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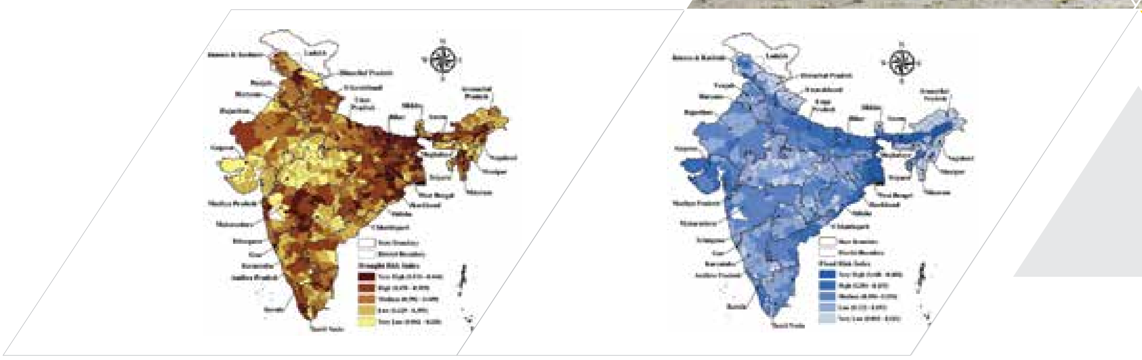
District-Level Climate Risk Assessment for India: Mapping Flood and Drought Risks Using IPCC Framework

USER MANUAL



Indian Institute of Technology Mandi

Indian Institute of Technology Guwahati

CSTEP

District-Level Climate Risk Assessment for India: Mapping Flood and Drought Risks Using IPCC Framework

User Manual

Submitted by
Indian Institute of Technology Mandi
Indian Institute of Technology Guwahati
Center for Study of Science, Technology and Policy, Bengaluru

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Climate Change Risk Assessment and Mapping at State and District Level in India

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PART A

GUIDELINES FOR CLIMATE RISK ASSESSMENT

Guidelines For Climate Risk Assessment

1. Introduction

Climate change presents a significant challenge to society, affecting both individual and collective decision-making (Adger et al., 2018). It interconnects human, social, and institutional systems with dynamic environmental processes, leading to cascading risks across ecosystems and economies. The Sixth Assessment Report (2021) by the Intergovernmental Panel on Climate Change (IPCC AR6) states that recent climatic changes are unprecedented, with global warming projected to increase by 1°C to 1.5°C under low greenhouse gas emission scenarios and up to 5.7°C under very high scenarios. This rise is expected to amplify extreme weather events, such as heatwaves and droughts, with severe implications for flooding and ecosystem stability. Ecosystem services vital for agriculture, forestry, and fisheries are declining, highlighting the inadequacy of current adaptation measures, especially for vulnerable populations. The IPCC AR6-WG-2 (2022) warns that a 1.5°C rise by 2040 will worsen biodiversity loss and food security, disproportionately affecting vulnerable regions.

While adaptation is crucial, progress is hindered by limited resources, low citizen engagement, and financing issues. Although ecosystem-based adaptation provides co-benefits, its effectiveness diminishes with rising temperatures. Integrated approaches to address interconnected risks are essential, and overcoming existing barriers is vital for mitigating climate change impacts and advancing sustainable solutions.

2. Risks of Climate Change

Climate change poses growing challenges as its impacts become increasingly complex. The likelihood of multiple climatic hazards occurring simultaneously is rising, often interacting with non-climatic risks to amplify overall risk. Managing these risks requires a comprehensive strategy that addresses the interplay between climatic and non-climatic factors to ensure community well-being and system sustainability. According to IPCC WG-2 (2022), near-term risks are shaped more by vulnerability, exposure, and socioeconomic factors than by variations in climate hazards across emission scenarios. Regions with high vulnerability, non-climate stressors, or proximity to thermal thresholds face heightened risks. Assessing risk is further complicated by the dynamic interactions of spatial, temporal, and multiple risk factors.

There are many different ways to define risk.

- Risk = probability x consequence
- Event risk: probability of occurrence of event associated with adverse outcomes
- Outcome risk: probability of occurrence of adverse outcome (linked to event risk and mediated by sensitivity/vulnerability of exposed system)

- Risk is associated with a "trigger" event or "hazard," and impacts mediated by characteristics of the exposed system
- Risk = f (hazard, vulnerability)

However, the preeminent and widely embraced framework for comprehensively defining risk is the one articulated by the IPCC in 2014. This framework encapsulates a holistic understanding of risk, acknowledging the interplay between hazards and vulnerabilities in shaping adverse outcomes.

2.1 IPCC Risk Definition and Framework

The risk definition and framework presented in this manual is adopted from the AR5 framework of the IPCC (2014), which is also adopted in IPCC-AR6 (IPCC, 2022), and is presented in Figure A-1. As defined by IPCC, risk in the context of climate change results from dynamic interactions of climate-related hazards with exposure and vulnerability of the affected human or ecological system. Hazard, exposure, and vulnerability may each be subject to uncertainty in terms of magnitude and likelihood of occurrence, and each may change over time and space due to socioeconomic development, adaptation responses and human decisions.

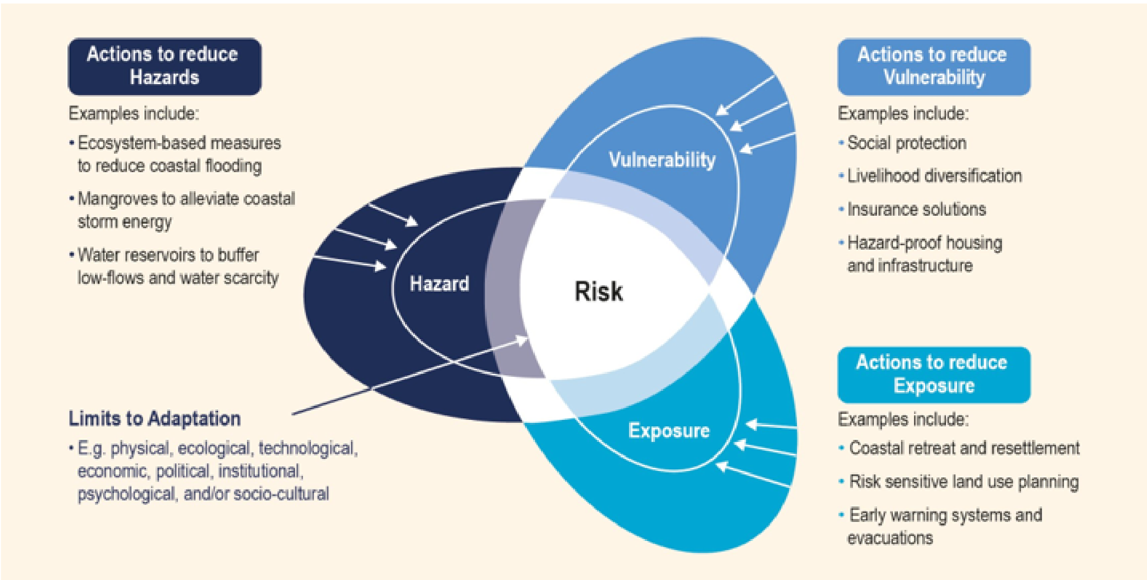

Figure A-1: IPCC Risk Framework (IPCC, 2014)

Risk (R)	The potential for consequences where something of value is at stake and where the outcome is uncertain, recognizing the diversity of values. Risk is often represented as probability of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur. Risk results from the interaction of vulnerability, exposure, and hazard.
Hazard (H)	The potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources. In this report, the term hazard usually refers to climate-related physical events such as droughts, floods, hurricanes, etc.
Exposure (E)	The presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected.
Vulnerability (V)	The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

The assessment of potential risks to an ecosystem, infrastructure, cropping systems, or community hinges on the dynamic interplay of various factors. These include the nature and intensity of the hazard, the magnitude of exposure experienced by communities and ecosystems, and the susceptibility and adaptability of these entities—their sensitivity and adaptive capacity—to specific climate hazards. Risk can be assessed for a single hazard or a set of hazards within a given region by accounting for their frequency and intensity based on historical trends.

2.1.1 Hazard-specific Risk Assessment

A climate hazard refers to a climate extreme or trend with the potential to cause adverse consequences for specific elements within an affected system (Reisinger et al., 2020). Various hazards emerge from climate extremes, whether related to temperature (extreme heat or cold) or precipitation (rainfall or snow). These encompass heat, cold, wet and dry conditions, spanning both mean and extreme variations, alongside cryosphere hazards (snow cover, ice extent, permafrost) and oceanic hazards (marine heatwaves). Some hazards manifest gradually or are slow-onset events (e.g., drought and desertification), while others are abrupt or rapid onset events (e.g., cyclones and floods).

Risk assessment can be conducted for a singular hazard or multiple hazards, falling into various categories or types. A single climatic hazard, such as a flood, has the potential to inflict significant loss and damage to human life and assets. In some instances, the simultaneous occurrence of multiple hazards can escalate risks and impacts. For instance, heat stress followed by drought may lead to the occurrence of forest fires.

2.2 Why Assess Risks Associated with Climate Change?

Risk assessments offer a systematic approach to understanding climate change risks, enabling the prioritization of adaptation policies and efficient management strategies. Consequently, climate risk assessment becomes the cornerstone of effective climate risk management. This entails analysing the repercussions, probabilities, and responses to the impacts of climate change, all while considering available options within prevailing constraints. By identifying risks and assessing the extent of their impact on individuals, assets, value chains, infrastructure, settlements, and ecosystems, climate risk assessments provide decision-makers with actionable insights.

Vulnerability and risk assessments are critical first steps in addressing climate change, guiding the development of adaptation or resilience policies, programmes, and projects. While many initiatives currently focus on vulnerability assessment, there is a growing need to advance beyond vulnerability-centric approaches and transition towards a more inclusive evaluation that incorporates risk in the development and execution of adaptation and resilience programs and projects. Integrating risk assessments into adaptation efforts offers a more holistic understanding of climate challenges and improves management outcomes. As experience in this field grows, tools such as risk indices and maps are increasingly recognized for their value in shaping and enhancing adaptation initiatives.

Risk assessment is necessary for multiple reasons and will help:

- **Identify and Prioritize Risks:** Assess and rank regions, districts, cropping systems, and communities susceptible to climate change-related damages and losses.
- **Inform Adaptation Planning:** Communicate to decision-makers the need to address not only hazards but also the drivers of exposure and vulnerability in adaptation planning.
- **Anticipate Changing Risks:** Understand how risks, based on historical or recent climate trends will evolve or intensify under different climate change scenarios.
- **Predict High-Risk Areas:** Determine which districts, regions, and communities will face elevated risks or increased impacts in the coming decades due to climate change.
- **Quantify Risk Components:** Assess and quantify the extent of risk attributed to hazards, exposure, and vulnerability individually, as well as their combined impact (Hazard + Exposure + Vulnerability). Also, highlight that exposure and vulnerability are significant contributors to loss and damage from climate change, sometimes outweighing the impact of hazards. It also helps provide a realistic depiction of climate change risks compared to vulnerability assessments, which usually is estimated independent of climate hazards.
- **Identify Key Risk Drivers:** Determine the primary drivers of risk to communities and ecosystems, whether they stem from hazards, exposure, vulnerability, or a combination, and identify key indicators contributing most to overall risk.
- **Project Identification for Funding:** Identify tangible adaptation projects suitable for funding from donors, bankers, and other agencies, integrating considerations of climatic hazards, exposure, and vulnerability.

Mapping climate change risks using a common framework is integral for understanding the entry point of interventions. This approach aids in identifying the key risk drivers—whether they stem from hazards, exposure, or vulnerability—providing a comprehensive understanding of the challenges at hand. By delineating the scope for adaptation and highlighting potential maladaptation pitfalls to be avoided, this exercise becomes a guiding tool for states. Moreover, it serves as a practical resource for optimizing the utilization of adaptation funds over a specified time horizon. For instance, addressing vulnerability may be feasible in the short to medium term, while mitigating exposure requires a more prolonged commitment and substantial financial investment. Armed with this information, states are empowered to prioritize interventions, ensuring a strategic and efficient allocation of resources to tackle the most pressing climate risks.

In the current guidelines, the focus is on two predominant hazards in India —droughts and floods. As a slow-onset disaster, drought is primarily characterised by a lack of precipitation for prolonged periods of time. However, drought is a relative term, and may be defined in multiple ways. The IPCC defines drought as 'a period of abnormally dry weather long enough to cause a serious hydrological imbalance' (IPCC, 2019). Contrary to droughts, floods result from excessive rainfall. The IPCC defines floods as, 'the overflowing of the normal confines of a stream or other bodies of water, or the accumulation of water over areas that are not normally submerged' (IPCC, 2019). The different definitions of droughts and floods, and their characterisation in the context of this risk assessment guideline are discussed in Section 3.1.1.

Why Focus on Droughts and Floods?

Various regions, including states and districts, face distinct exposure to a range of hazards. Coastal areas are exposed to storms, cyclones and hurricanes, while mountainous regions are exposed to floods and landslides. Tropical or low-latitude regions are particularly prone to severe heat stress, although temperate and high latitude areas may also experience significant challenges in this regard.

