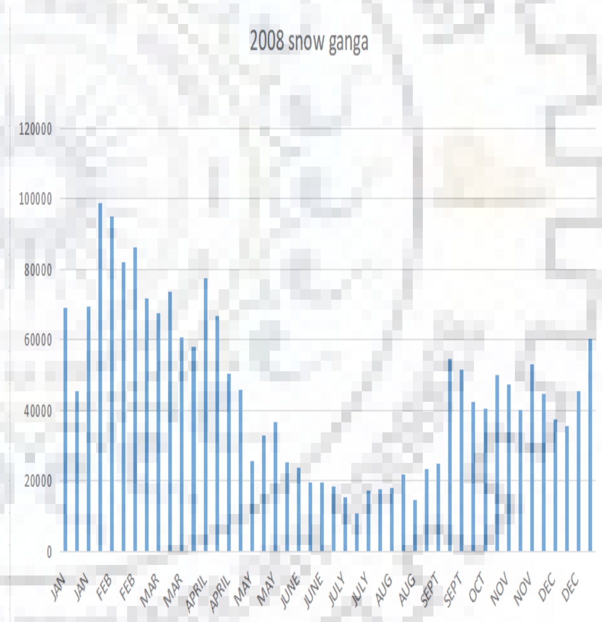
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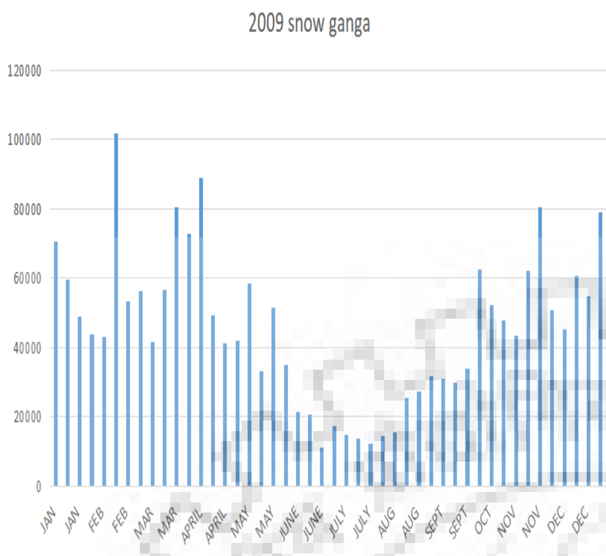
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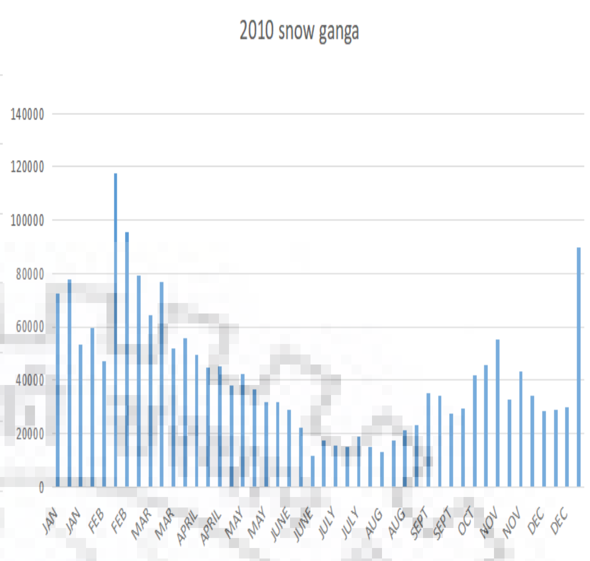
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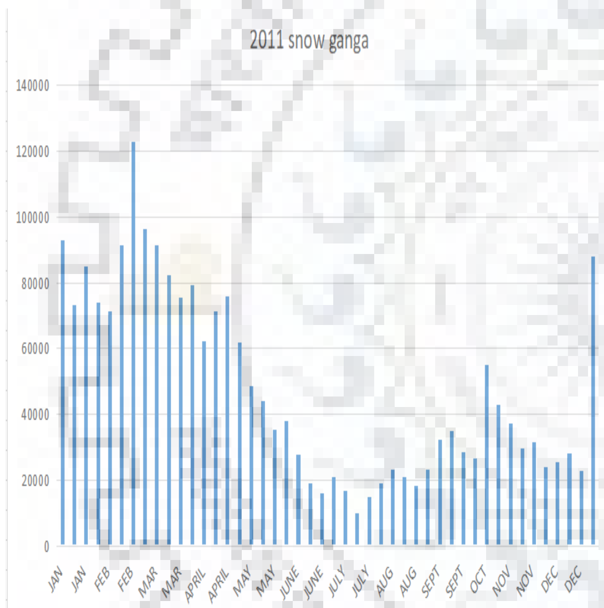
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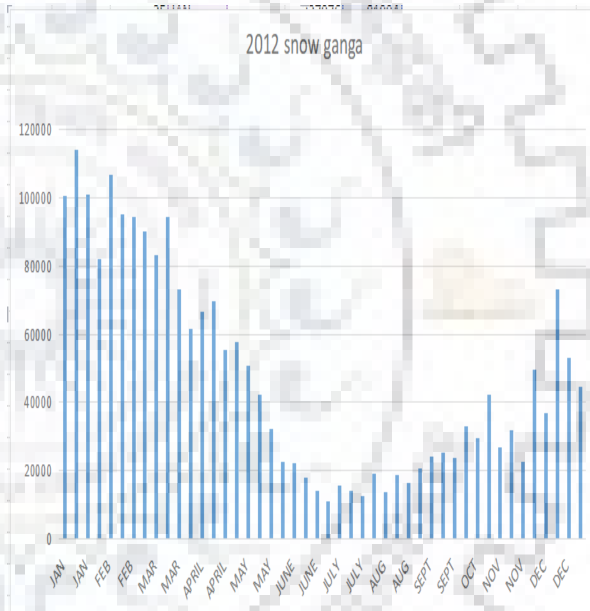
JAN JAN FEB FEB MAR MAR APRIL APRIL MAY MAY JUNE JUNE JULY JULY AUG AUG SEPT SEPT OCT NOV NOV DEC DEC


2012 snow ganga
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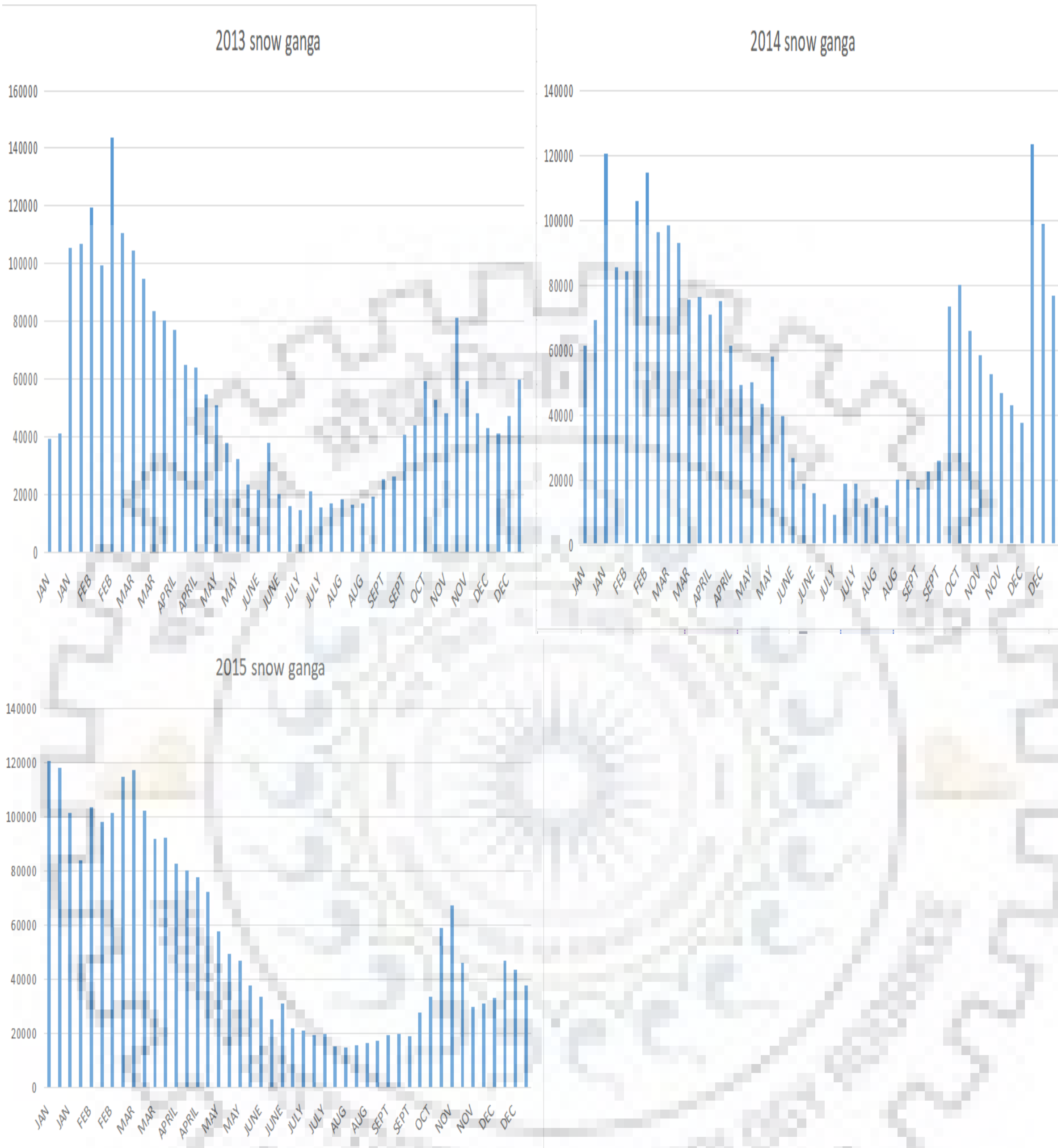
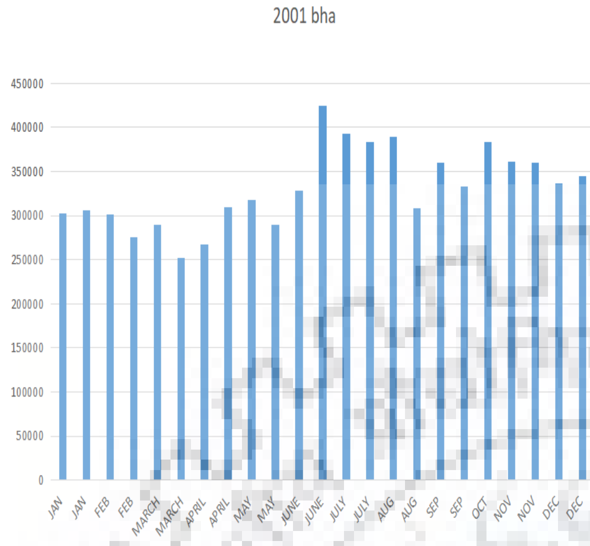
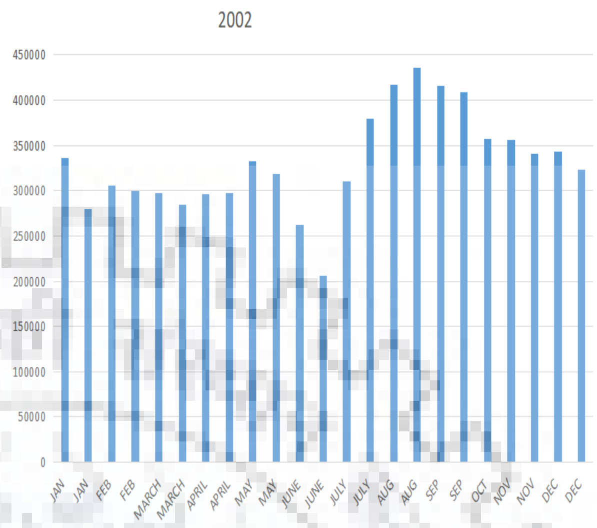
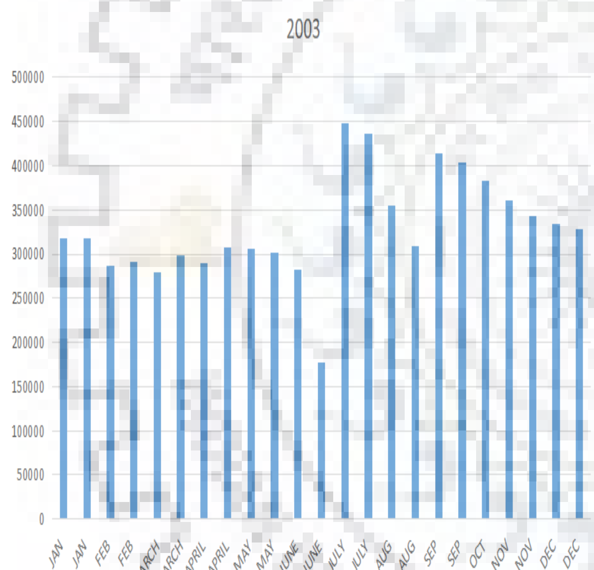


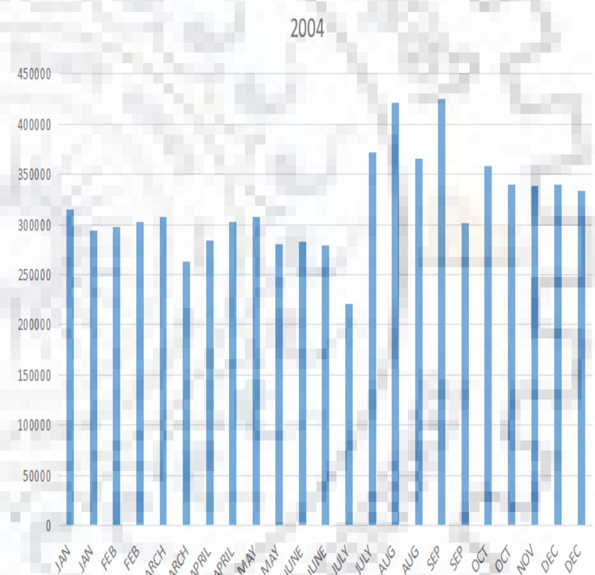
Figure 17: Ganga -Snow area 2001-16 (Monthly)

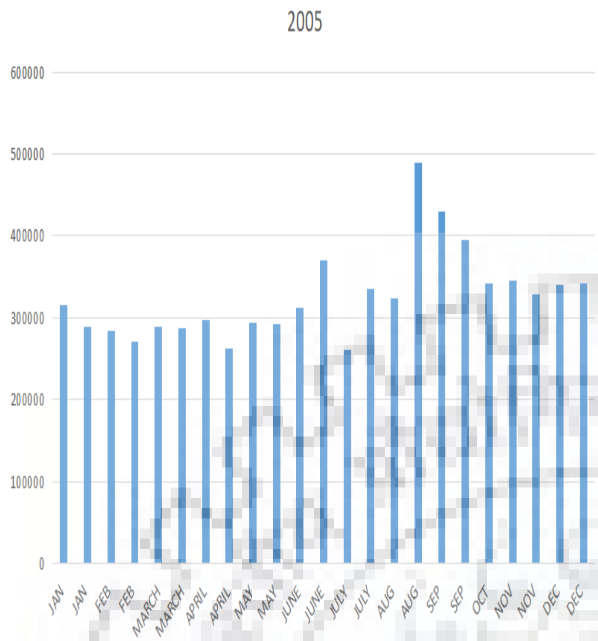
6.3 Vegetation in Brahmaputra basin, 2001-2016