Droughts and floods, on the other hand, are prevalent across a majority of countries, states, districts or regions. In India, according to IMD, 87% of districts are drought-prone, and 30% are at risk of floods. Additionally, 14% of districts are vulnerable to cyclones, and 13% are exposed to heat waves. Many districts are exposed to both drought and flood events, and during certain years, a district may experience drought followed by floods within the same year.

Thus, the focus of the current assessment is on droughts and floods, due to their significant socioeconomic impacts in India, but the methods and guidelines can be applied to assess risks from other hazards as well.

3. Assessing Hazard, Exposure, Vulnerability, and Development of the Risk Index

Risk is a result of interaction among the three components namely, hazard, exposure and vulnerability as described in the IPCC-Risk Framework (Figure A-1). In the subsequent subsections, we discuss assessment of each of these components—Hazard, Exposure and Vulnerability. In Table A-1, a summary of steps in risk assessment or risk index development is presented.

Table A-1: Detailed Steps for Climate Risk Assessment

Step 1	Define the objectives of risk assessment: Current Risk assessment	1. Assist in adaptation planning 2. Prioritising adaptation investment
Step 2	Define the type of risks to be assessed: Hazard-specific risk assessment under current climate	1. Drought hazard 2. Flood hazard 3. Others
Step 3	Define the region / scale for risk assessment and define the boundary for risk assessment; District, State and Country	1. State & district 2. Cropping systems
Step 4	Define the risk framework Hazard, Exposure, Vulnerability based framework	IPCC, 2014 Risk Framework

Step 5	HAZARD INDEX ASSESSMENT	
Step 5.1	Hazards for risk assessment under historical climate data	1. Drought hazard 2. Flood hazard
Step 5.2	Obtains historical climate data for the selected hazard: Daily / Monthly Rainfall data in mm at the district level or 0.25 x 0.25-degree gridded data.	1. Drought data 2. Flood data 3. Period: 30 to 50 years
Step 5.3	Select a method or equation to estimate the selected Hazard Index, Drought, and Flood hazards under current climate scenario	SPI = Standard Precipitation Index (Based on WMO) Geographic Information System (GIS) based flood susceptibility mapping using multi-criteria decision analysis (MCDA) techniques.
Step 5.4	Estimate the Drought Hazard Index and Flood Hazard Index	Drought / Wet events - Low / Moderate / Severe - How many years out of past 30 years - How many years out of projected 30 years Flooded area: - Very low/ Low/ Medium/ High / Very high - How many years out of past 30 years - How many years out of projected 30 years
Step 6	EXPOSURE INDEX ASSESSMENT	Ex; at District scale
Step 6.1	Select Hazard-specific exposure indicators and collect data for selected indicators under current climate.	- Select indicators for selected scale -Estimate current value of exposure indicators
Step 6.2	Normalize, give equal weights and estimate the Exposure Index at the scale selected under historical climate period	- Estimate Exposure Index
Step 7	VULNERABILITY INDEX ASSESSMENT	
Step 7.1	Select hazard-specific indicators for vulnerability assessment at the scale selected and compile data for the indicators under historical climate period.	- District scale - Current value of vulnerability indicators
Step 7.2	Normalize, give equal weights, and estimate the vulnerability Index at the scale for historical climate period.	
Step 8	RISK INDEX DEVELOPMENT	
Step 8.1	Estimate Risk Index using the equation: $Risk = \sqrt[3]{H \times V \times E}$ Where, H is Hazard, V is Vulnerability, and E is Exposure	Ex. At district/state scale
Step 8.2	Rank the districts / blocks / communities; based on the risk index values	- High / Moderate / Low Risk - Very high / High / Moderate / low / Very low
Step 8.3	Identify key drivers of risk.	- Hazard indicator - Exposure indicator - Vulnerability indicator
Step 8.4	Prepare Risk maps and classify and rank districts using a scale; High Risk – Moderate risk – low risk	- Hazard map, Exposure map, - Vulnerability map, Risk map

3.1 Assessment of Climate Hazard

According to IPCC AR6, WG2 (2022), hazard is defined as "the potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources."

3.1.1 Types of Hazards

Risks of climate change or the impacts of climate change are determined by the type, frequency, and intensity or severity of the hazard.

Hazard could be classified as:

- Direct climatic hazard event: Events such as high intensity rainfall, deficit rainfall, high temperatures, and cyclones could be considered as direct climatic hazards.
- Consequence of hazard events: Floods, droughts, coastal erosion, landslides, heat stress, etc. are direct consequences of climatic events. These consequences lead to loss of human and animal life, damage to property, assets, infrastructure, crops, etc.

Climate hazards could also be classified as:

- Changes in variability and extremes
    - Rainfall variability, seasonality - droughts
    - Changes in peak precipitation intensity (flood risk)
    - Changes in storm activity/behaviour/geographic distribution
    - Heat waves, wildfires, etc.
- Long-term changes/trends in average conditions
    - Warmer, wetter, drier, more saline groundwater, etc.
    - Shifts in climatic zones, ecological/species ranges.
- Abrupt/singular changes
    - Monsoon shifts
    - Landscape & ecosystem transitions
    - Glacial lake outbursts, etc.

3.1.2 Intensity and Frequency of Hazards

Both climatic hazard and consequential (or cascading) hazards such as drought or flood can have various levels of severity or intensity such as i) Mild drought/flood, ii) Moderate drought/flood, iii) Severe drought/flood.

Similarly, they may have different frequencies or number of events. For example, the frequency of droughts or floods represents the number of observed severe drought/flood seasons or events during a specific time period, say past 30 or 50 years. Likewise, there could be a number of Category 1 to Category-5 storm/cyclone events per year or over 30 or 50 years.

3.1.3 Definition of Drought and Flood Hazard

Numerous definitions of drought and flood can be found in literature. This section presents a few different definitions for each hazard and offers a rationale for choosing a specific definition in the context of this study.

3.1.3.1 Drought

The IPCC defines drought as a period of abnormally dry weather long enough to cause a serious hydrological imbalance' (IPCC, 2019). However, they acknowledge that drought is a relative term, and discussions around it, particularly in terms of precipitation deficit, must refer to the precipitation-related activity that is impacted. For example:

- ***Meteorological drought:*** A period with abnormal precipitation deficit.
- ***Agricultural drought:*** Shortage of precipitation during the growing season that adversely affects crop production and ecosystem function, primarily due to soil moisture stress.
- ***Hydrological drought:*** A deficiency in precipitation with consequences for runoff and percolation, predominantly influencing water supply and resulting in hydrological drought. Alterations in soil moisture and groundwater storage are further influenced by heightened actual evapotranspiration, compounded by decreased precipitation.

The IMD (Indian Meteorological Department) declares a drought in a region when the rainfall falls below 26% of its long-term normal. The severity of the drought is then categorized as either moderate (deficiency between 26% and 50%) or severe (deficiency exceeding 50%).

Similar to the terminology used by the IPCC to categorize droughts, the IMD also distinguishes between meteorological, agricultural, and hydrological droughts:

- **Meteorological Drought:** A meteorological drought is declared when the seasonal rainfall is less than 75% of the long-term average for a particular area. The assessment of seasonal rainfall typically includes the monsoon season spanning June, July, August, and September, as well as the retreating monsoon occurring in October, November, and December.
- **Agricultural Drought:** An agricultural drought occurs when the soil moisture levels in the topmost one meter of the soil are deficient for the specific crop being cultivated, resulting in significantly reduced crop yields.
- **Hydrological Drought:** A hydrological drought is defined by the impact of dry spells on surface or groundwater bodies. In this context, water resources fall short of meeting the demands of a given water management system. In this guideline, the focus of drought hazard assessment is on meteorological drought as defined by IMD. The only parameter required to gauge the probability of occurrence of this type of drought hazard is rainfall.

3.1.3.2 Flood

The IPCC defines floods as 'the overflowing of the normal confines of a stream or other bodies of water, or the accumulation of water over areas that are not normally submerged' (IPCC, 2019). Floods can be caused by unusually heavy rain, for example, during storms and cyclones.

Flooding in a region is influenced not solely by the intensity and duration of rainfall but also by the specific physical attributes of the ecosystem under consideration. These attributes encompass topography, river morphology, the presence of glaciers, soil properties, characteristics of vegetation, degree of urbanization, and more. This intricate interplay gives rise to various types of floods, including river floods, flash floods, urban floods, pluvial floods, sewer floods, coastal floods, and glacial lake outburst floods (IPCC, 2012). Moreover, the geographical impact of floods is highly diverse, ranging from localized inundation in urban areas to extensive flooding along major rivers affecting numerous villages. The root causes of flooding can be exclusively weather-related, such as intense precipitation, or anthropogenic, stemming from factors like unplanned urbanization. Often, flooding is a result of a complex interweaving of both natural and human-induced factors.

Globally, individuals are increasingly experiencing unfamiliar precipitation and warming patterns, including instances of extreme precipitation, prolonged dry spells, and intense heat events within a single year. These phenomena contribute to various hazards, such as floods, landslides, droughts, heatwaves, and even forest fires, resulting in the compounding impacts of these hazards. While numerous climate-related hazards affect our country, droughts and floods stand out as the most prevalent.

3.1.4 Methods for Quantifying Climate Hazards and Constructing the Hazard Index

A Hazard Index can be developed to assess historical climate trends over the past 30 to 50 years. The methodology employed in developing the index varies depending on the specific climatic hazard under consideration. Figure A2 provides a generic overview of the steps involved in assessing a hazard for climate risk assessment, while Figures A3, A4, A5, and A6 shows the various illustrations of hazard maps. However, the guidelines described in this manual focus on evaluating drought and flood hazards; detailed descriptions of which are provided in Parts B and C of this manual**,** respectively.

Figure A-2 Steps in hazard assessment

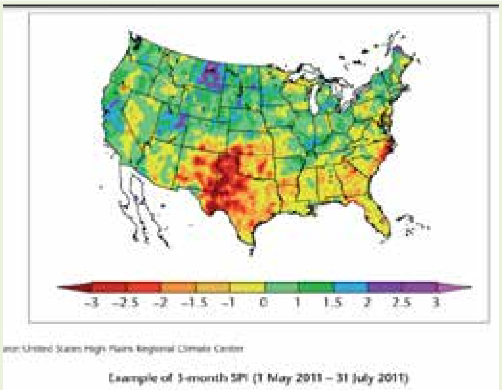

Figure A-3:3-month SPI map.

(Source: WMO 2012)

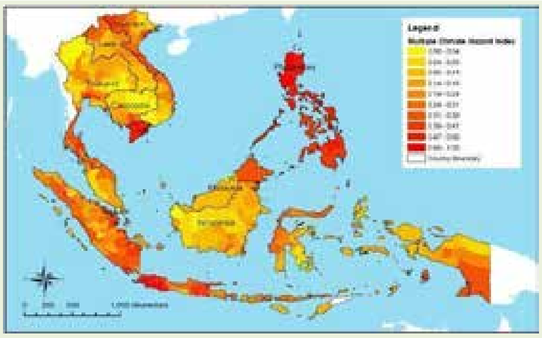

Figure A-4**:** Multiple Climate Hazard Index Map of Southeast Asia

(Source: International Development Research Center, Economy and Environment Programme for Southeast Asia)

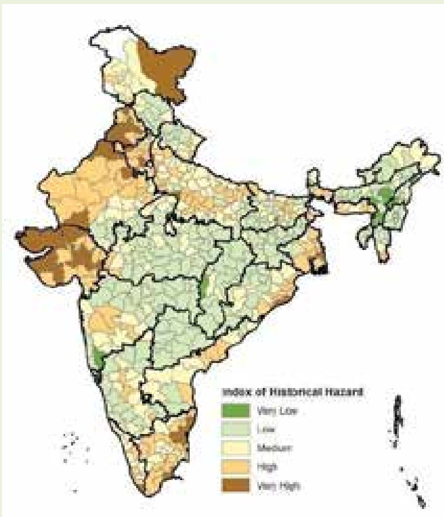

Figure A-5: Historical Multi-Hazards Map

(Source: CRIDA, 2021)

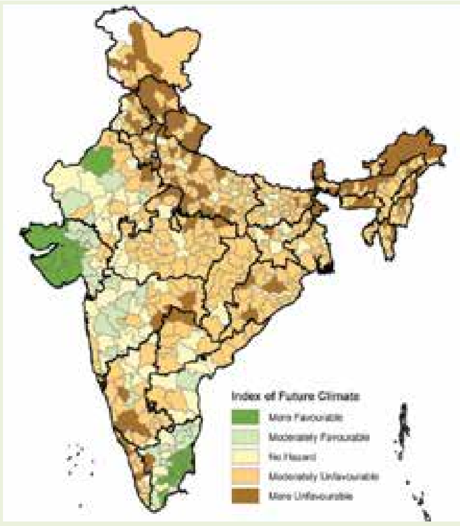

Figure A-6: Future Multi-Hazard Map

(Source: CRIDA, 2021)

3.1.4.1 Drought Hazard Assessment

Numerous methods exist for evaluating drought or flood hazards, with the World Meteorological Organization (WMO) offering a range of approaches, methods, and equations for constructing drought and flood indices (WMO, 2012). Among these, the Standard Precipitation Index (SPI), introduced by Mckee in 1993, stands out as one of the most widely utilized methods and indices for assessing drought conditions.

The Standardized Precipitation Index (SPI), as defined by Mckee et al. (1993), is based on the probability of observed precipitation across various time scales. The likelihood of observation is converted into an Index, with SPI initially designed to quantify precipitation deficits over multiple time scales. The SPI calculation for any given location is based on a long-term precipitation record for a specific period. WMO (2012) provides a user guide and software tool to facilitate the development of SPI for drought assessment. Table A-2 presents SPI as an index, reflecting different levels of dryness and wetness severity.

Advantages of using SPI

- **Widespread applicability:** The SPI is a widely employed and straightforward tool for assessing drought hazards.
- **Accessible resources:** Toolkits and software supporting SPI are readily available, facilitating its implementation for a diverse range of users.
- **Meteorological basis:** SPI relies exclusively on meteorological parameters, particularly rainfall data, which includes the measurement of rainfall intensity in millimeters per day.
- **Simplicity in design:** The simplicity of SPI's design enhances its usability and effectiveness in drought hazard assessment.
- **International comparisons:** SPI enables comparisons across different regions and countries, providing a standardized metric for evaluating drought risk on a global scale.

Table A-2: Classification of SPI values

Value	Classification
2.0+	Extremely Wet
1.5 to 1.99	Severely Wet
1.0 to 1.49	Moderately Wet
-0.99 to 0.99	Near Normal
-1.0 to -1.49	Moderately Dry
-1.5 to -1.99	Severely Dry
-2 and less	Extremely Dry

Source: SPI User Guide, WMO (2012)

The frequency or probability of occurrence of dry or wet events could be expressed as the number of events of a given type and severity of hazard; an example is given in Table A-3.

Table A-3: Probability of occurrence of dry events

SPI	Category	No. of times in 100 years	The severity of the event
0 to -0.99	Mild Dryness/Drought	33	1 in 3 years
-1.00 to -0.49	Moderate Dryness/Drought	10	1 in 10 years
-1.5 to -1.99	Severe Dryness/Drought	5	1 in 20 years
<-2.0	Extreme Dryness/Drought	2.5	1 in 50 years

The SPI computation relies on historical precipitation data from a designated weather station, wherein the precipitation accumulation over a specific time frame is juxtaposed with the corresponding period in the historical record of that location. Data needed to compute SPI for historical and future time periods is given below:

Parameters	Historical	Resolution
Monthly Rainfall	IMD gridded data (1970-2019)	0.25° x 0.25°

The index is calculated based on the mean and standard deviation of rainfall for a particular district. It offers a scale as seen in Table A-2, which indicates the severity, as well as, the return period of droughts depending on the value. The SPI index can be calculated for different time scales (3, 6, 12 and 24 months).

- SPI3 indicates the comparison of short to medium-term moisture conditions.
- SPI6 indicates trends in seasonal rainfall.
- SPI9 indicates inter-seasonal precipitation patterns over medium timescales and,
- SPI12-SPI24 indicates long-term precipitation patterns.

The SPI metrics enable the assessment of diverse potential impacts associated with meteorological droughts. In the current hazard evaluation, SPI6 is specifically employed. The computed SPI6 values are subsequently juxtaposed against standardized benchmarks.

For a comprehensive description of the methodology and detailed step-by-step guidance for computing the Drought Hazard Index using SPI, refer to **Part B** of this manual.

3.1.4.2 Flood Hazard Assessment

Identification and delineation of areas prone to flooding in any given region or basin is the first step to flood risk assessment and an important flood prevention tool (Lin et al., 2020). Multiple flood modelling techniques exist, each serving a specific purpose in flood risk assessment, mitigation, and management. Two of the most commonly adopted approaches for deriving flood risk maps are the hydrologic-hydraulic modelling (HHM) and the Geographic Information System (GIS) based flood susceptibility mapping using multi-criteria decision analysis (MCDA) techniques. Flood susceptibility mapping (FSM) integrating GIS and MCDA is the process of assessing and mapping areas that are prone to flooding and is a widely used, scientifically robust technique (Mahmoud and Gan, 2018a, 2018b; González-Arqueros, Mendoza, Bocco, and Castillo, 2018; Das, 2020; Dash and Sar, 2020; Chen, 2022; Gupta and Dixit, 2022). It involves analysing multiple factors such as topography, geography, geomorphology, rainfall patterns, and historical flood records to evaluate the vulnerability of an area to flooding.

Rationale for FSM: The primary objective of FSM is to identify areas that are at high risk of flooding, enabling better planning, land management, and disaster preparedness.

The FSM method can provide a rapid assessment of flood-prone areas, especially in locations with no prior flood modelling information or have limited resources and data. This method can be applied to any particular region and scale such as a district or state and is not restricted to hydrological boundaries.

On the other hand, physical attribute-based flood modelling methods require high-quality data, such as long-term rainfall patterns, river flow data, hydraulic properties of the area, etc. and employ complex calculations (Mudashiru et al., 2022). These data intensive methods also require specialized software and significant computational resources, along with high technical expertise. In areas with limited access to such resources, the FSM approach is therefore a relatively simpler technique that does not require advanced computational skills, making it more accessible and practical for flood hazard assessment.

Advantages of FSM
● Simple, yet reliable and rapid assessment of flood prone areas. ● Can be employed in both gauged and ungauged locations, with limited data availability and resources and no prior flood modelling. ● Applicable to any particular region and scale and not restricted by hydrological boundaries.

Broad steps for flood hazard assessment:

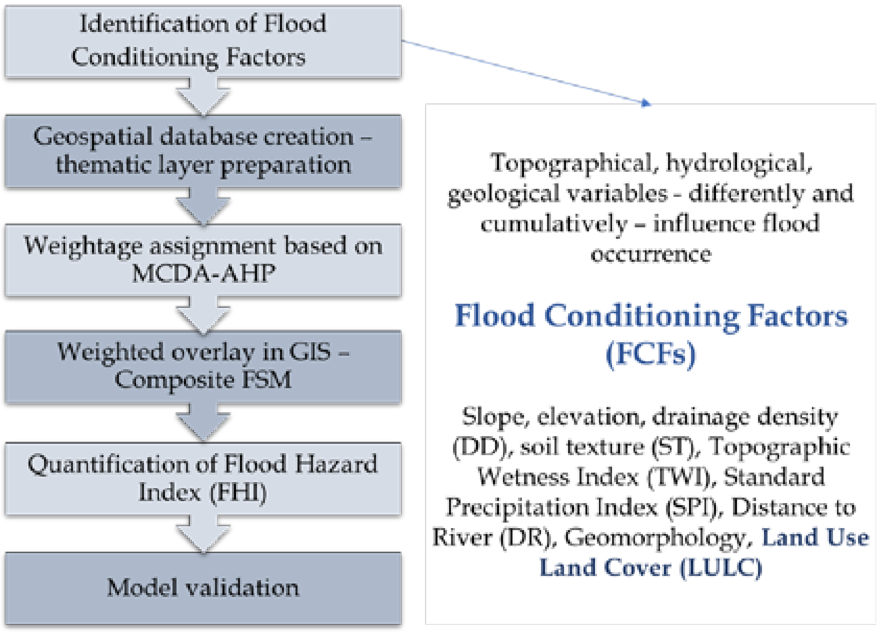

Figure A-7 Steps in flood hazard index assessment

Part C of the Manual provides a step-by-step procedure with examples for using the FSM methodology for flood hazard assessment.

3.2 Assessment of Exposure

Not all hazards automatically translate into risks; it is the interaction of hazards with exposed systems that gives rise to risks. Exposure does not necessarily equate to vulnerability; individuals or communities can be exposed to a hazard but possess the means to mitigate risk effectively. For instance, residing in a floodplain exposes one to flood hazards, but with appropriate modifications to building structures and behaviours, vulnerability can be reduced.

The selection and quantification of exposure indicators are contingent upon the scale of hazard assessment. Consequently, it is feasible to choose and quantify broad indicators at the district level using secondary sources of information. These indicators may encompass sensitive areas such as rainfed croplands and forest lands, as well as specific populations like rural communities or those living below the poverty line.

The selection of an exposure indicator must align with the resolution of the chosen hazard to ensure accurate risk assessment. For instance, if a hazard is determined at a 0.25° x 0.25° resolution, but exposure indicators are specified at the district level, the hazard value will be uniform across all districts. This uniformity may lead to inaccuracies, as different districts may exhibit varying exposure indicators, implying a consistent hazard level across all, which could be misleading.

Steps in Exposure Index Development

Figure A-8 Steps in exposure index assessment

Indicators to represent exposure to a hazard could be:

- Socioeconomic indicators: Percentage of rainfed farmers in the area, percentage of households or number of people living in flood-prone areas, percentage of SC/ST or BPL population, population density.
- Biophysical indicators: Area under rainfed crops, an area with a high slope gradient, and an extent of area under low-lying conditions.

An illustrative Exposure Map is provided below (Figure A-9):

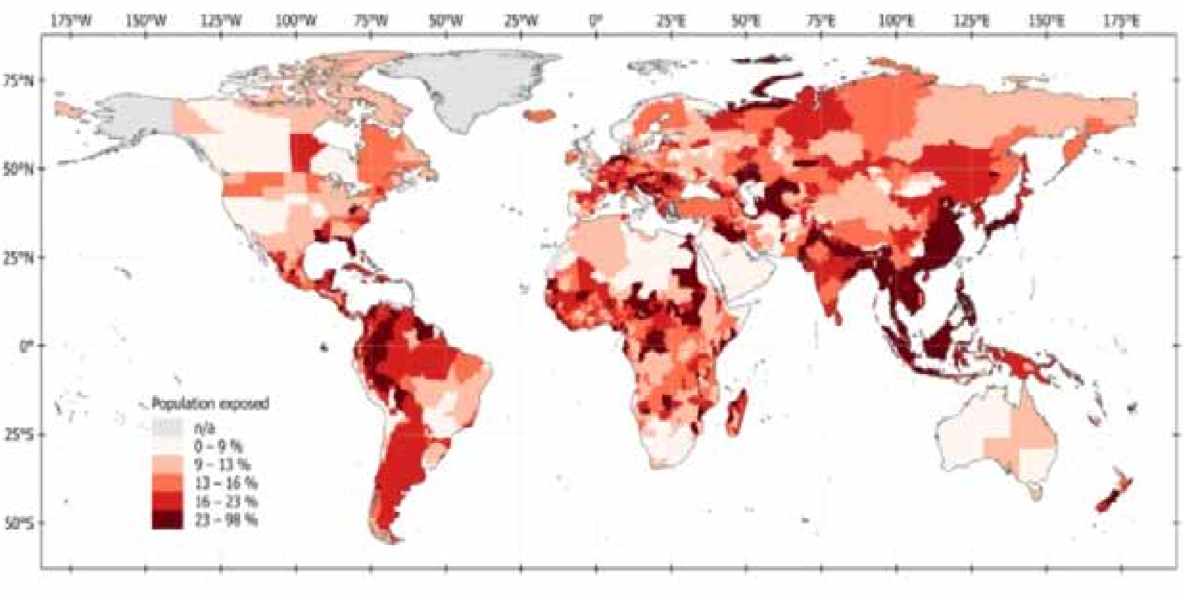

Figure A-9 Population exposed to Flood ***(Source: Rentschler, Salhab and Jafino, 2022)***

3.3 Assessment of Vulnerability

Vulnerability, in this conceptualization, can be specific to certain hazards or encompass a broader perspective. In the context of our current project, which aims to formulate a risk index related to floods and droughts, the emphasis is on developing a vulnerability index that is specific to the hazards in question. This hazard-specific vulnerability index will provide a targeted assessment of the system's susceptibility to the adverse impacts associated specifically with floods and droughts.

Steps in Vulnerability Index Development

Figure A-10 Steps in hazard-specific vulnerability assessment

Illustration of the Vulnerability Map (Figure A-11 and Figure A-12) is provided below:

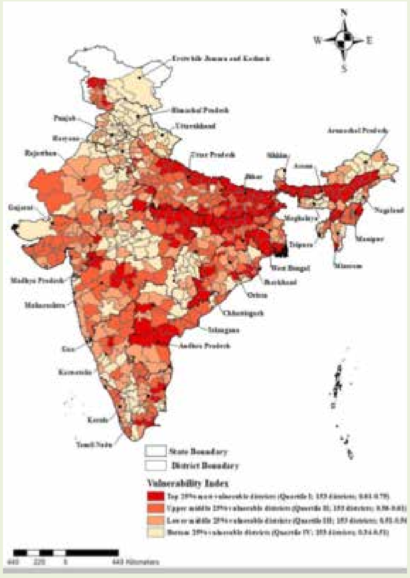

Figure A-11 Vulnerability map of India *(Source: CRIDA, 2021)*

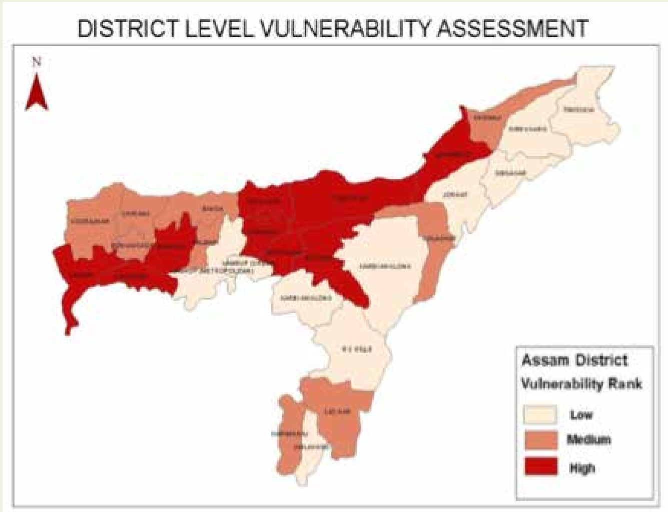

Figure A-12 Vulnerability category map of Assam *(Source: Climate Vulnerability Assessment for the Indian Himalayan Region Using a Common Framework, 2018-19)*

3.4 Development of Risk Index

Risk is the function of hazard, exposure, and vulnerability index values. The risk index could be estimated by giving weights based on experience and knowledge. The risk index could be estimated using the following equation:

$$Risk = \sqrt[3]{H \times V \times E}$$

Where H is Hazard, V is Vulnerability, and E is Exposure.