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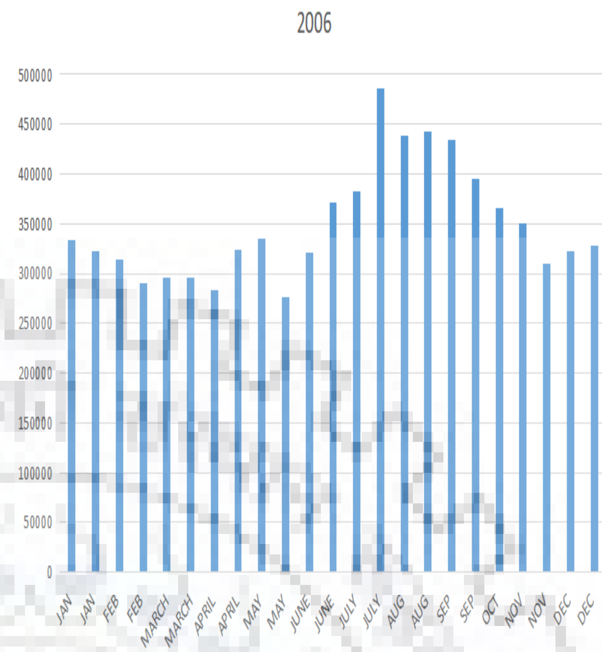
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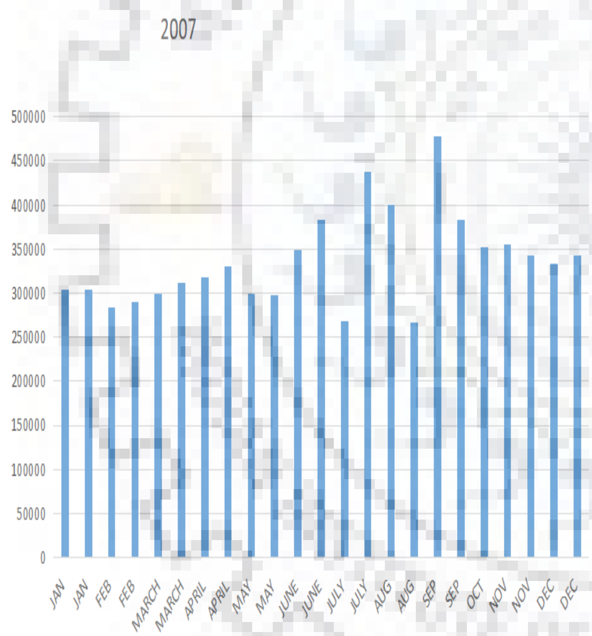
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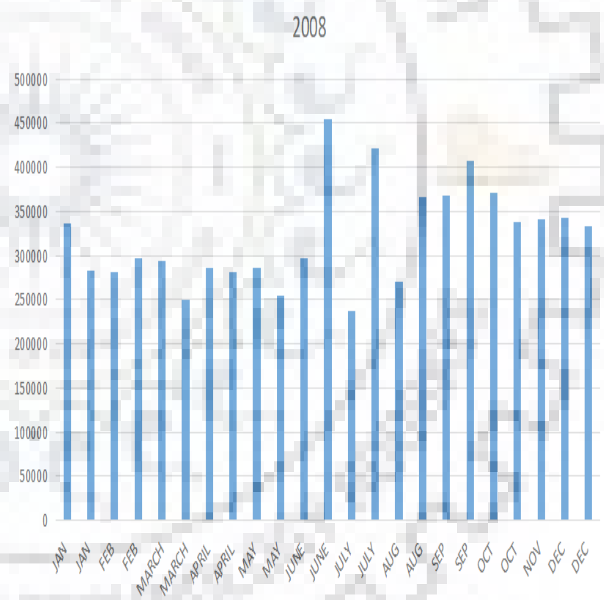
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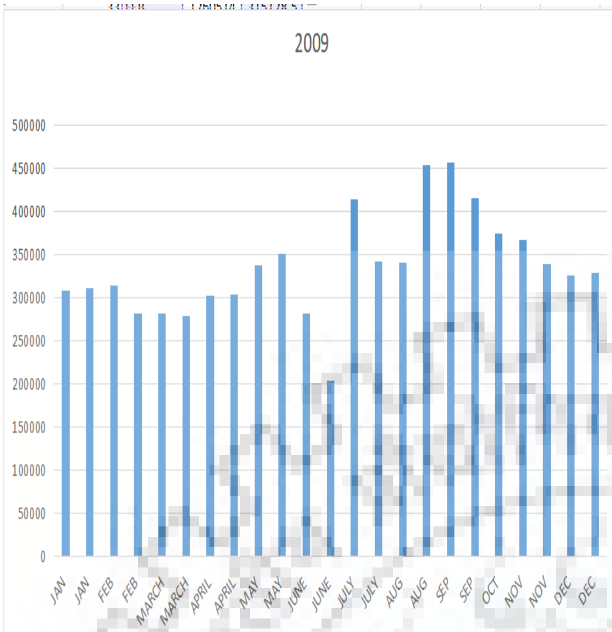
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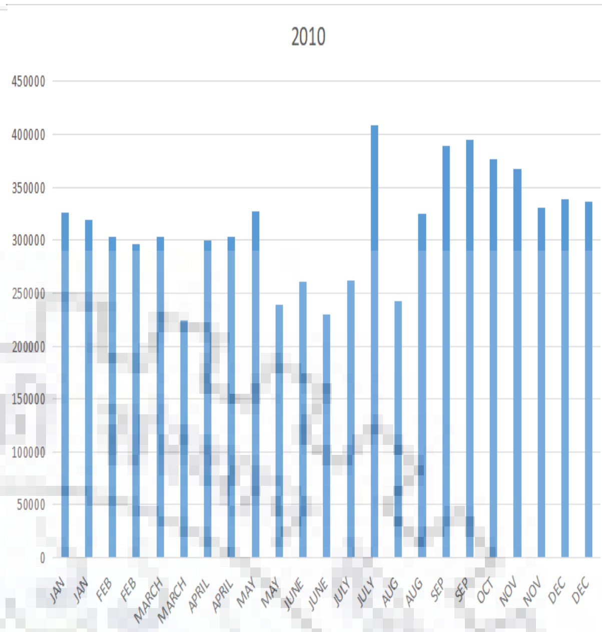
2010
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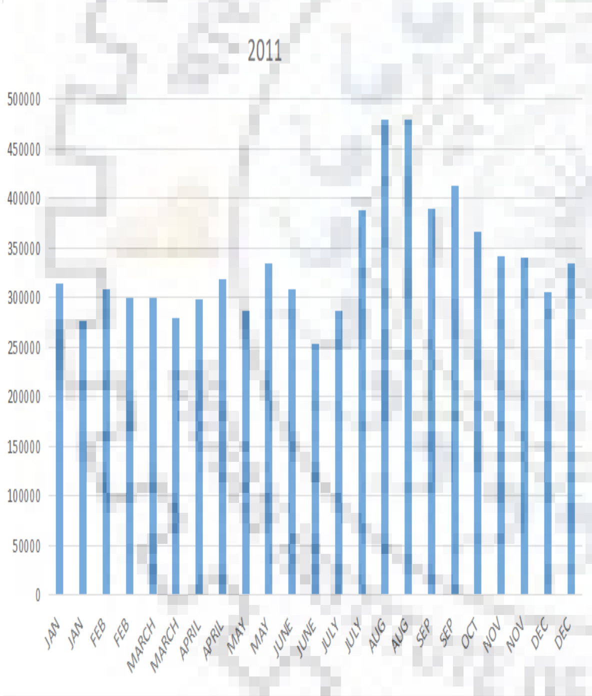
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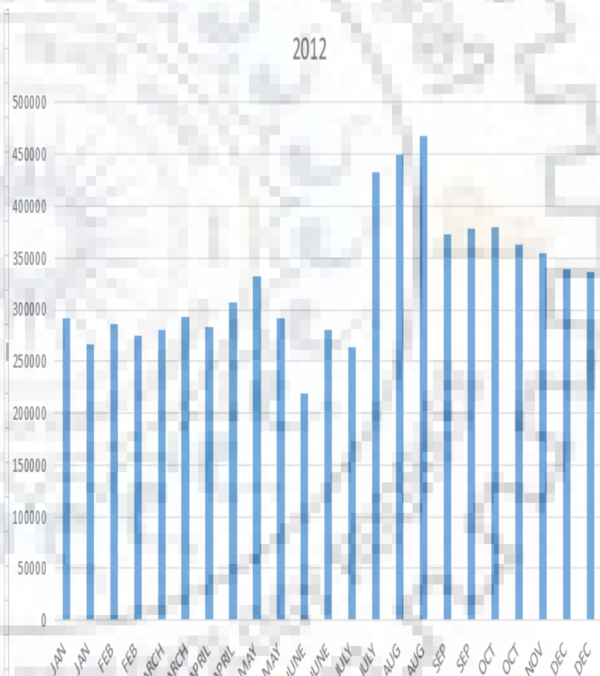
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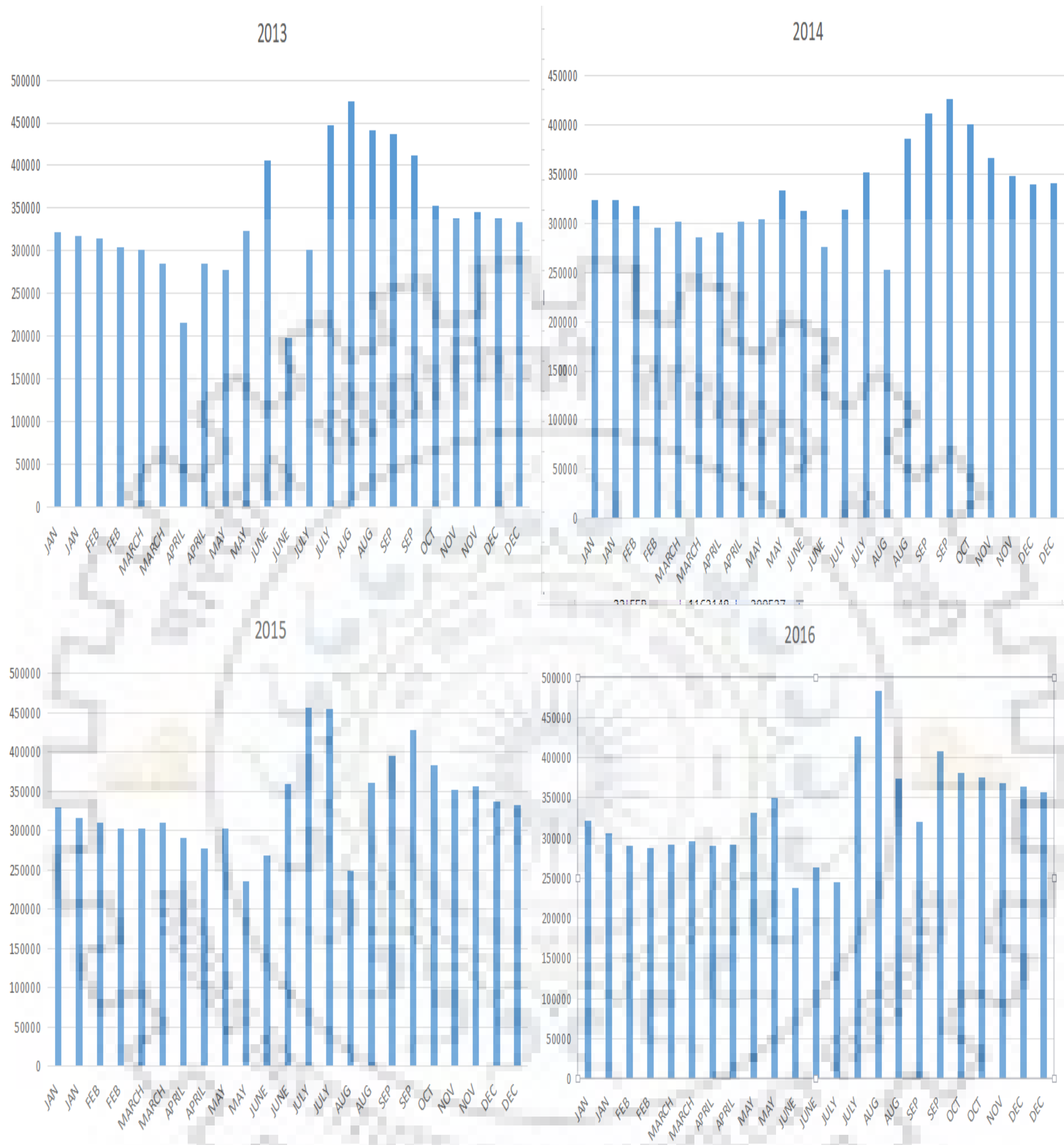
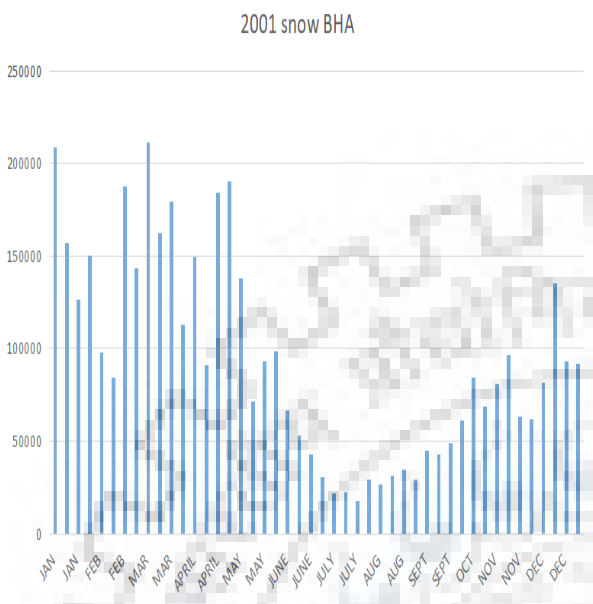
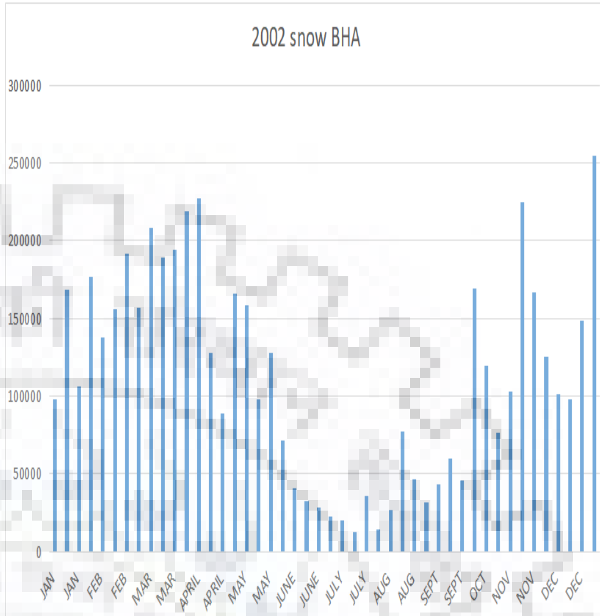
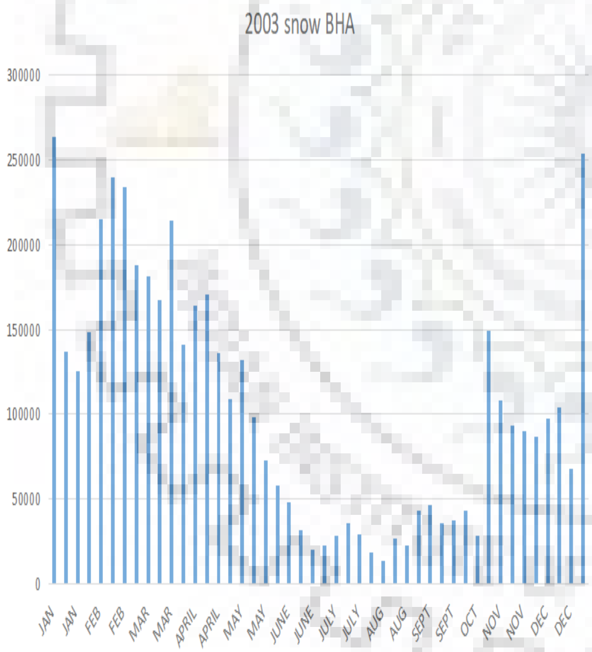