The use of geometric mean is the best way of calculating the average value of components when they are in ratios. Further, unlike the arithmetic mean, geometric mean does not assume substitutability between dimensions. Various important global indicators, such as the Human Development Index (UNDP, 2021), are calculated based on exactly a similar method of normalization and taking geometric mean)

Steps in Risk Index Development

1. Estimate the Index values for hazard, exposure, and vulnerability
2. Combine Hazard, Exposure, and Vulnerability into a single index
3. Estimate risk using the equation: Risk = $\sqrt[3]{(H \times V \times E)}$
4. Rank the state/districts/blocks using the Risk Index
5. Classify the risks into High/Moderate/Low for the scale selected, such as state/district/block
6. Prepare a risk map using the risk severity classes: High, Moderate, Low
7. Identify the key drivers of Risk: Hazard / Exposure / Vulnerability Indicators

Examples of risk maps: Very few studies have developed risk indices or risk index-based maps that are fully consistent with the IPCC-2014 risk framework. There are vulnerability maps, exposure maps, and hazard maps. The combined implication of hazard, exposure, and vulnerability to climate change risk is inadequately understood and rarely applied. Some examples are provided in Figures A-13 and A-14:

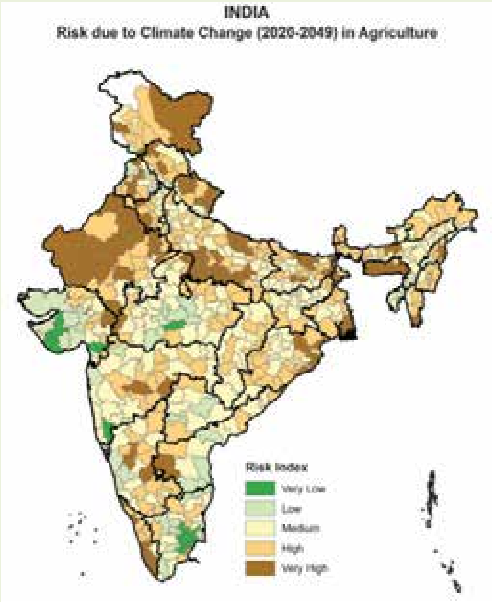

Figure A-13 Climate change Risk Map

(Source: CRIDA, 2021)

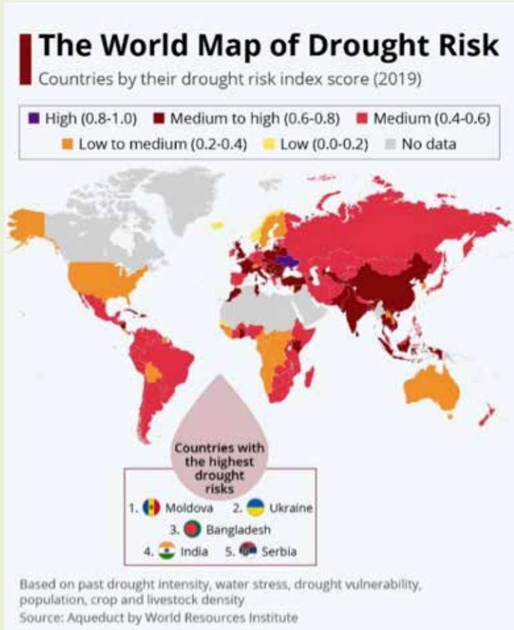

Figure A-14 Drought Risk Map of the World

(Source: Aqueduct Project, WRI)

4. Risk Assessment for Adaptation Planning

All adaptation frameworks and toolkits systematically integrate considerations of vulnerability, risk, or a combination of both throughout the various stages of developing adaptation strategies, projects, or practices. An illustrative instance of such integration can be observed in Figure A-15, showcasing an Adaptation Tool that explicitly incorporates "Vulnerability and Risk" as pivotal components within its framework.

The incorporation of risk and vulnerability assessments within adaptation initiatives serves as a valuable resource for developers of adaptation programmes or projects. The Adaptation Support Tool, consisting of six sequential steps, places the assessment of climate change-related risk and vulnerability as the second crucial step. This positioning underscores the significance of early consideration of these factors in the adaptation process. By systematically evaluating risk and vulnerability upfront, the tool lays the groundwork for identifying appropriate adaptation options.

Furthermore, the flexibility of conducting risk and vulnerability assessments is emphasized, suggesting that such evaluations can occur not only at the project's initiation but also during the monitoring and evaluation stages (Figure A -16). This dual approach enables a comprehensive understanding of how the implementation of adaptation programs or projects influences the prevailing risk and vulnerability dynamics. It facilitates a continuous feedback loop, allowing for adjustments and improvements based on the evolving context throughout the project life cycle.

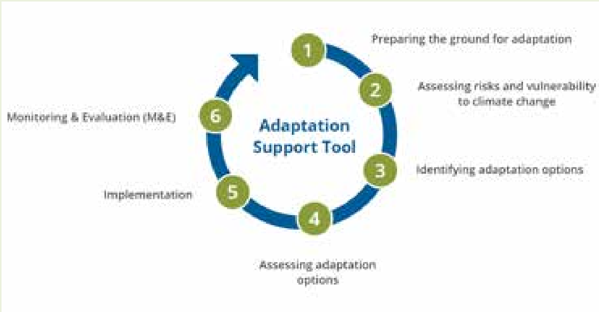

Figure A-15 Risk assessment for adaptation planning (*Source: Climate-Adapt from European Union, https://climate-adapt.eea.europa.eu/#t-adapt*)

Figure A-16 Steps to Resilience Framework *(Source: US Climate Resilience Framework)*

5. Utility and Application of Risk Index

The utility and application of a Risk Index are multifaceted and play a crucial role in enhancing climate resilience and adaptation planning. Some of the potential applications or utility of risk assessment and index are as follows:

1. Help stakeholders to identify the critical hazards faced by the region, district, communities, cropping systems, etc.
2. Help stakeholders to identify the most consequential and important risks faced by the districts, communities, and ecosystems both under current climate scenarios and projected climate change scenarios.
3. Help stakeholders to identify the risk hotspots of climate change in the context of selected hazards.
4. Identify the critical indicators of hazard, exposure, and vulnerability based on their contribution to the risk index and individual indices such as hazard, exposure, or vulnerability index.
5. Prioritize the state/district/blocks/cropping systems for adaptation planning and funding utilizing the risk index, the indicators used, and the major drivers of risk, hazard, exposure, and vulnerability.
6. Enable adaptation project developers to convince the funding agencies of the rationale for adaptation programs or projects, leading to the utilization of risk maps in adaptation planning and development to enable development of focused and prioritized adaptation interventions.

6. Challenges and Limitations of Risk Assessment

Vulnerability assessment is more popular and broadly used than risk assessment and mapping. There are a large number of research publications, manuals, and toolkits on vulnerability assessment compared to risk assessment. However, risk assessment is more useful than vulnerability since it incorporates climate hazards, which provide information on the most vulnerable regions for a specific hazard. Nevertheless, there are many challenges and limitations in applying risk assessment tools:

Challenges in Risk Assessment

- Selection of hazard: Whether to select a single hazard or a combination of hazards.
- Definitions of drought/flood: there are multiple definitions of flood and drought.
- Data: Obtaining historical data for hazards, such as daily rainfall or temperature, at the scale required and analysis is a challenge for many.
- Climate change modelling and projections: What scale, what period, which scenarios, and which models should be selected? Further, the capacity to access and utilize climate change model projections in developing hazard indices could be a limitation.
- Defining the hazard thresholds for different levels of intensity or severity of hazard could vary from region to region.
- There are multiple equations to estimate the hazard and its severity and frequency.
- Selection of indicators for exposure and vulnerability and obtaining data for these indicators.
- Very often, there could be overlaps between indicators used for vulnerability and exposure.
- Giving appropriate weights to the indicators of exposure and vulnerability. Further, giving weights to hazard index, exposure index, and vulnerability index could be challenging.
- Technical capacity is required to develop a hazard index and risk index.
- Interpretation and utilization of the risk indices and maps.

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PART B

STEP-BY-STEP PROCEDURE FOR DROUGHT HAZARD INDEX DEVELOPMENT

Drought Hazard Index Development

Drought Hazard Index (DHI) is calculated to assess and quantify the hazard associated with drought conditions in a particular region. Here we provide a step-by-step procedure to calculate DHI.

Steps for Computing DHI

- Download SPI generator: Use following link and download: https://drought.unl.edu/Monitoring/SPI/SPIProgram.aspx
- Run the application after extracting all the files
- The application requires MicrosoftNET 4.0 framework and can be compiled as a 32 or 64-bit executable. The application consists of two files: a vb.net 4.0 application and a c#.net 4.0 DLL.
    - 'SPIGenerator.exe' – the Windows console application.
    - StandardPrecipitationIndex.dll – the SPI DLL.
- The application reads precipitation data and supports different time scales and data types (weekly, monthly). It outputs SPI data and, optionally, frequency and drought period data. The application could be run as a Windows GUI (Graphical User Interface) application or executed from the command line.
    - Running as a Windows application produces the following program flow:

Retrieve and verify input parameters >> Parse input file >> Aggregate data >> Calculate SPI >> Write results to file.

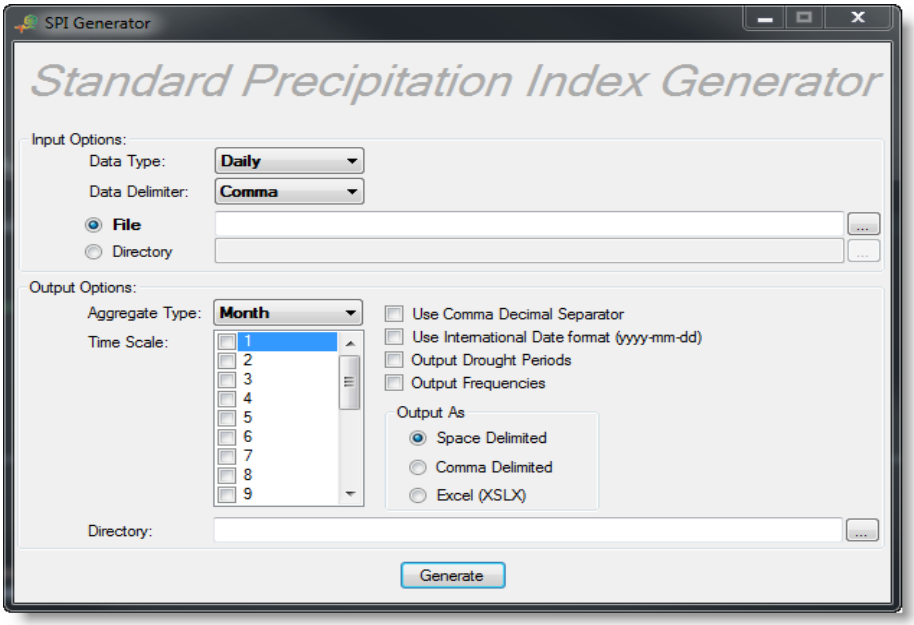
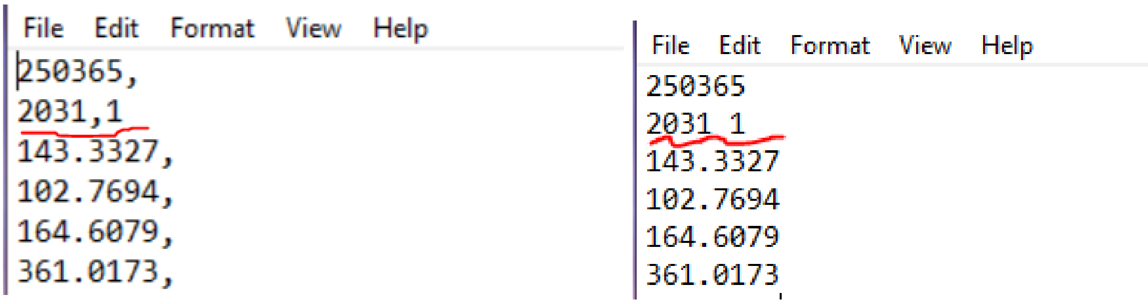


Figure B-1 The main Program Screen of SPI Generator

- Execution of SPI as Windows GUI:
    - The application will output data to a space-delimited, comma-separated, or Excel file. The file format is the same using either the Windows GUI or command line as shown in Figure B-1.
    - Select the Data delimiter based on your input file (Comma or Space) as shown in Figure B-2.