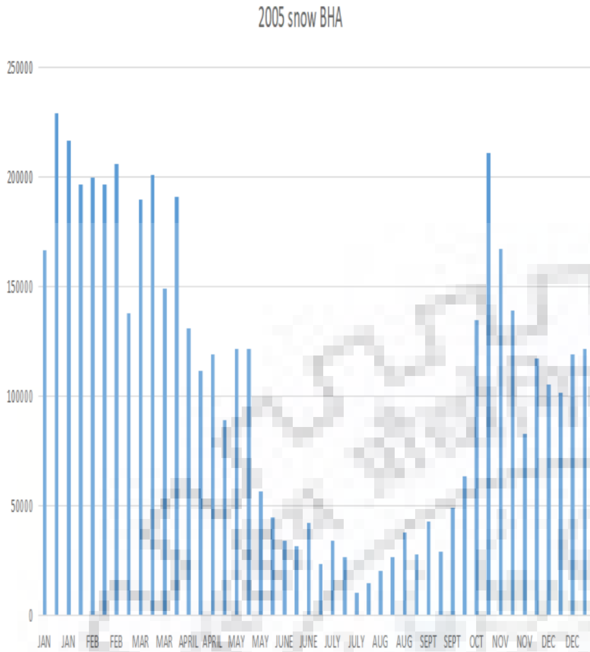
Figure 18: Brahmaputra -Vegetation area 2001-16 (Monthly)

6.4 Snow in Brahmaputra basin, 2001-2016








2005 snow BHA
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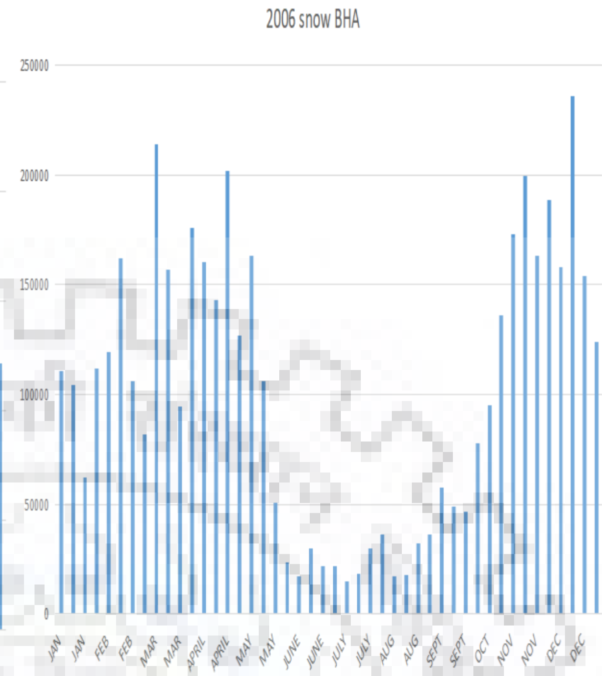
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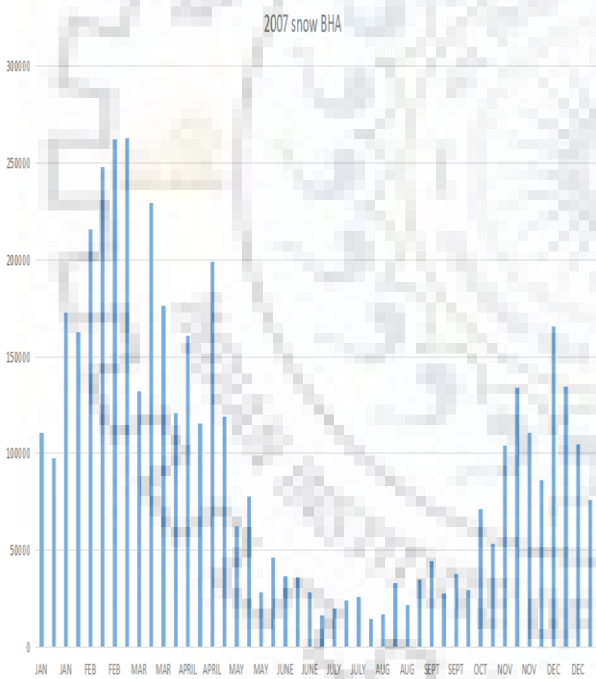
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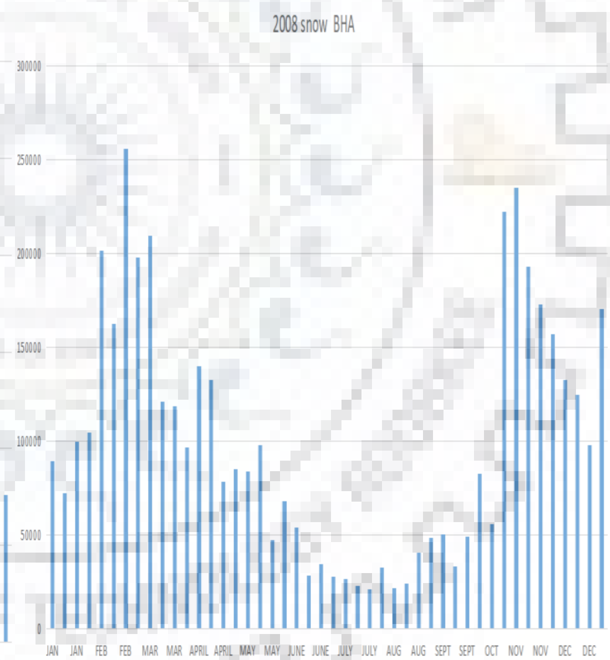
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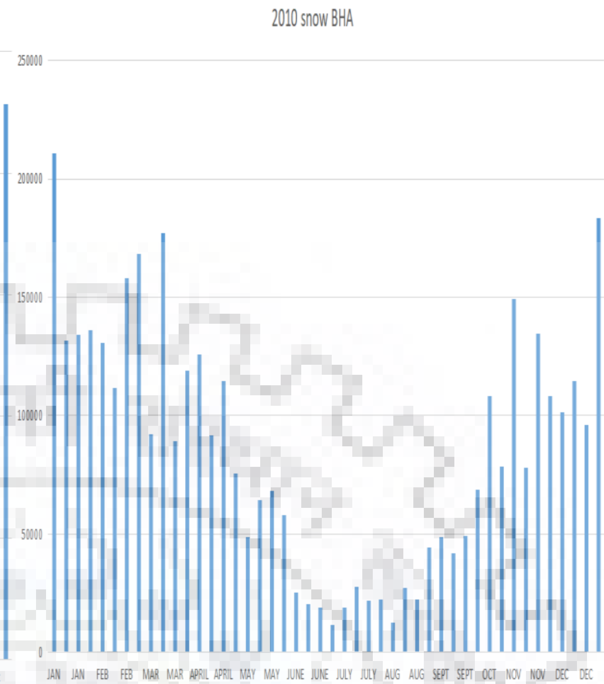
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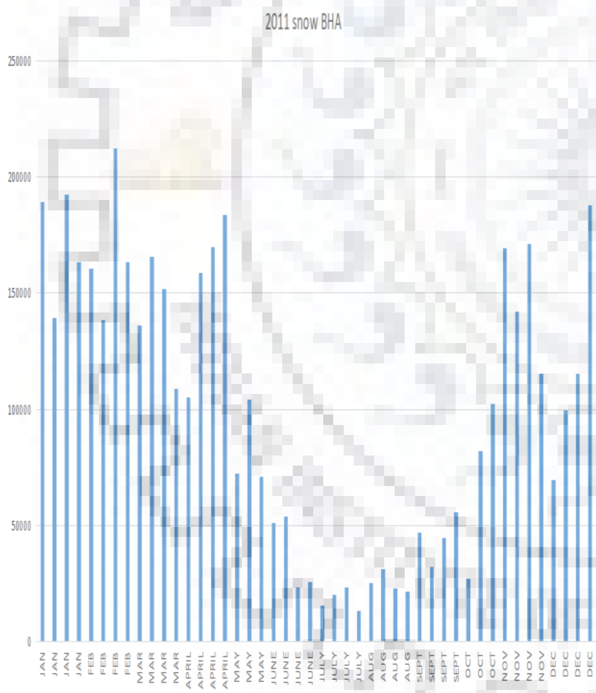
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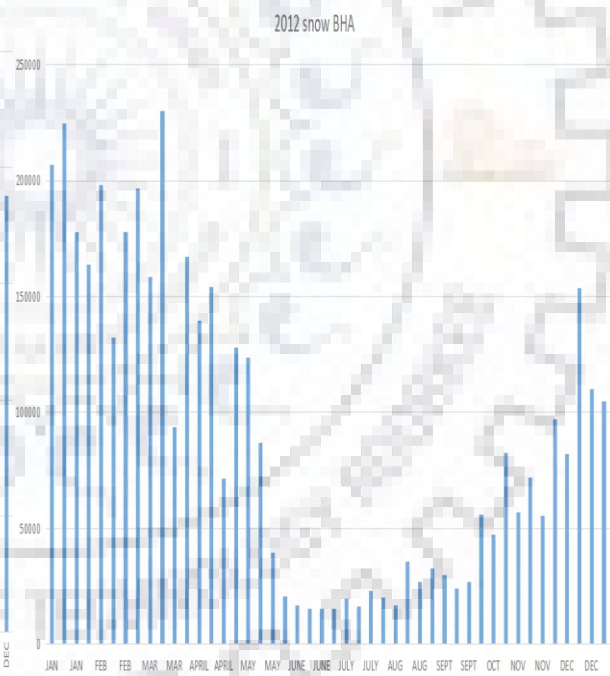
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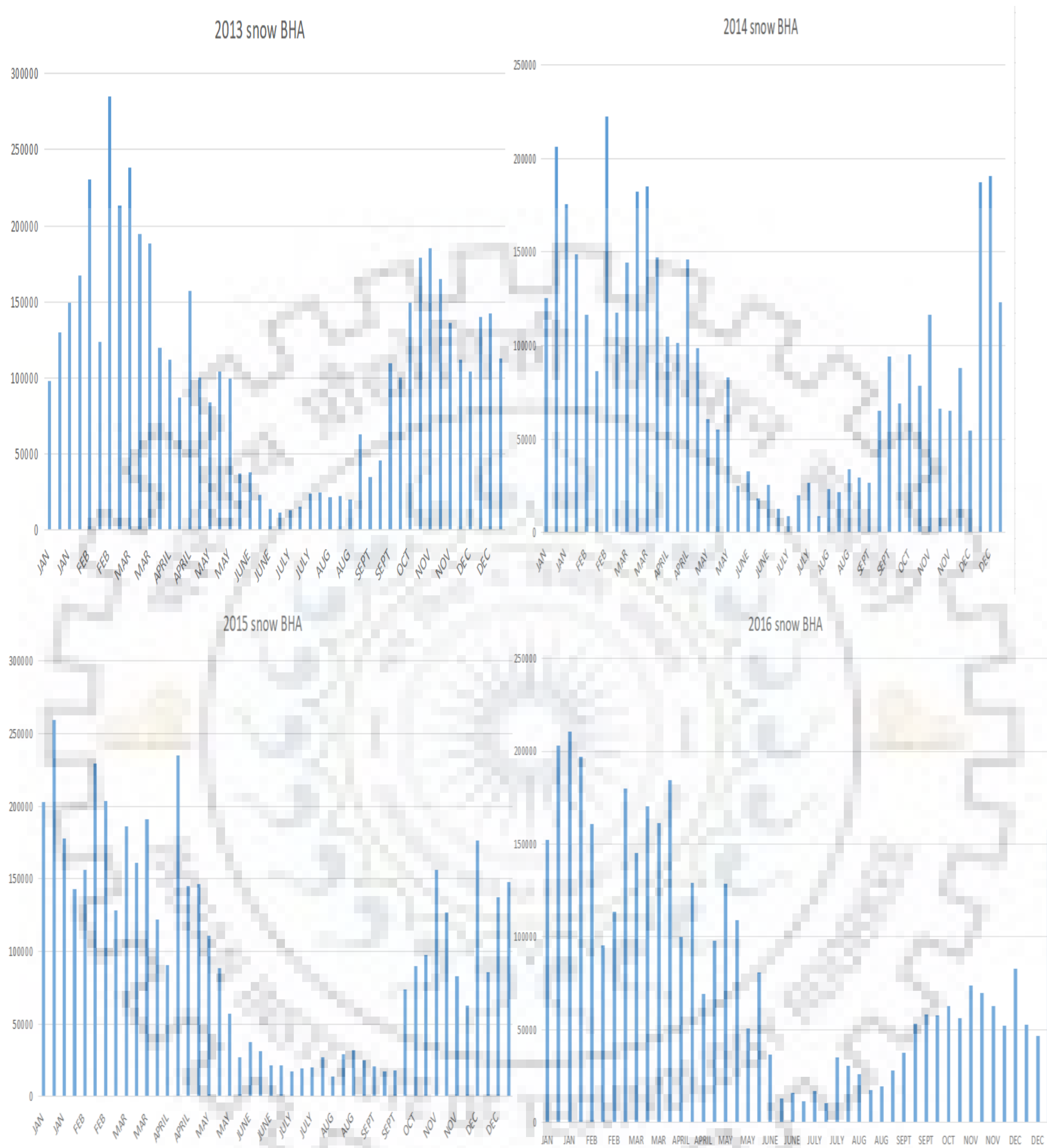
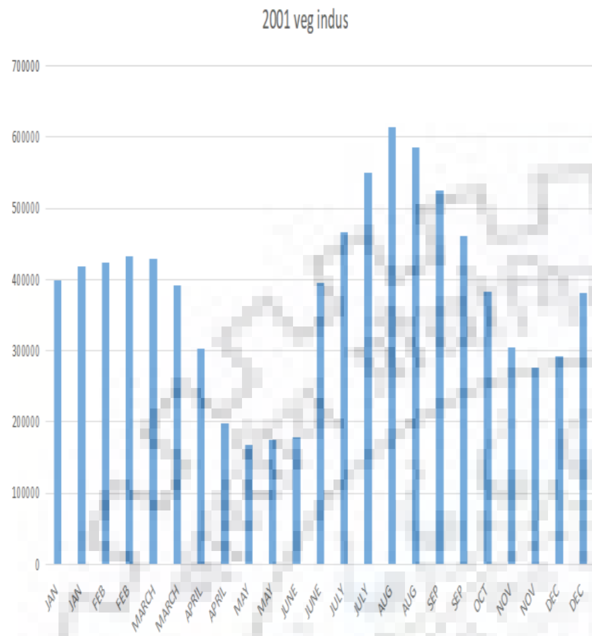
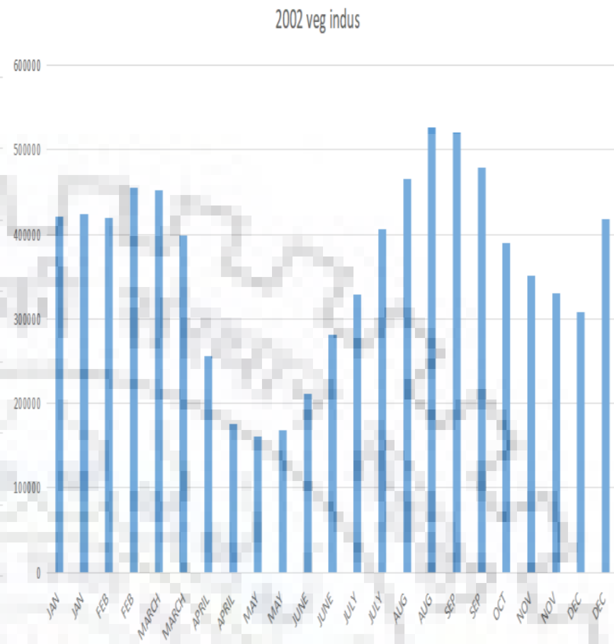
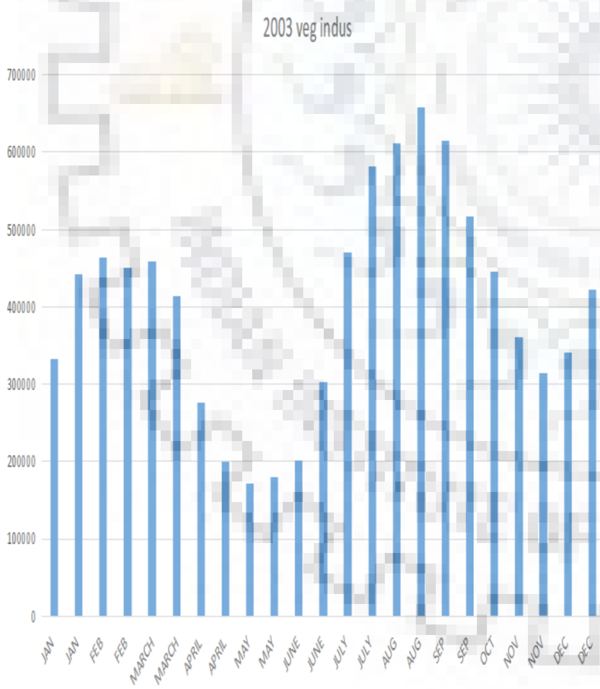


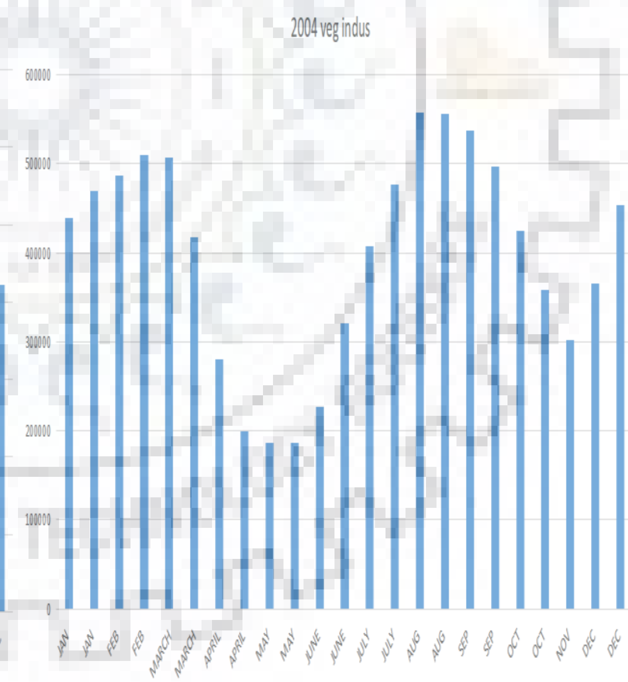
Figure 19: Brahmaputra -Snow area 2001-16 (Monthly)

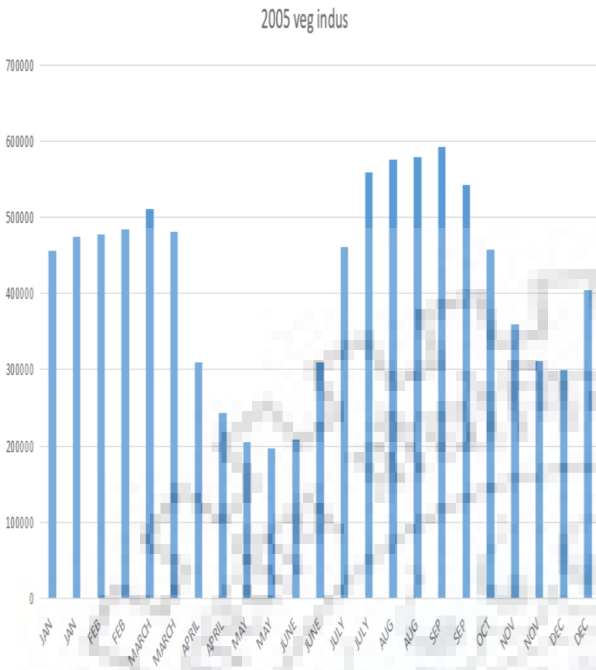
6.5 Vegetation in Indus basin, 2001-2016







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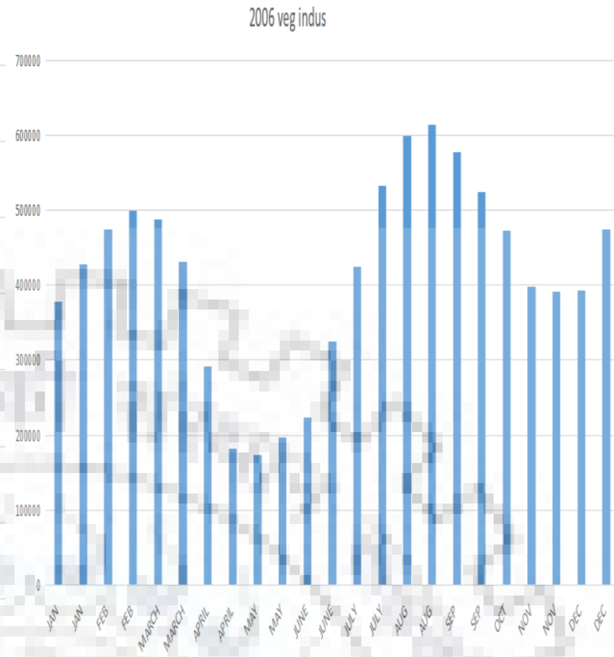
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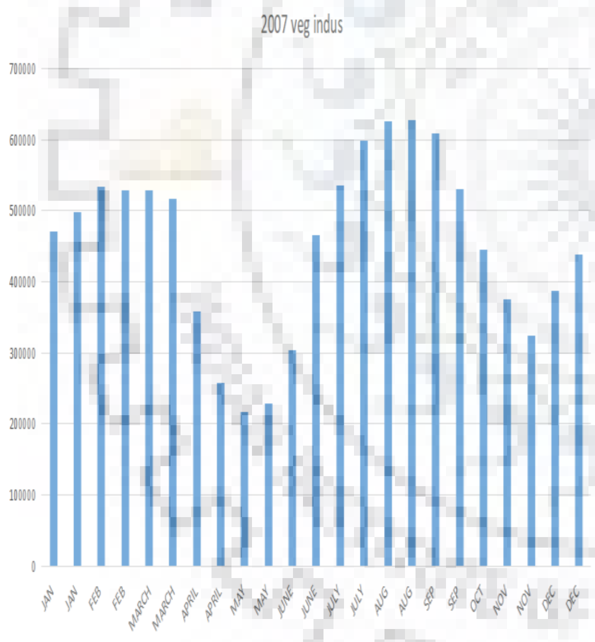
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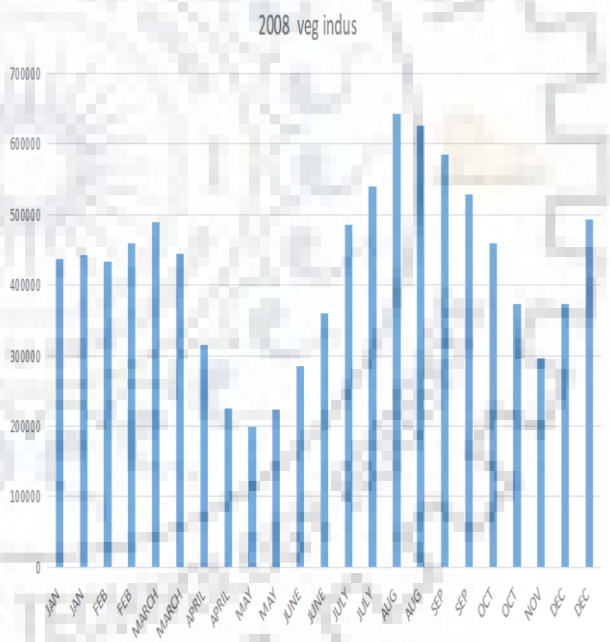
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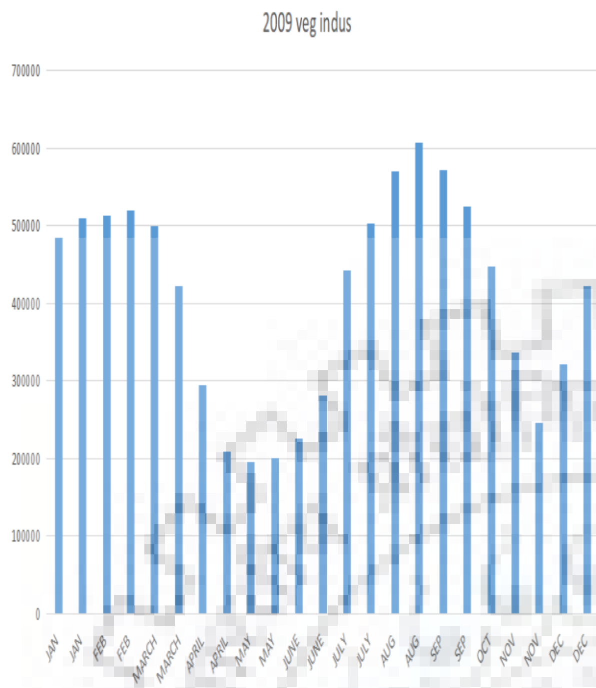
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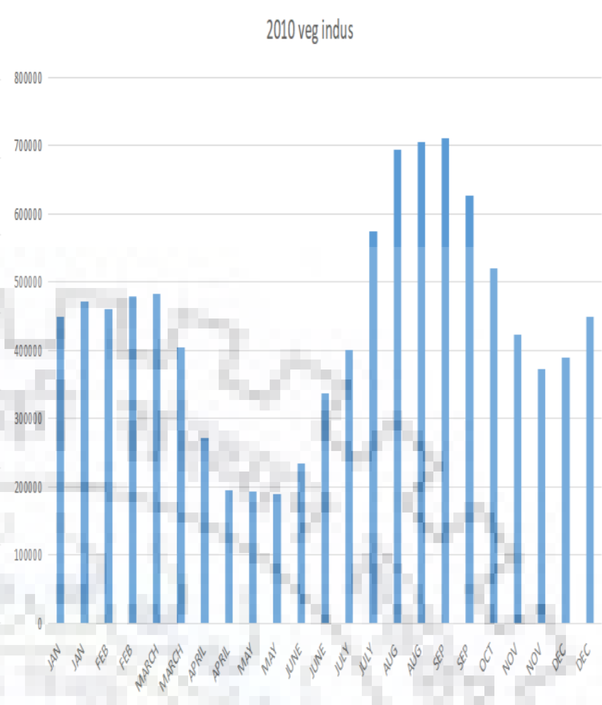
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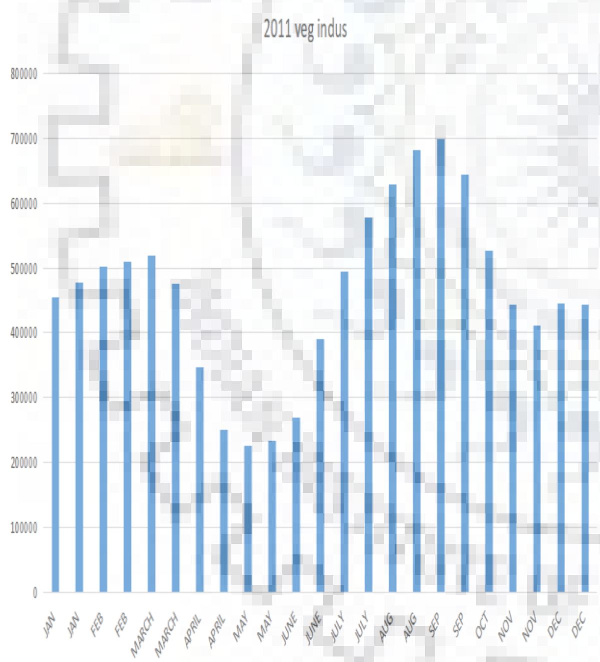
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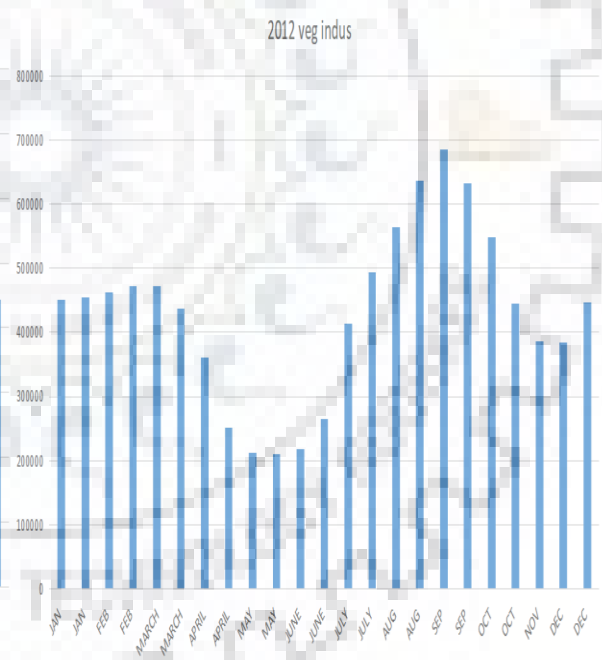
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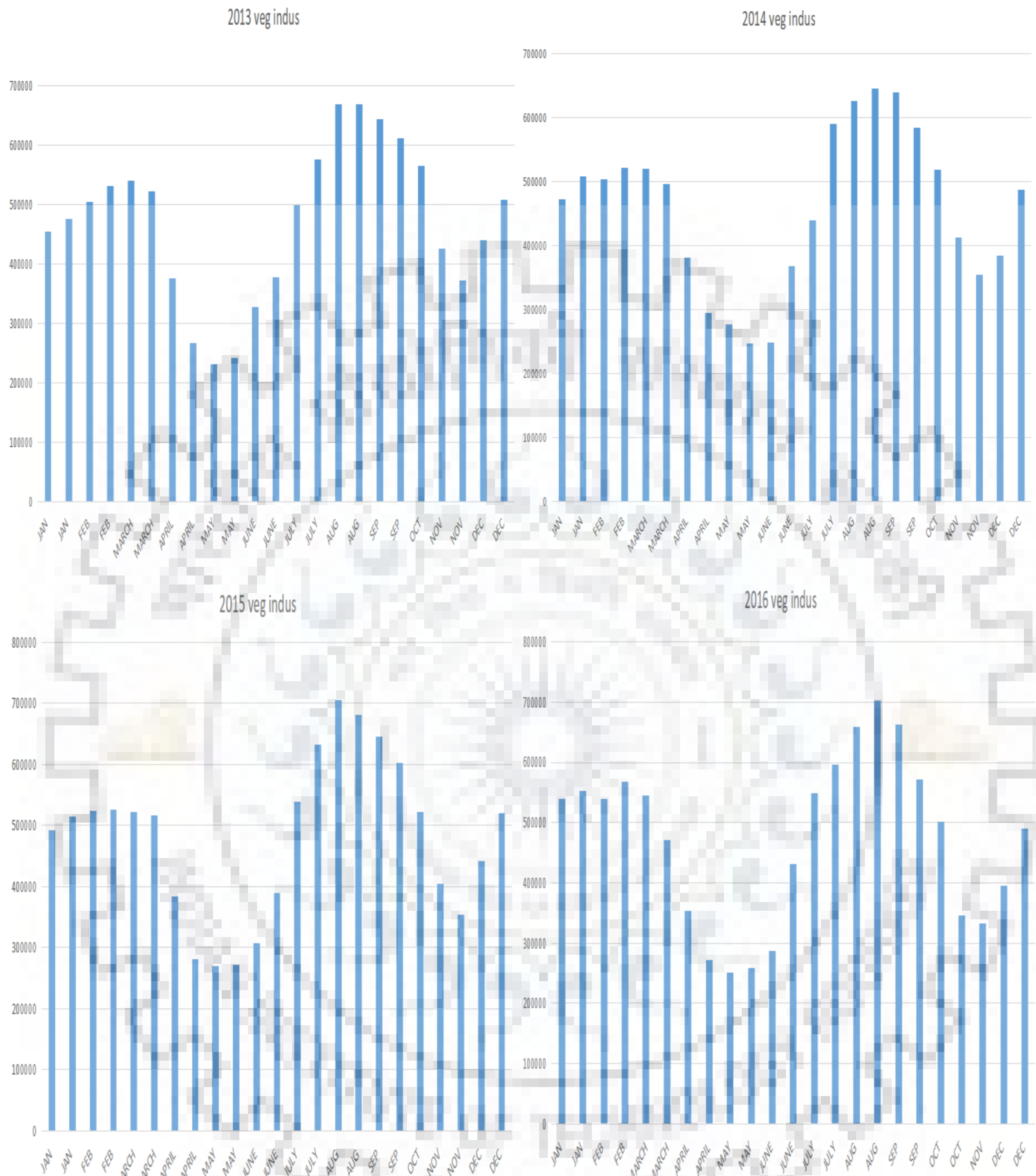
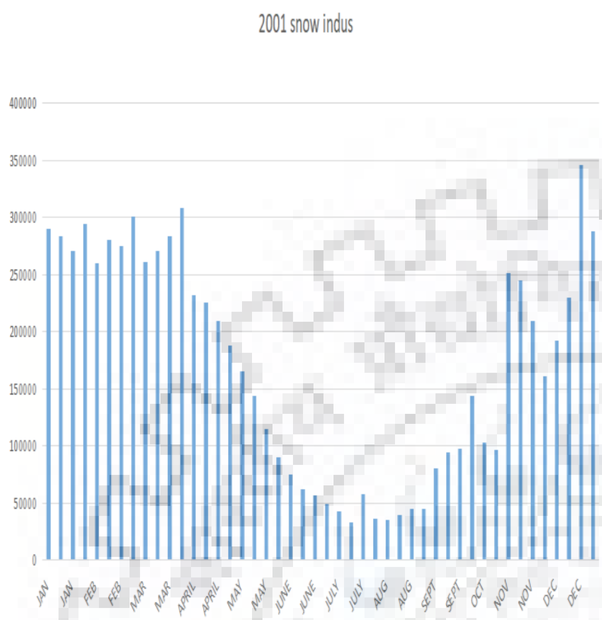
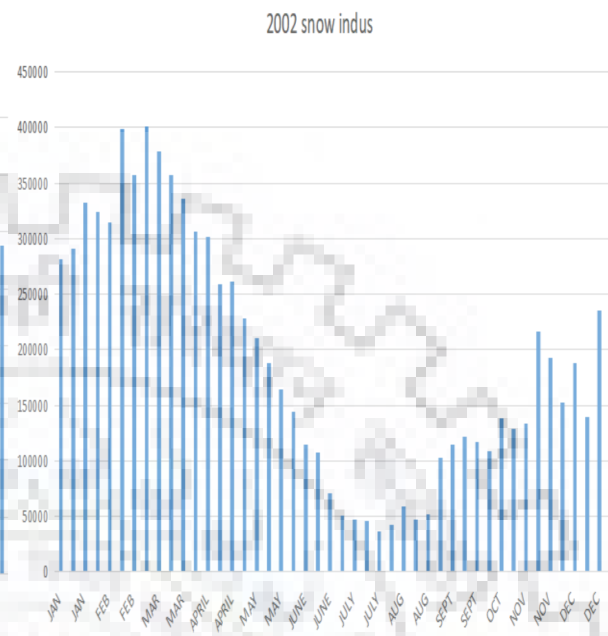
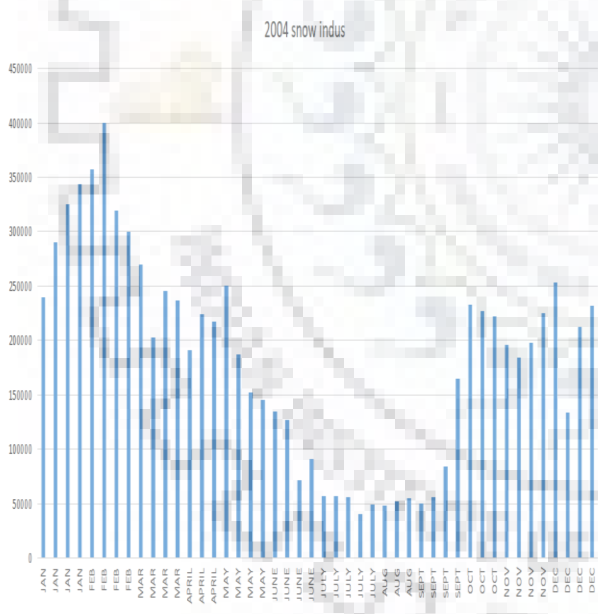