(Check Input File if its "Comma" or "Space" separated)

Figure B-2 Format of input dataset

- **Select Data Type:** Monthly
- **Select Data delimiter:** (Comma).
- **Select File/Directory:** File and click [...] to select the sample file for Rainfall data. (Example dataset is available for area of interest (West Bengal) Observed Climate (1970 to 2019) (Folder Location: 'Dataset/Rainfall/His/DistrictName').
- **Select Time Scale:** 6 Month (For SPI 6)
- **Create an Output Directory:** (For example dataset: select file Observed Climate (1970 to 2019) (Folder Location: 'Dataset\SPI_Result\WB_SPI_Output_His') as shown in Figure B-3.

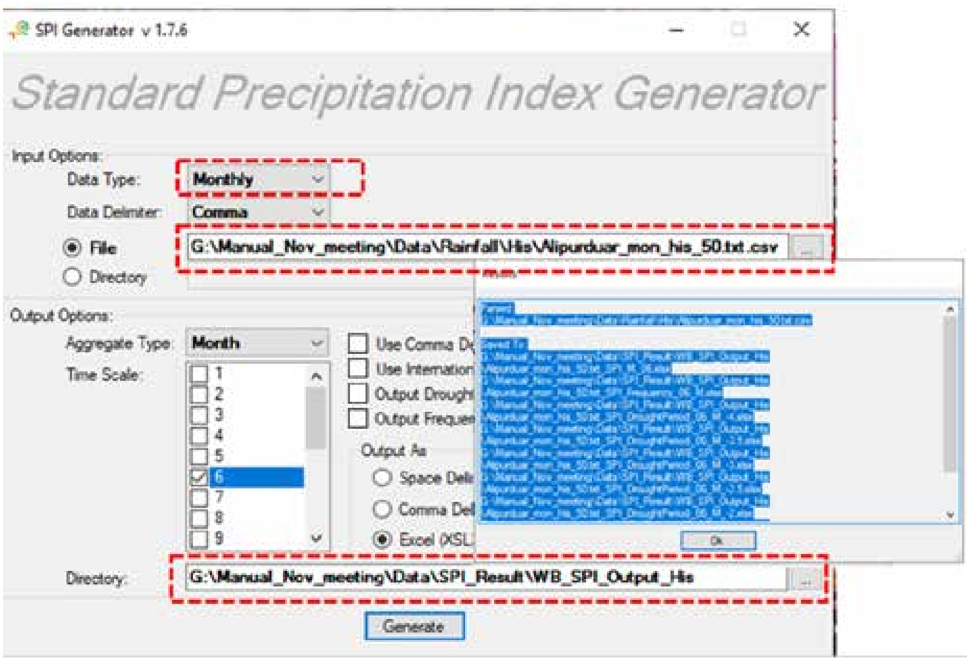


Figure B-3 Example input for SPI Generator

- The calculated SPI 6 values are compared with SPI values corresponding to moderate, severe, and extreme dry/wet events (refer to the Table B-1).

Table B-1 SPI Classification based on severity

SPI VALUE	CLASSIFICATION
≥ 2.0	Extremely wet
1.5 to 1.99	Very wet
1.0 to 1.49	Moderately wet
-0.99 to 0.99	Near Normal
-1.0 to -1.49	Moderately Dry
-1.5 to -1.99	Severely Dry
-2 and less	Extremely Dry

- The SPI value is used to categorize drought as moderate, severe, and extreme based on the severity. Every class related to drought severity is given a certain weight, and rating scores are assigned based on the normal cumulative probability function to drought hazard assessment using severity and occurrence probability. To assign the weight and rating scores:
    - o Moderate Dry (DWm) when the SPI value is between-1.00 to -1.49 is weighted as 1, Severely Dry (DWs) when the SPI value is between -1.50 to -1.99 is weighted as 2, and Extremely Dry (DWe) when SPI value is less than -2 is weighted as 3, and other SPI classes weighted as 0 as shown in Table B-2.
    - o Rating scores vary from 1 to 4 in increasing order, splitting the interval of percentage in each drought range as shown in Table B-2.
    - o The weights and ratings used to obtain the Drought hazard index (DHI) is based on Equation 1:

Drought Hazard Index = (DWm x DRm) + (DWs x DRs) + (DWe x DRe) (Equation B-1)

where DRm= ratings assigned to moderate droughts based on a percentage of occurrence; DWm= weight scores for moderate drought; DRs = ratings assigned to severe droughts based on a percentage of occurrence; DWs= weight scores for severe droughts; DRe= ratings assigned to extreme drought based on a percentage of occurrence; DWe= weight scores for extreme drought.

Table B-2 Weights and ratings used to obtain the Drought Hazard Index

Classification	Weight	Occurrences	Rating
Moderately Dry	1	≤ 9.0	1
		9.1-10.0	2
		10.1-11.0	3
		≥11.1	4
Severely Dry	2	≤ 3.5	1
		3.6-4.5	2
		4.6-5.5	3
		≥5.6	4
Extremely Dry	3	≤ 1.5	1
		1.6-2.0	2
		2.1-2.5	3
		≥2.6	4

- Remove the -99 value from the obtained SPI 6; Remove the Date column; Sort the SPI value from smallest to greatest; Describe the probability distribution (cumulative distribution function (cdf)) and obtain the occurrence assigned rating based on the occurrence value shown in Table 2. Use equation 1 to obtain the Drought Hazard Index.

- Sample Results for observed Climate for ‘Alipurduar’ is shown in excel file Folder: ‘Dataset\DHI\Alipurduar_mon_his _SPI_M_06.xlsx’.
- Repeat for all the districts.

Rank	Sort_spi	o.p	Final HAS
1	-2.96	0.001678	3
2	-2.84	0.003356	3
3	-2.73	0.005034	3
4	-2.64	0.006711	3
5	-2.23	0.008389	3
6	-2.23	0.010067	3
7	-2.12	0.011745	3
8	-2.06	0.013423	3
9	-2.05	0.015101	6
10	-1.95	0.016779	2
11	-1.88	0.018456	2
12	-1.85	0.020134	2
13	-1.78	0.021812	2
14	-1.73	0.02349	2
15	-1.68	0.025168	2
16	-1.65	0.026846	2
17	-1.65	0.028523	2
18	-1.64	0.030201	2
19	-1.61	0.031879	2
20	-1.57	0.033557	2
21	-1.55	0.035235	4

Extreme drought	30
Severe drought	42
Moderate drought	182
DHI	254

- In order to determine the range of hazards for each State, the DHI values of each state are normalized by dividing it by 1000 to get the final DHI.
- “Calculation of Hazard-specific Exposure Index”. This DHI value would then be combined with the normalized hazard-specific exposure and vulnerability indicator values to calculate the final Drought Risk Index (DRI) of each district within the AOI/state (“WB”).

PART C

STEP-BY-STEP PROCEDURE FOR FLOOD HAZARD INDEX DEVELOPMENT

Flood Hazard Assessment

Identification and delineation of areas prone to flooding in any given region or basin is the first step to flood hazard assessment and an important flood prevention tool (Lin et al., 2020). Multiple flood modelling techniques exist, each serving a specific purpose in flood risk assessment, mitigation, and management. Two of the most common approaches for deriving flood hazard maps are the hydrologic-hydraulic modelling method (HHM) and the Geographic Information System (GIS) based flood susceptibility mapping using multi-criteria decision analysis (MCDA) techniques. Flood susceptibility mapping (FSM) integrating GIS and MCDA is the process of assessing and mapping areas that are prone to flooding and is a widely used, scientifically robust technique (Mahmoud and Gan, 2018a, 2018b; González-Arqueros, Mendoza, Bocco, and Castillo, 2018; Das, 2020; Dash and Sar, 2020; Chen, 2022; Gupta and Dixit, 2022). It involves selection of multiple flood conditioning factors such as topography, geography, geomorphology, and rainfall patterns relevant to the study area.

Preparation of the thematic layers

Flood conditioning factors (also known as flood hazard indicators) are the topographical, hydrological, and geological variables that differently and cumulatively influence the occurrence of floods in an area (Tehrany et al., 2019). The most relevant and common FCFs are slope, elevation, drainage density (DD), soil texture (ST), Topographic Wetness Index (TWI), SPI (probability of occurrence of severe and extreme wet events), distance from river (DR), geomorphology, and Land Use Land Cover. Selection of these factors can be based on a comprehensive literature review or expert knowledge and is specific to the area of study. Therefore, additional factors can be included based on the geographical location.

1. Slope and Elevation

Slope represents the topographic gradient or steepness of a surface, while elevation is the height of a particular location from the ground or sea level (i.e., from a fixed reference point). Topographic slope and elevation have significant influence upon the processes of surface run-off, infiltration, and water accumulation, as well as the flow velocity and flood power (Das, 2020). Hence, areas at lower elevation with a flat topography and low slope tend to have greater susceptibility to flooding and water stagnation, as opposed to areas at higher elevation and steep slopes (Das, 2020; Gupta & Dixit, 2022; Tehrany et al., 2019).

The raster layers for both factors were extracted from HydroSHEDS DEM of 3-arc seconds resolution and divided into five classes ranging from 5 to 1 based on natural breaks in GIS.

- *Preparing the thematic layer:* Open GIS platform and add the downloaded India DEM file to the interface. Then, add the state boundary shapefile. The DEM file for the concerned state will be extracted from the India DEM file using the state boundary shapefile. Hence, the India DEM file is clipped to the shape of the state or area of interest (AOI) as shown in Figure C-1.

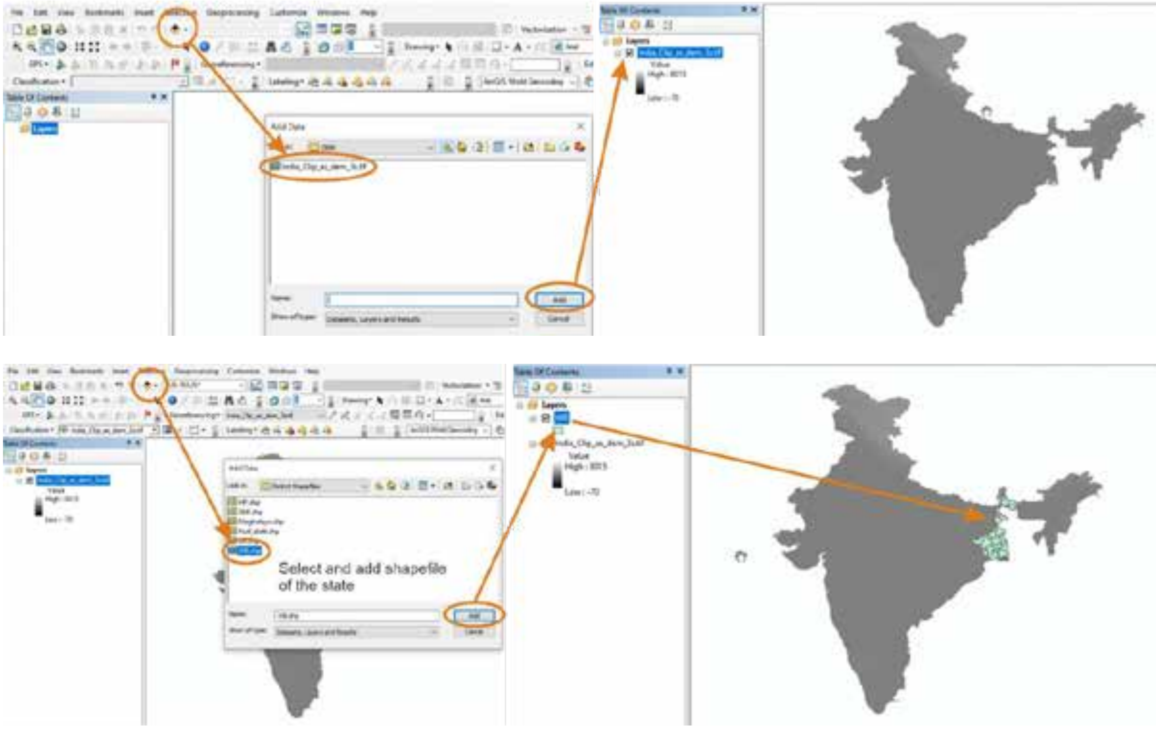


Figure C-1 Add the AOI/state boundary shapefile & DEM

- *Clip to study area:* Add shapefile of the state (state boundary downloaded from Survey of India website) to Layers → Go to 'Geoprocessing' → Go to 'Search' → Search for 'Clip' → Select Clip (Data Management Tools) → In the 'Input Raster', select the India DEM layer (which contains the dataset to be clipped) from the dropdown menu → In the 'Output extent', select the state boundary shapefile (the study state 'WB' boundary shapefile in this case) → Check the checkbox that says 'Use Input features for clipping geometry' → In the 'Output Raster Dataset', browse to the folder where you want to store the files, assign a name (e.g., WB_elevation.tif) and save → Click OK, when done. The state DEM layer or elevation layer is the output file (Figure C-2).

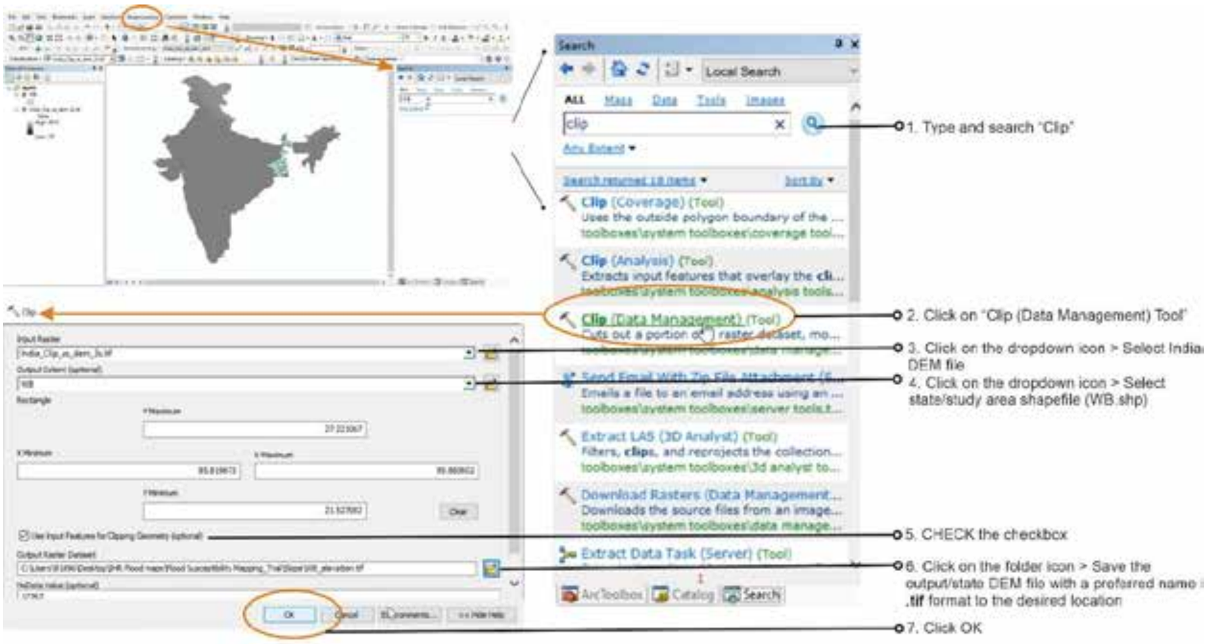


Figure C-2 Clip AOI/state boundary DEM from India DEM

- *Slope layer:* Go to ‘Geoprocessing’ → Select ‘Arc Toolbox’ → Click on ‘Spatial Analyst Tools’ → ‘Surface’ → ‘Click on ‘Slope’ → In ‘Input raster’, select the elevation layer from dropdown menu → In ‘Output raster’, browse to the folder where you want to store the files, assign a name (e.g., WB_slope.tif) and save → In ‘Output measurement’, select ‘PERCENT_RISE’ → Click OK. Slope layer of the state is now ready (Figure C-3).

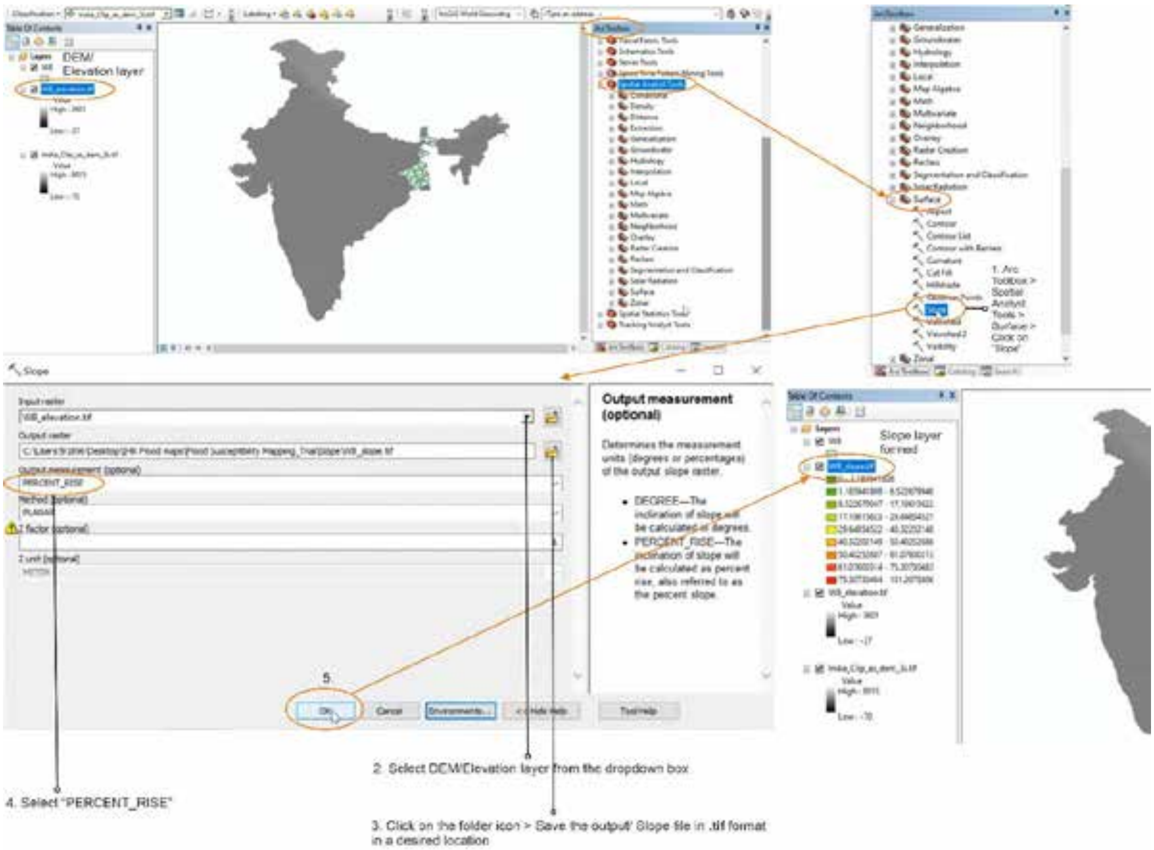


Figure C-3 Calculation of percentage slope

- *Reclassifying elevation layer:* Go to ‘Geoprocessing’ → Select ‘Arc Toolbox’ → Click on ‘Spatial Analyst Tools’ → ‘Go to ‘Reclass’ → ‘Click on ‘Reclassify’ → In ‘ Input raster’, select the elevation layer from dropdown menu → Click on ‘Classify’ → Select ‘Natural Breaks’ in the method → Select ‘5’ in the classes and click OK → Click on ‘Reverse New Values’ so that class 1 is assigned to the highest value of elevation and class 5 is assigned to the lowest value of elevation → In ‘Output raster’, browse to the folder where you want to store the files, assign a name (e.g., WB_elevation_reclass.tif) and save → Click OK. Elevation layer of the state is now reclassified into 5 classes (Figure C-4).

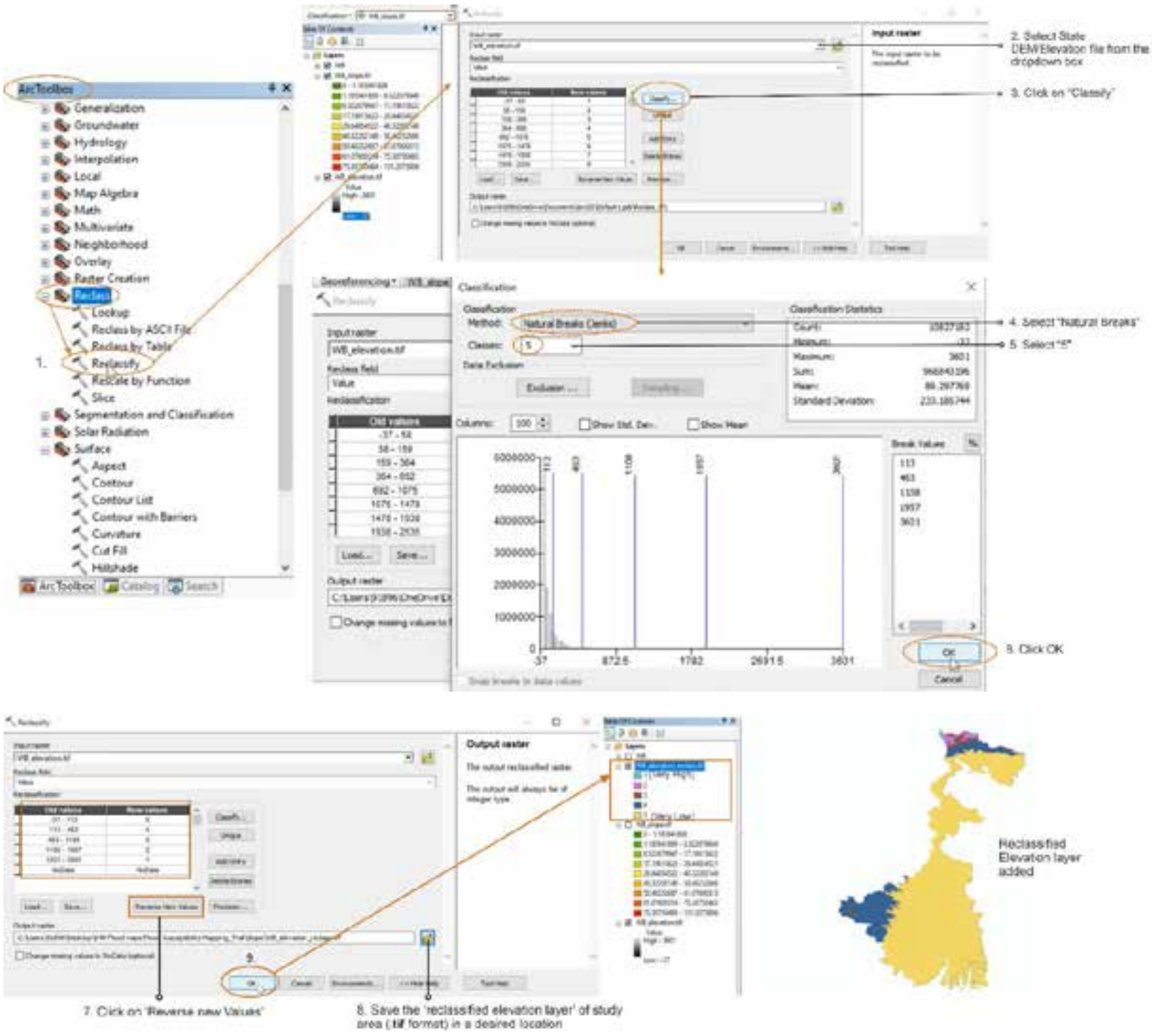


Figure C-4 Reclassification of elevation layer

- *Reclassifying Slope layer:* Go to 'Geoprocessing' → Select 'Arc Toolbox' → Click on 'Spatial Analyst Tools' → 'Go to 'Reclass' → 'Click on 'Reclassify' → In ' Input raster', select the slope layer from dropdown menu → Click on 'Classify' → Select 'Natural Breaks' in the method → Select '5' in the classes and click OK → Click on 'Reverse New Values' so that class 1 is assigned to the highest value of slope and class 5 is assigned to the lowest value of slope → In 'Output raster', browse to the folder where you want to store the files, assign a name (e.g., WB_slope_reclass.tif) and save → Click OK. Slope layer of the state is now reclassified into 5 classes (Figure C-5).

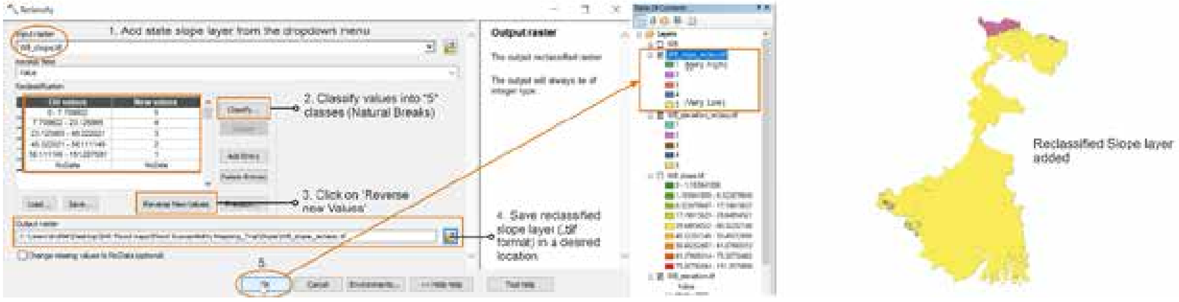


Figure C-5 Reclassification of slope layer

2. Drainage Density

Drainage density represents the sum of the stream channel lengths per unit area of the basin (Carlston, 1963). It is considered a basic parameter influencing the hydrological processes within a basin such as infiltration, overland flow, soil saturation, runoff etc. (Gao et al., 2022). A higher drainage density indicates higher surface run-off, and thus higher flood susceptibility in regions with a dense stream network (Das, 2019).