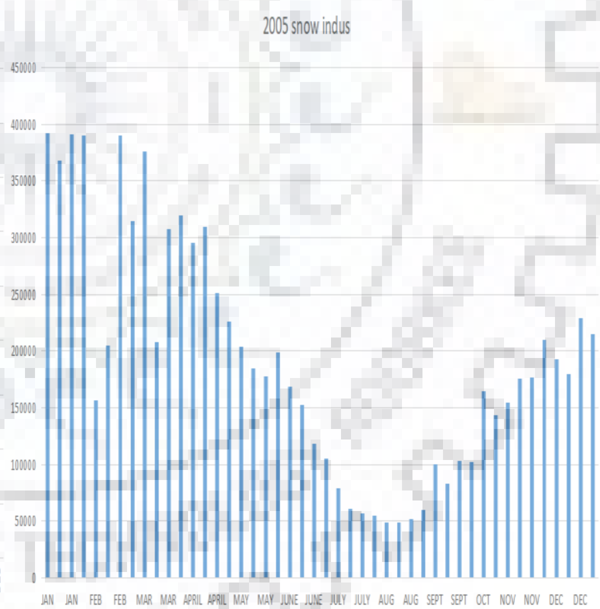
<u>Figure 20</u>: Indus -Vegetation area 2001-16 (Monthly)

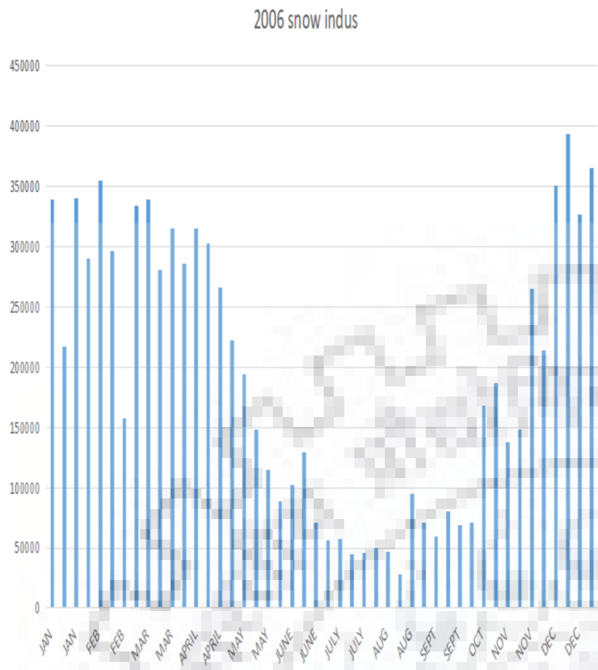
6.6 Snow in Indus basin, 2001-2016







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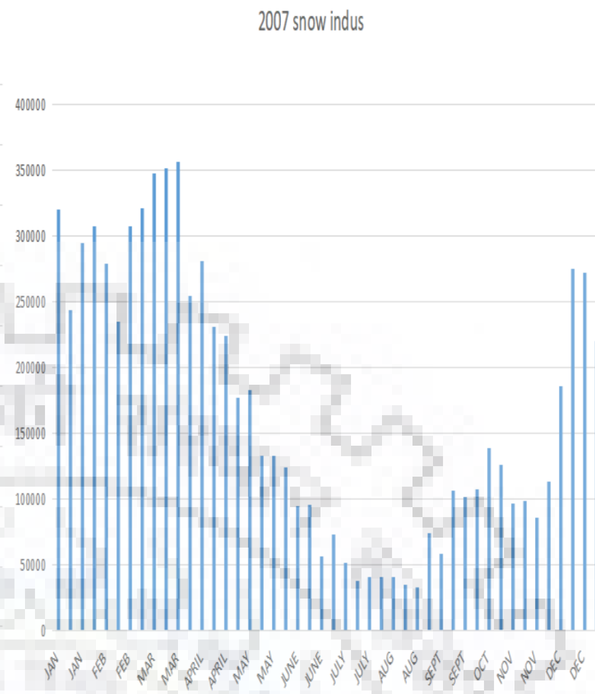
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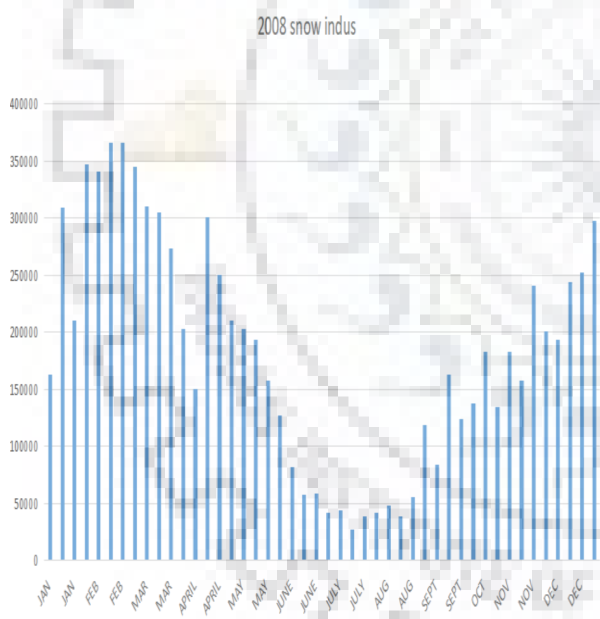
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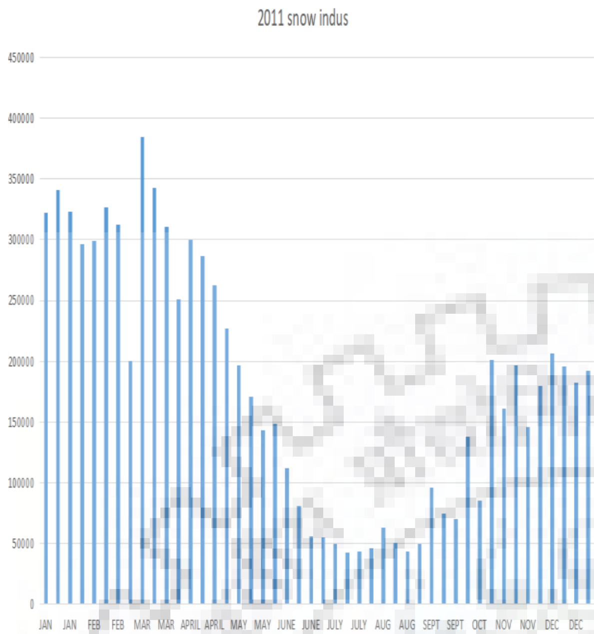
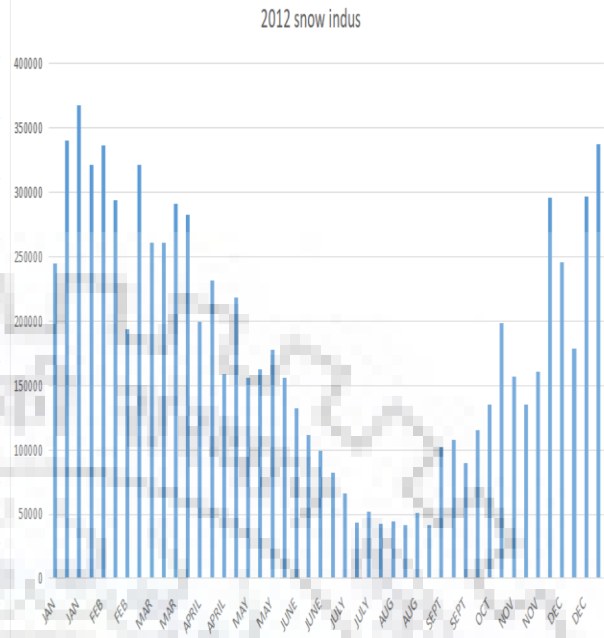
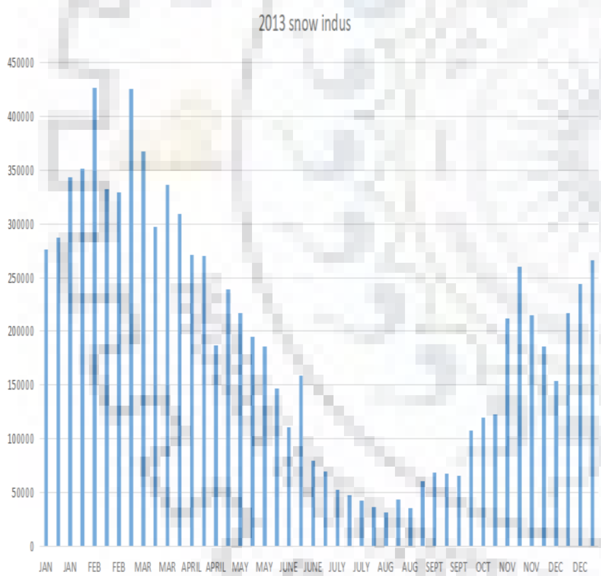
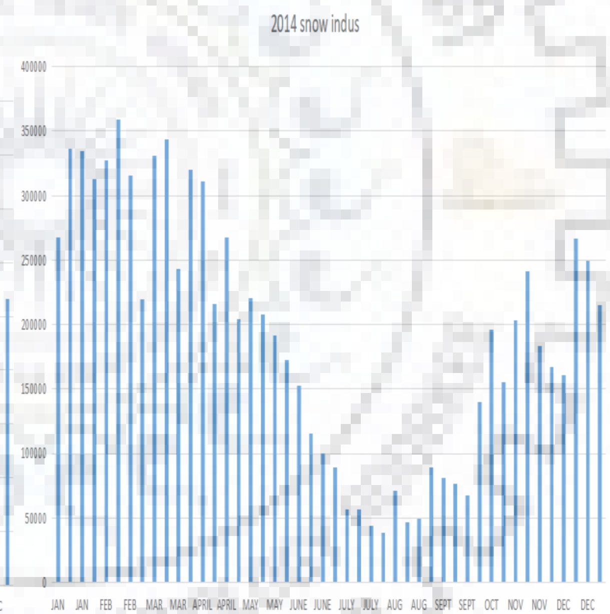

2011 snow indus


2012 snow indus


2013 snow indus


2014 snow indus

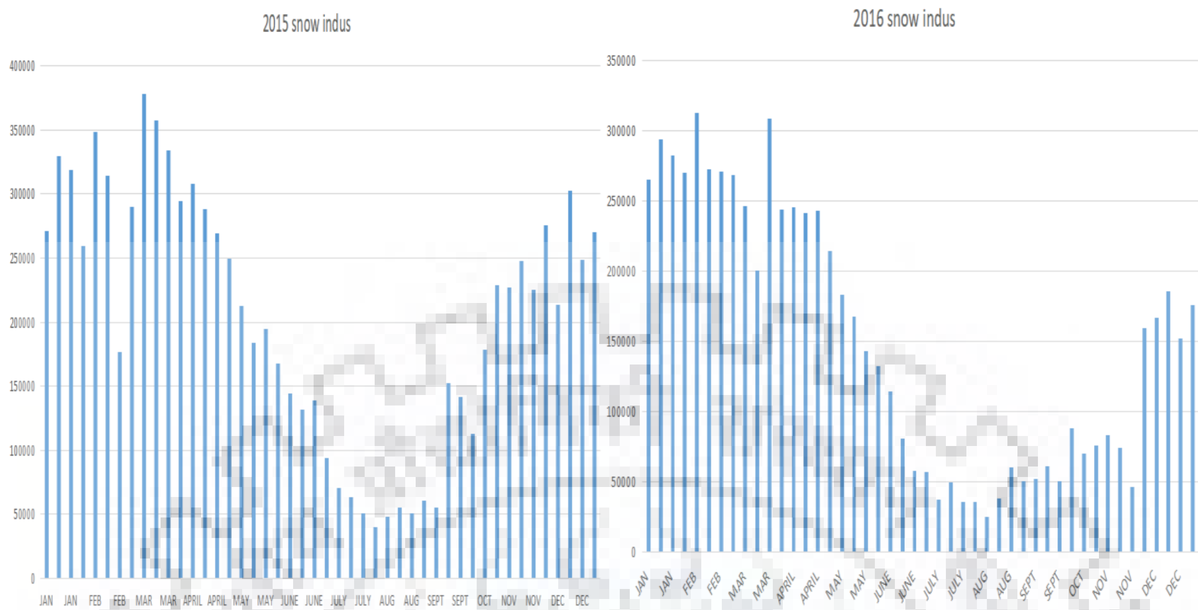


Figure 21: Indus -Snow area 2001-16 (Monthly)

PART 2

For Figures 22 to 33,

X-axis represents elevation zones from 1-18, with 1 representing elevation of 0-500 m in increments of 500.

Y-axis represents snow/tree cover area

Z-axis represents years ranging 2001-2016 (color coded for easier reference), for which the data has been analyzed.