The drainage network of the study area was determined from the global HydroRIVERS dataset and divided into five classes ranging from 5 to 1 based on natural breaks in GIS.

Preparing the thematic layer

- *Add shapefile of the AOI state*: (state boundary downloaded from Survey of India website) to Layers
  Connect dataset folder: To Add click on → Add data Box will appear → click to connect dataset folder →Select location to '\Dataset'→ Click **OK** (displayed below in Figure C-6)

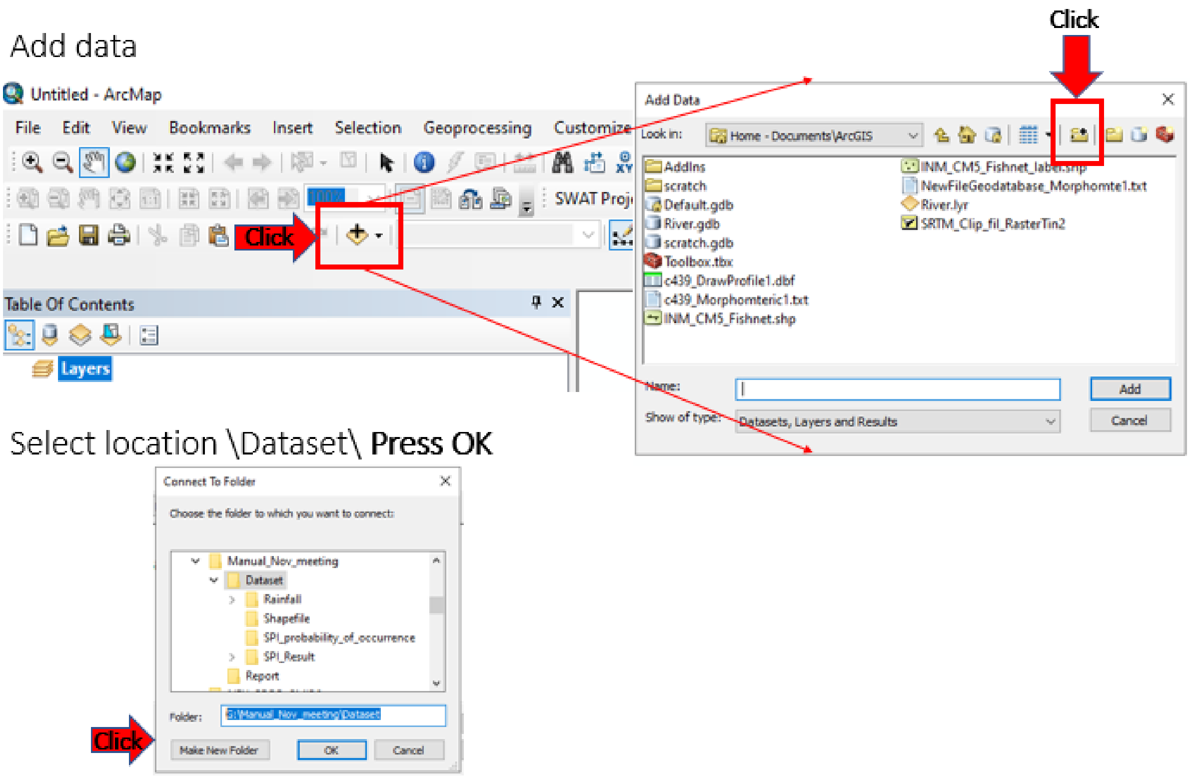


Figure C-6 Connect dataset folder

- To add the AOI District shapefile → Double click on **Shapefile** folder → click on State boundary shapefile ('**WB_State'**) → Click **ADD** (displayed below in Figure C-7).

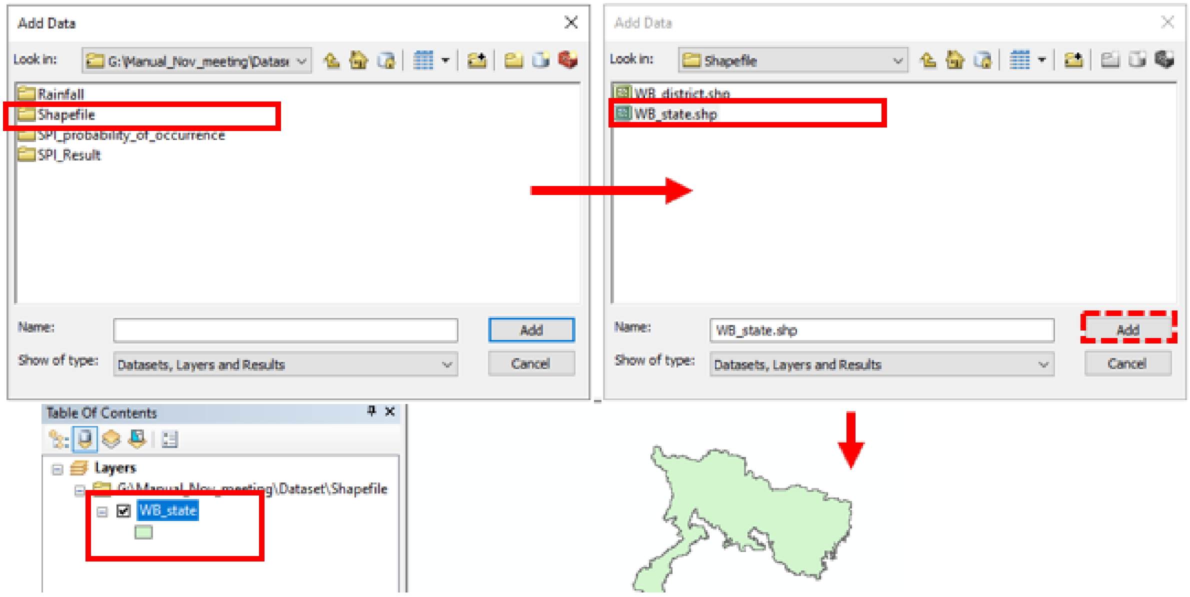


Figure C-7 Add the AOI / District shapefile

- To *Add the Hydroshed Rivers network shapefile* → Double click on **Shapefile** folder → click on Hydrosheds database network shapefile ('**India_HydroRivers.shp'**) → Click **ADD** **(**displayed below in Figure C-8)

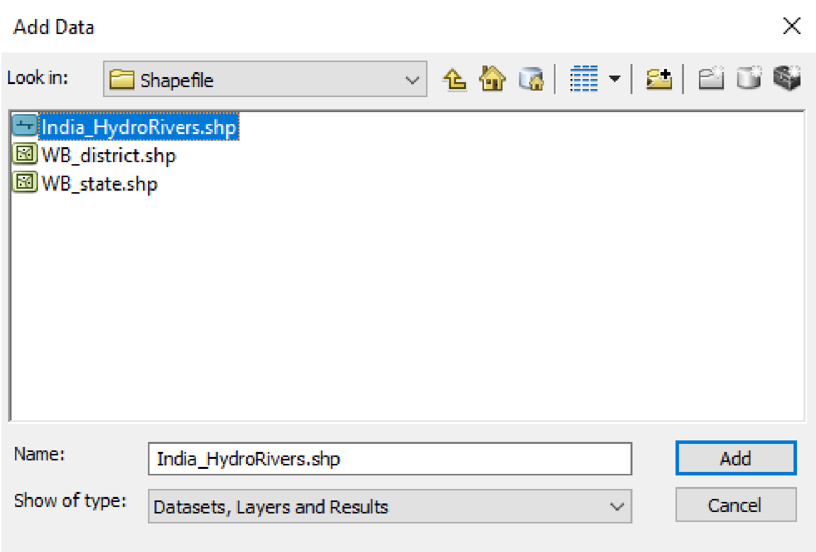


Figure C-8 Add the Hydroshed Rivers network shapefile

- *Clip to study area:* In ArcToolbox, go to 'Analysis Tools' → select the 'Extract' → select the 'Clip' tool → In the 'Clip features' window, select the 'Input Features', India_HydroRivers layer (which contains the dataset to be clipped) from the dropdown menu → In the 'Clip features', select the layer containing state boundary shapefile ('WB_state') → In the 'Output Feature Class' browse to the folder where you want to store the files, assign a name (e.g., Dataset\Raster\Distance from River\WB_HydroRiver.shp) and save → Click **OK**. **(**displayed below in Figure C-9)

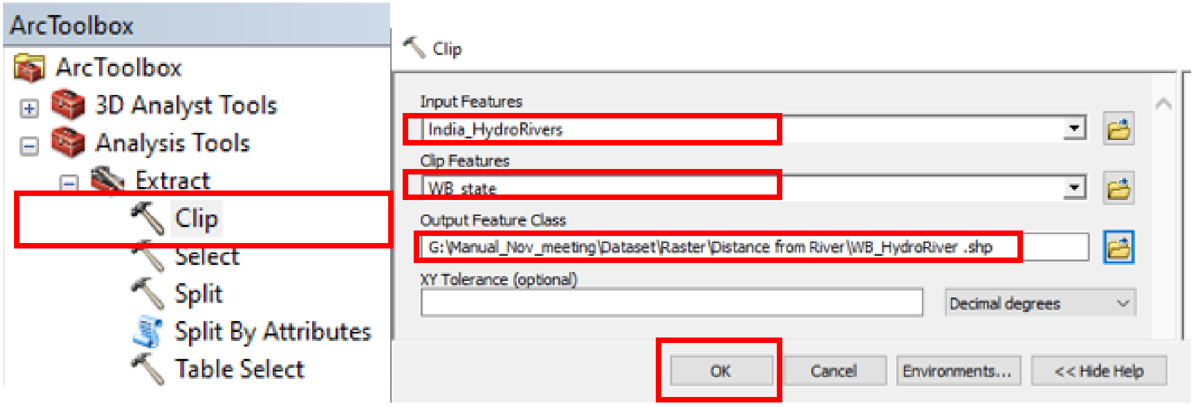


Figure C-9 Clip Hydroshed Rivers network shapefile for AOI

- *Line Density/ Drainage Density layer:* Go to 'Geoprocessing' → Select 'Arc Toolbox' → Click on 'Spatial Analyst Tools' → Go to 'Density' → Click on 'Line Density'. A dialog box for 'Line Density' appears. In 'Input polyline features', select 'stream line' layer of the state from the dropdown menu (e.g., WB_HydroRiver.tif). In 'Output raster', browse to the folder where you want to store the files, assign a name (e.g., WB_Line_Density.tif) and save → In 'Output cell size', browse to the folder and select the DEM file, assign a name (e.g., DEM.tif) and save →Click on 'Environments' → A dialog box of 'Environment Settings' appear → Go to 'Processing Extent' → In 'Extent', select the 'state boundary shapefile' → Now, go to 'Raster Analysis' → In 'Mask', select the 'state boundary shapefile' again → Click OK of 'Environment Settings' dialog box → Click OK of 'Line Density' dialog box → Line Density or Drainage Density layer of the state is ready (Figure C-10). Uncheck 'streamline' layer in the 'Table of contents' section, so that Line/Drainage Density layer is visible as shown in Figure C-11.