6.7 Elevation zone - area - time plots

6.7.1 Indus Basin

I. Snowline, March

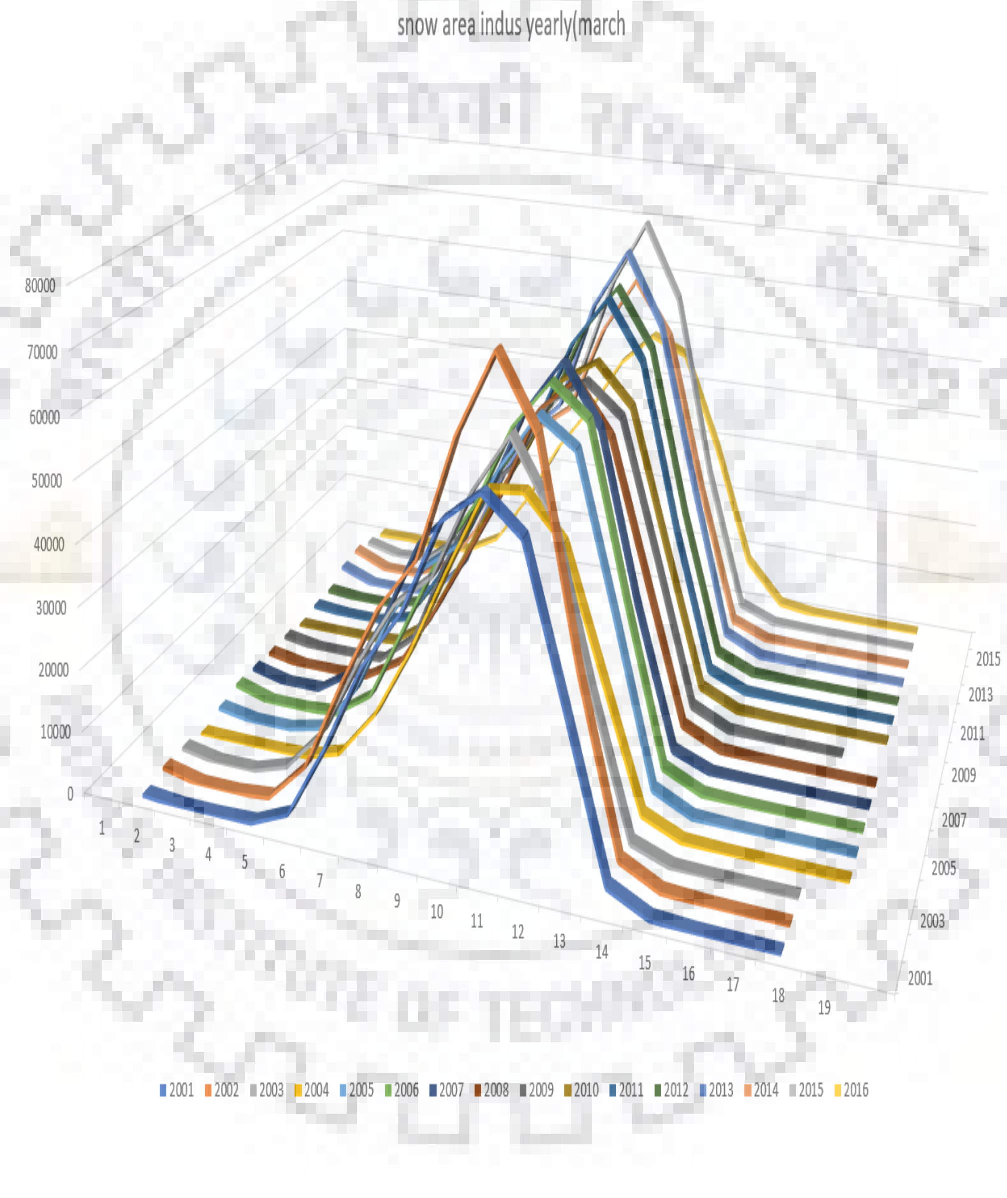


Figure 22: Snow Area- Elevation zone(March) (Yearly) INDUS

II. Treeline, March

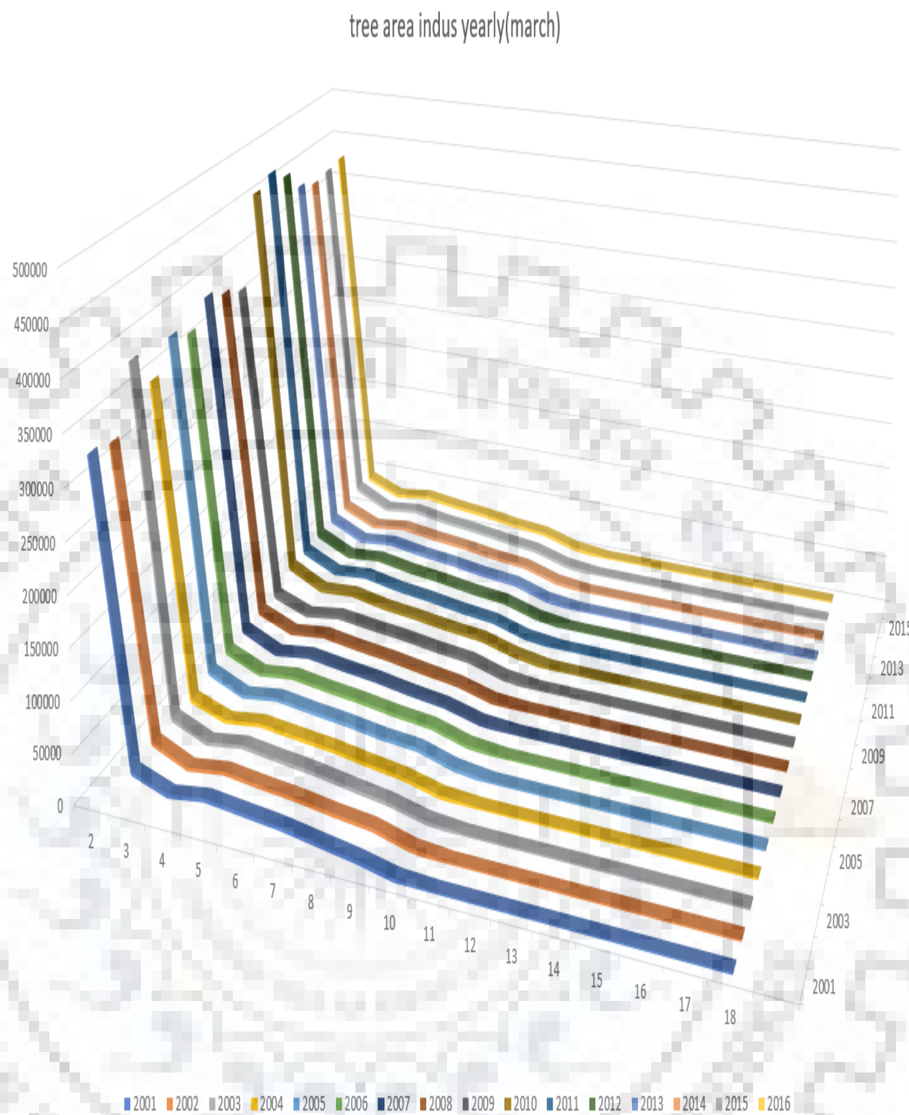


Figure 23: Tree Area- Elevation zone(March) (Yearly) INDUS

III. Snowline, September

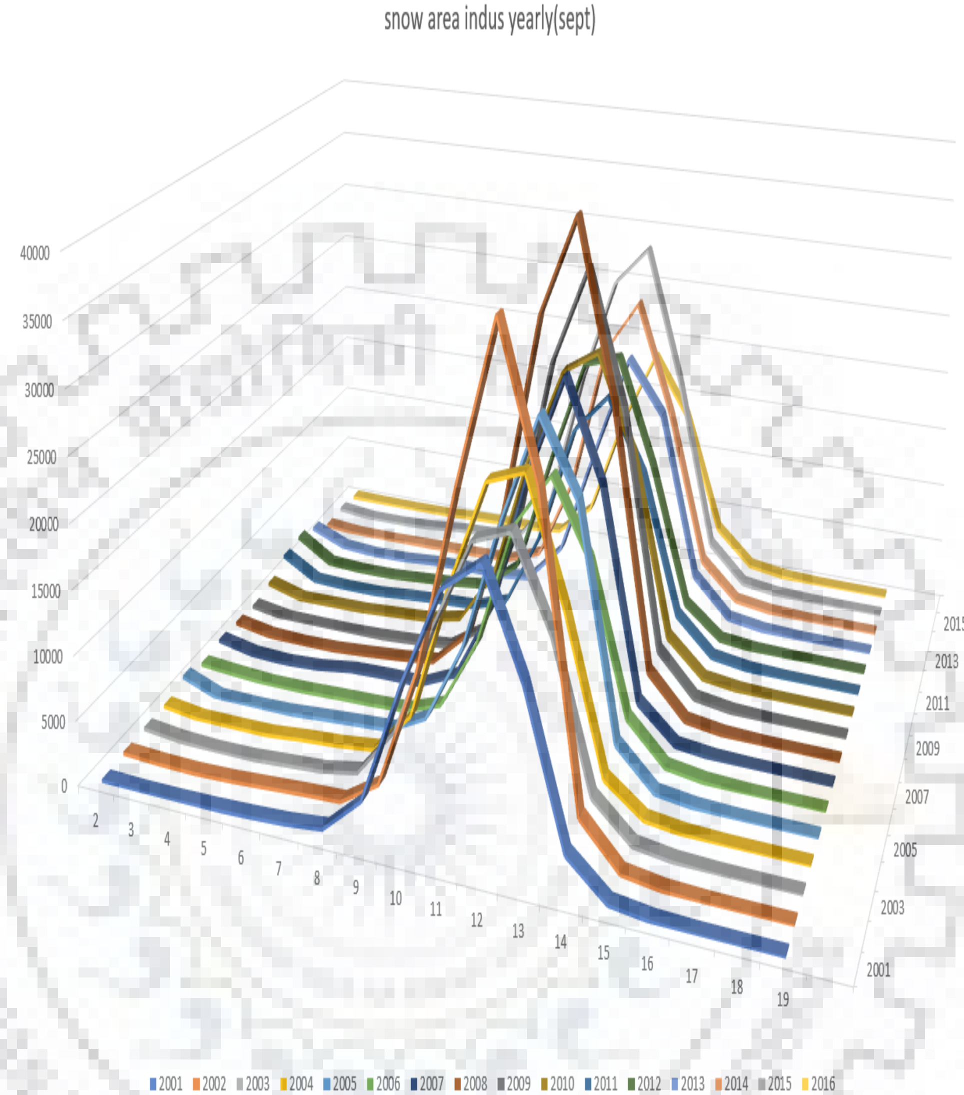


Figure 24: Snow Area- Elevation zone(Sept) (Yearly) INDUS

I. Treeline, September

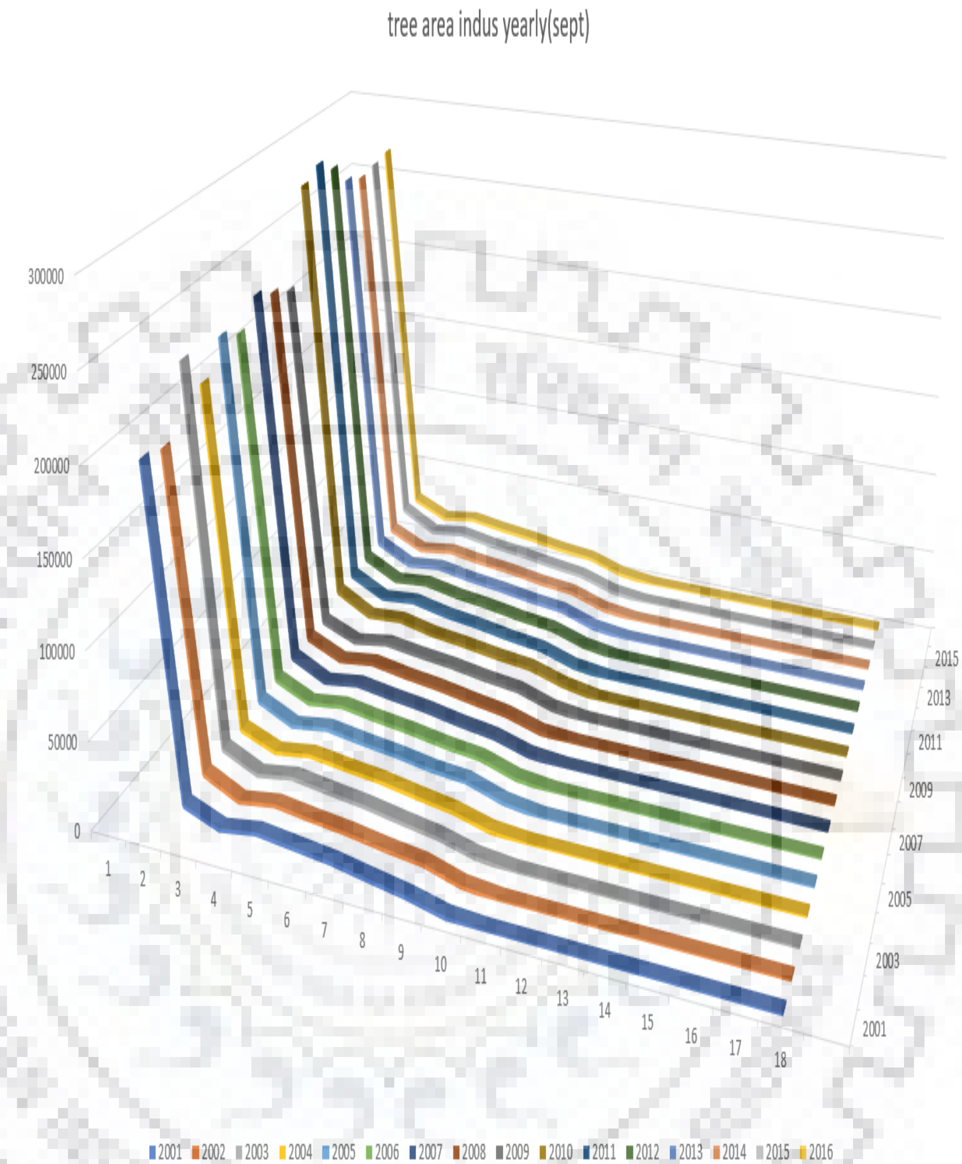


Figure 25: Tree Area- Elevation zone(Sept) (Yearly) INDUS

6.7.2 Brahmaputra Basin

I. Snowline, March

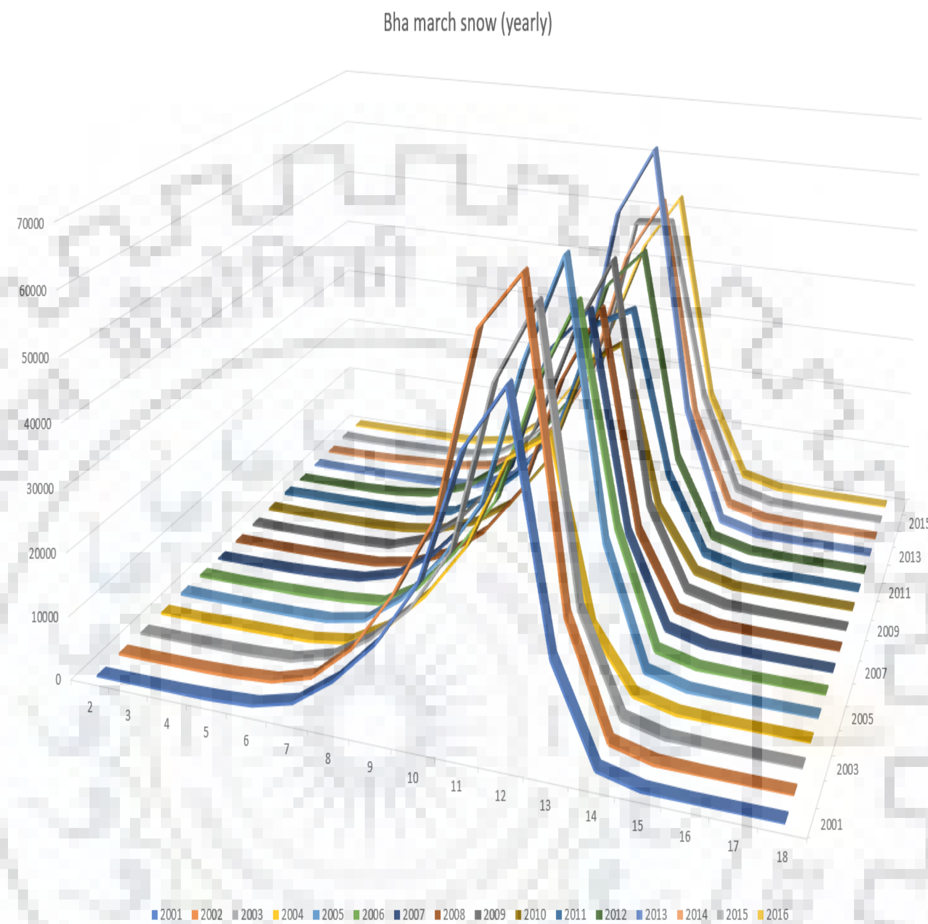


Figure 26: Snow Area- Elevation zone(March) (Yearly) Brahmaputra

II. Treeline, March

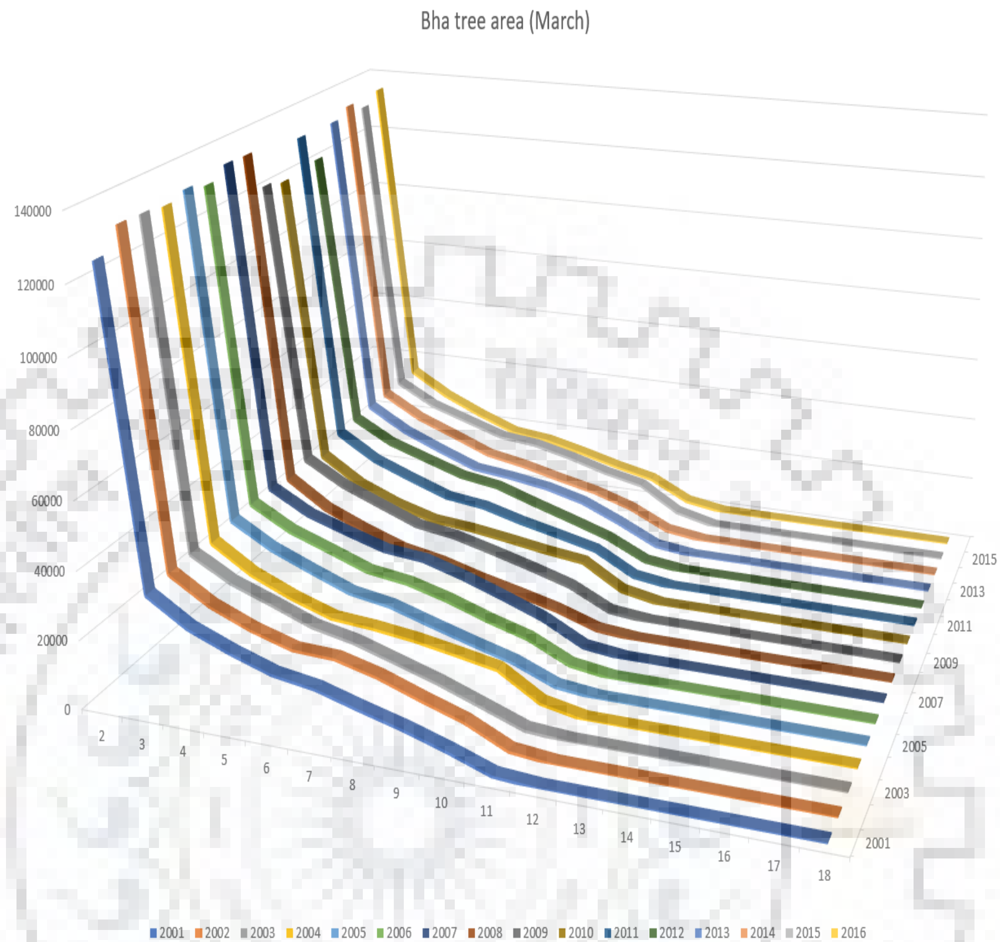


Figure 27: Tree Area- Elevation zone(March) (Yearly) Brahmaputra

III. Snowline, September

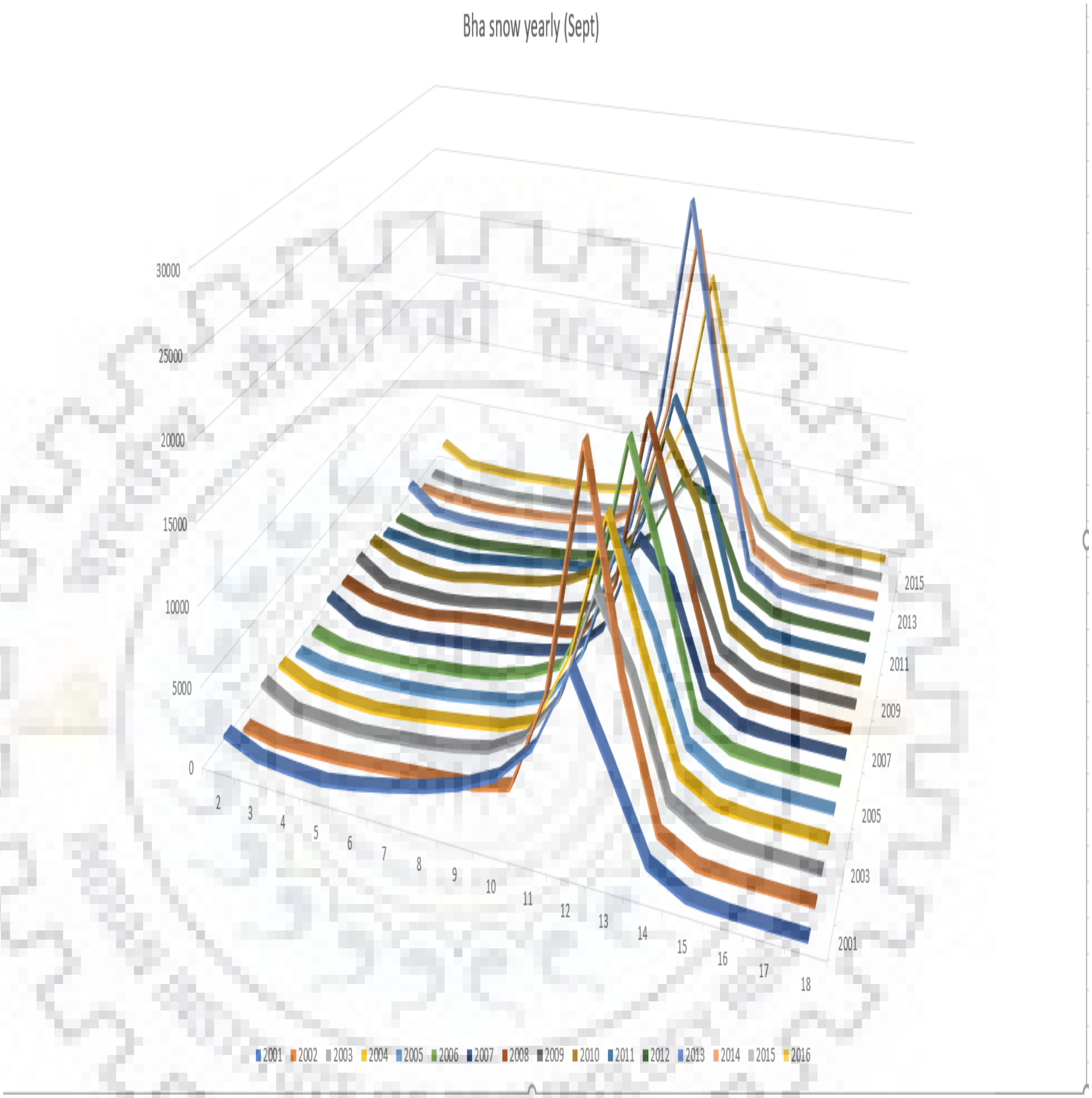


Figure 28: Snow Area- Elevation zone(Sept) (Yearly) Brahmaputra

IV. Treeline, September

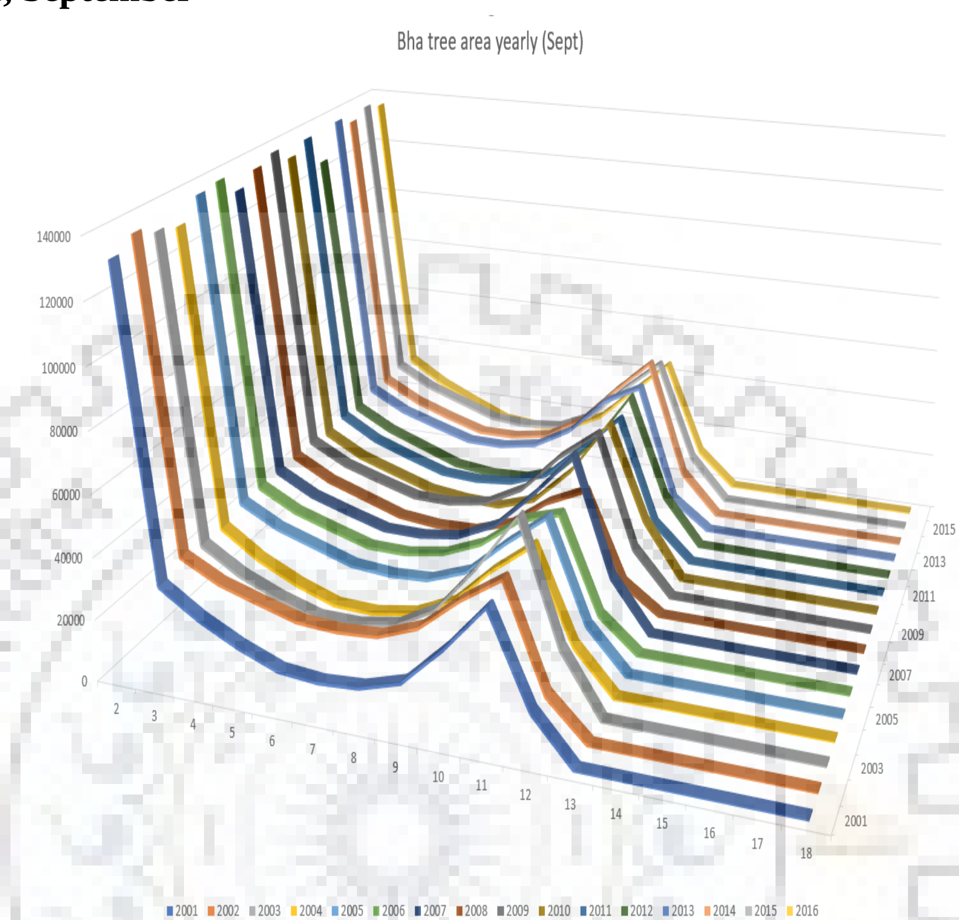


Figure 29: Tree Area- Elevation zone(Sept) (Yearly) Brahmaputra

6.7.3 Ganga Basin

I. Snowline, March

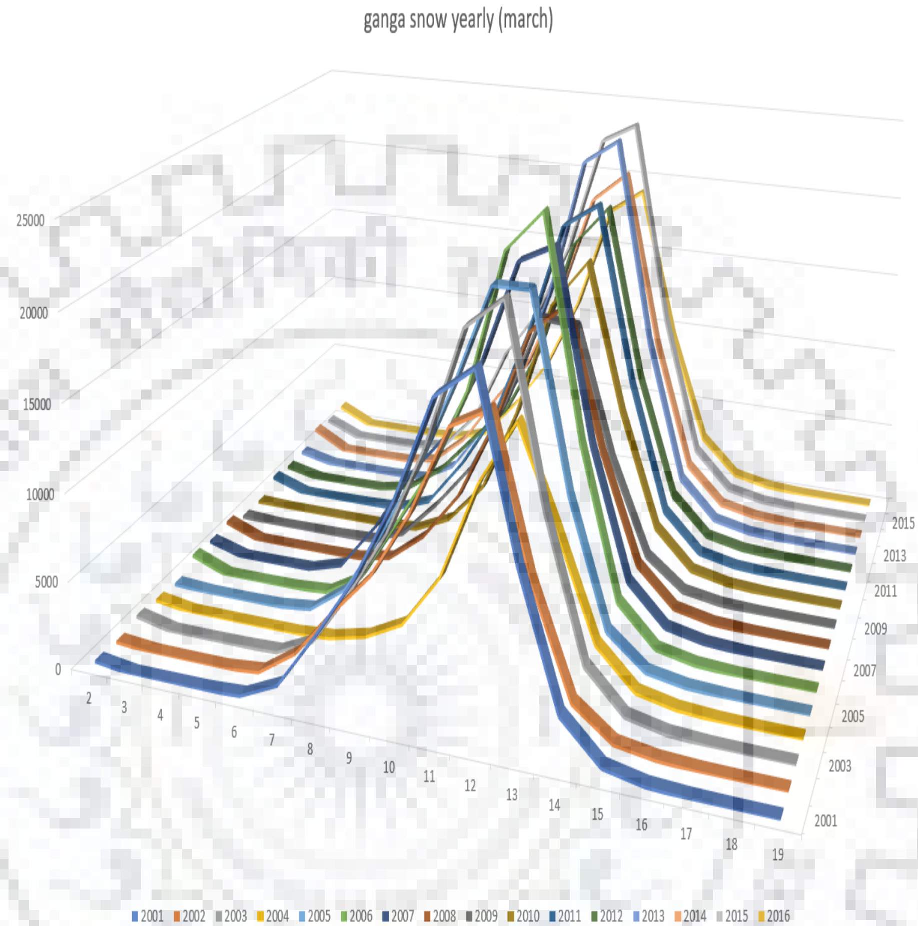


Figure 30: Snow Area- Elevation zone(March) (Yearly) Ganga

II. Treeline, March

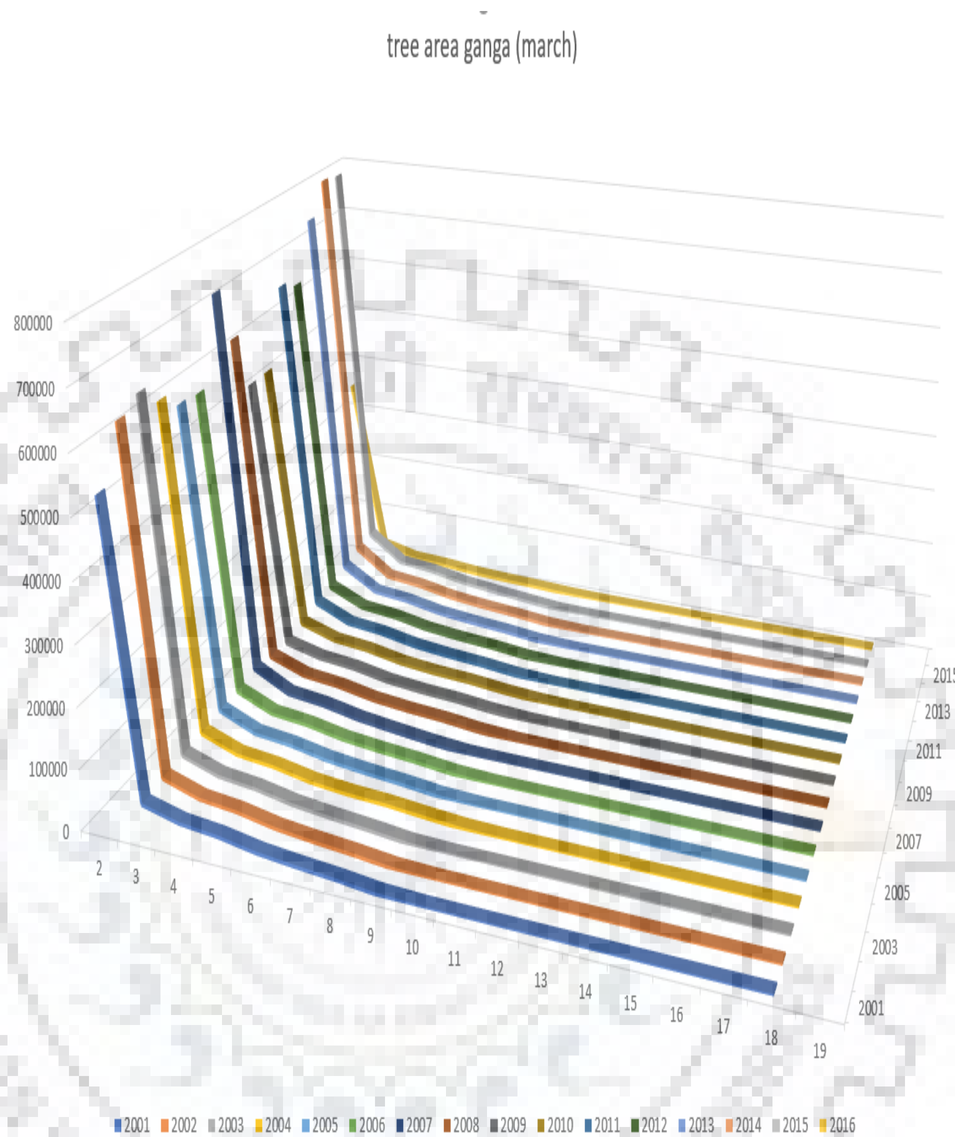
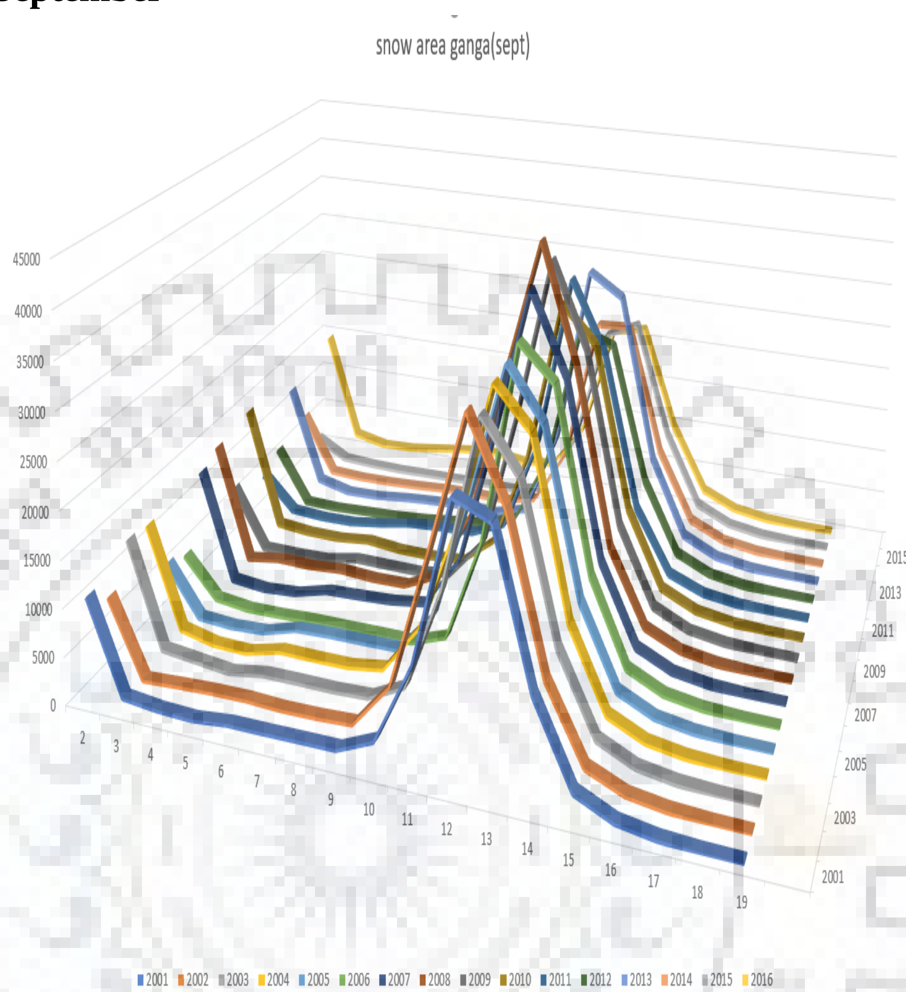


Figure 31: Tree Area- Elevation zone(March) (Yearly) Ganga

III. Snowline, September



IV. **Figure 32**: Snow Area- Elevation zone(Sept) (Yearly) Ganga

V. Treeline, September

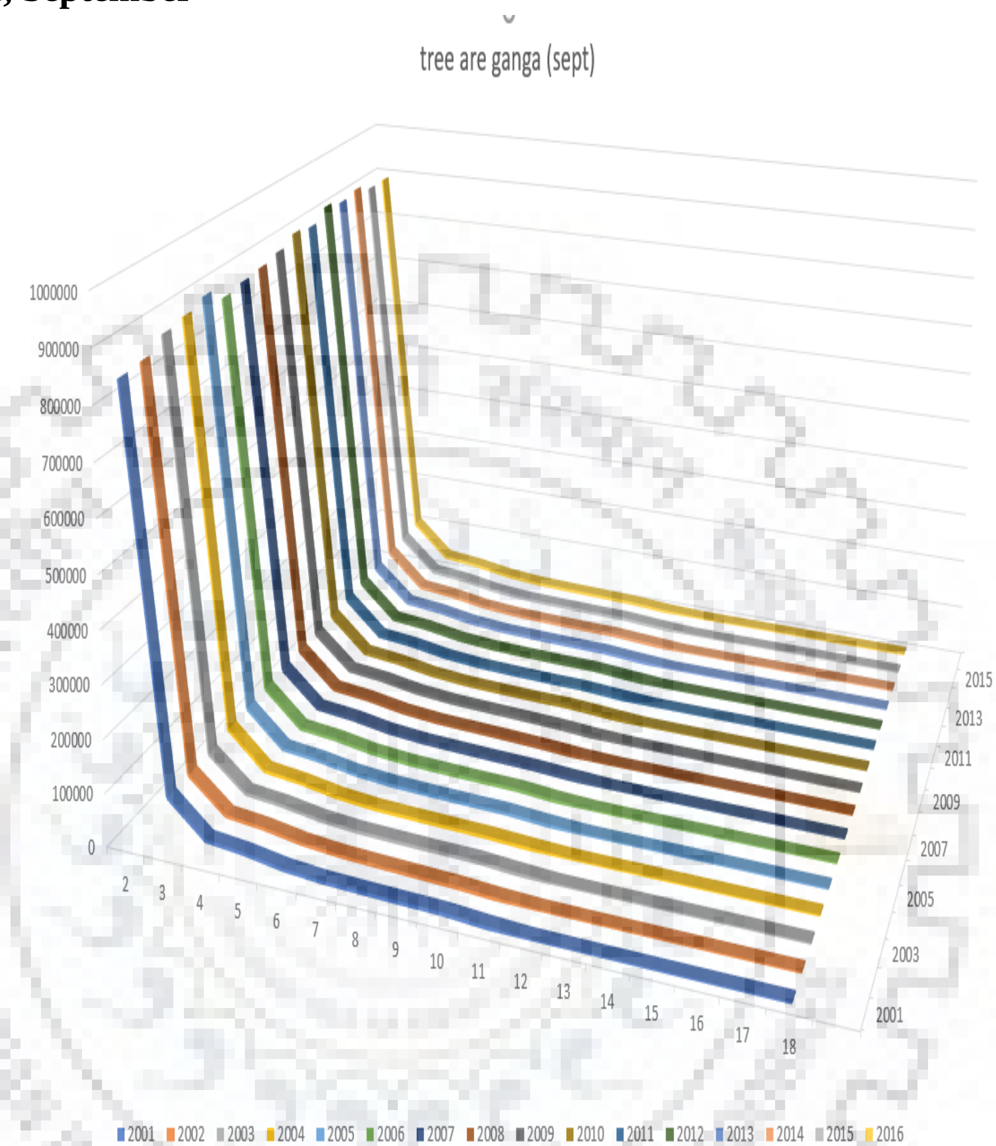


Figure 33: Tree Area- Elevation zone(Sept) (Yearly) Ganga

7. Inference

Once the elevation-area-time plots are generated, we can make some conclusions based on our observations as follows:
1.The amount of snow in March is less than the snow in September for each basin. The elevations zone in which the snow is found are slightly different for September when compared to March. Indicating Upward snowline movement.
2.Snowline has an upward shift from 2001-2016, which can be seen by the shortening of the elevation zone width.
3.The tree line doesn’t change significantly in the same year for different periods, however treeline changes can be observed when compiling Large Data over several years.
4.Indus Basin doesn’t show much change in the tree cover area.
5. Brahmaputra Basin has an upward shifting tree line from 2001-2016.
6. Ganga Basin doesn’t show much change in the tree cover area.

8. Conclusions

- The code for the automation of extraction and preprocessing of data was developed on Google Earth Engine (JavaScript)
- There is an upward shift in the snow line for the basins, from 2001-2016, despite the increasing and decreasing amount of snow the elevation band width drops.
- An overall upward shift as seen in the Brahmaputra basin’s tree line, making the tree line move to higher elevations.

9. Recommendations.

The Data, Graphs and Results generated during this work will help in making sophisticated models that can help in predicting the snow melt, tree cover area throughout the year, which in result can help in predicting the climatic changes in our atmosphere.

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