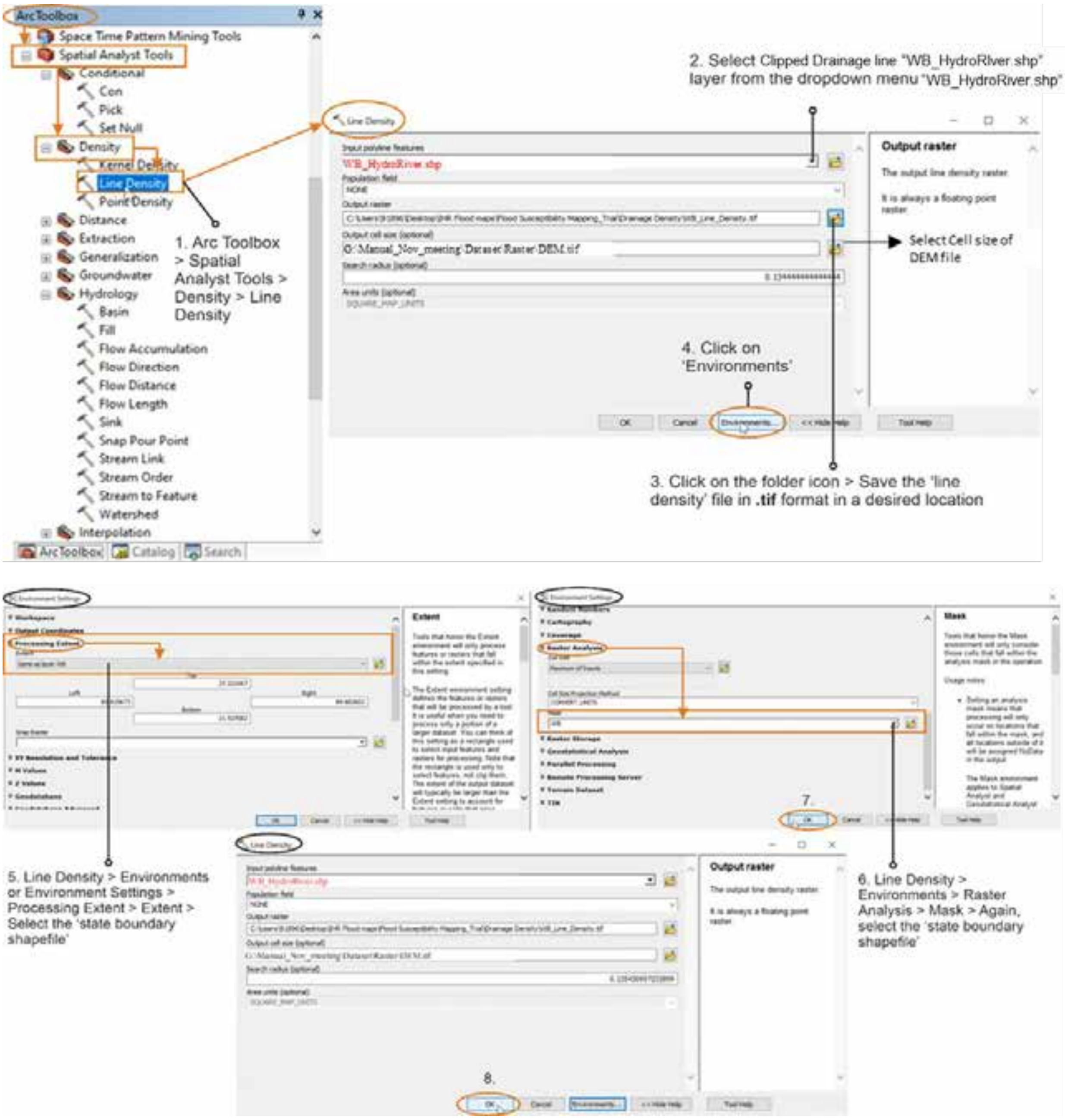


Figure C-10: Obtain drainage density layer using streamline

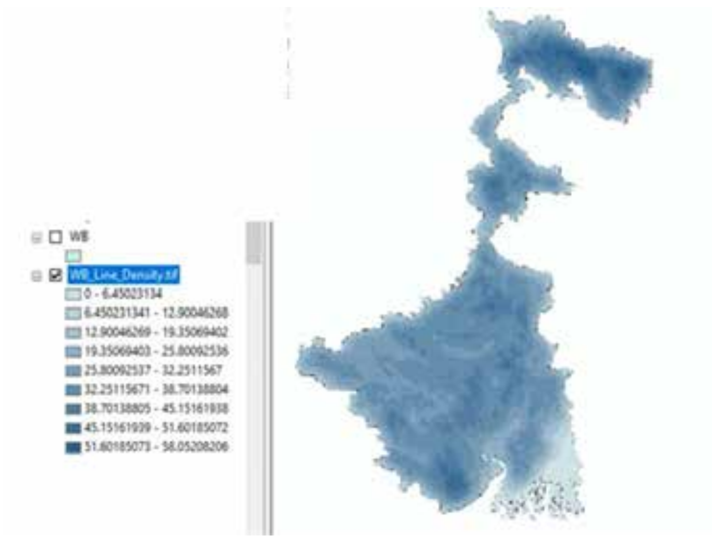


Figure C-11 Output drainage density layer

- *Reclassifying Line/Drainage Density layer:* Go to 'Geoprocessing' → Select 'Arc Toolbox' → Click on 'Spatial Analyst Tools' → 'Go to 'Reclass' → 'Click on 'Reclassify' → In ' Input raster', select the 'line density' layer from dropdown menu → Click on 'Classify' → Select 'Natural Breaks' in the method → Select '5' in the classes and click OK → In 'Output raster', browse to the folder where you want to store the files, assign a name (e.g., WB_DD_reclass.tif) and save → Click OK. Drainage density layer of the state is now reclassified into 5 classes (Figure C-12).

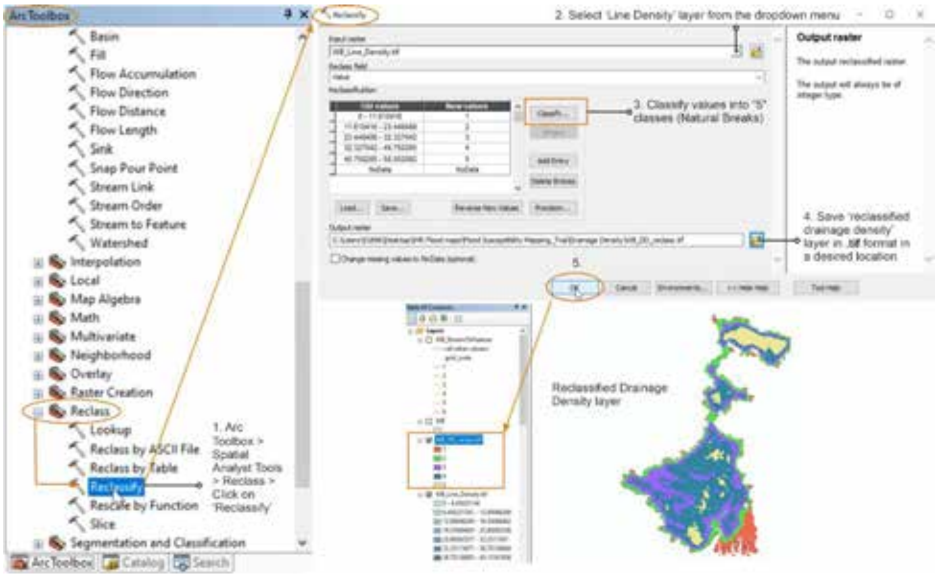


Figure C-12 Reclassification of drainage density layer

- *Changing the colour scheme of reclassified DD layer:* Right click on 'reclassified drainage density' layer in the 'Table of Contents' section → Click on 'Properties → A dialog box of 'Layer Properties' appear → Click on 'Symbology' → In 'Unique values' section, select a desired color palette in 'Color Scheme' → Click OK (Figure C-13).

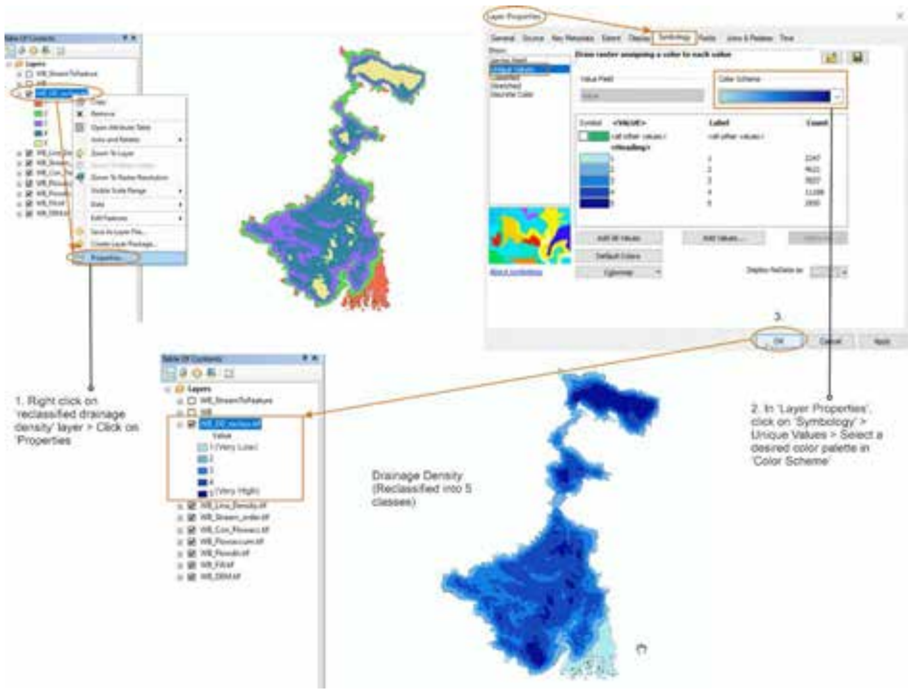


Figure C-13 Assign a colour scheme to the reclassified drainage density layer

3. Topographic Wetness Index (TWI)

This indicator signifies the effect of topography on flow accumulation at any given location in a catchment and other hydrological processes (Gokceoglu et al., 2005; Nachappa et al., 2020). The TWI is calculated as “ln(a/tanβ), where a is the local upslope area draining through a certain point per unit contour length and tanβ is the local slope” (Sorensen et al., 2006). It shows the spatial distribution of soil moisture and areas that are prone to generating overland flows (Das, 2020).

Similar to the generation of slope and elevation layers, HydroSHEDS DEM was used to derive the TWI in this study and values reclassified from 1 to 5 as per their susceptibility to flood. A higher TWI indicates higher susceptibility to floods.

- *Preparing the thematic layer:* Open GIS platform and add the downloaded ‘India Flow Accumulation’ layer to the interface. Clip to the area of interest after adding the state shapefile as shown in slope & elevation. Hence, the India flow accumulation file is clipped to the shape of the state or area of interest (AOI).
- *Slope in degrees layer:* Go to ‘Geoprocessing’ → Select ‘Arc Toolbox’ → Click on ‘Spatial Analyst Tools’ → Go to ‘Surface’ → Click on ‘Slope’. A dialog box for ‘Slope’ appears as shown in Figure 3-1. In ‘Input raster’, select clipped ‘DEM’ layer of the state from the dropdown menu (add it first) → In ‘Output raster’, browse to the folder where you want to store the files, assign a name (e.g., WB_slope_deg.tif) and save → Select ‘DEGREE’ in ‘Output measurement’ → Click **OK** → Slope (in degree) layer is ready (Figure C-14).

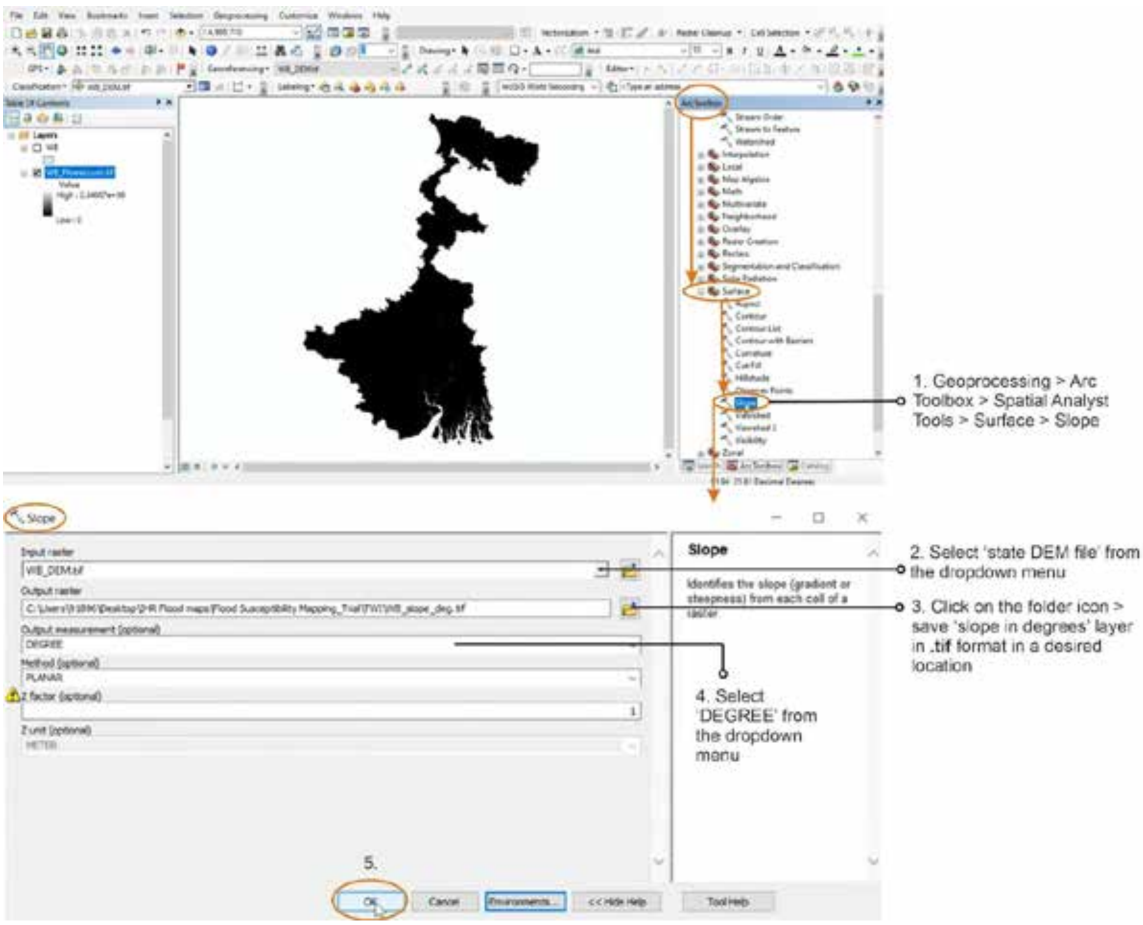


Figure C-14 Calculation of degree slope

- *Radius of slope/ Radian slope layer:* Go to ‘Geoprocessing’ → Select ‘Arc Toolbox’ → Click on ‘Spatial Analyst Tools’ → Go to ‘Map Algebra’ → Click on ‘Raster Calculator.’ A dialog box for ‘Raster Calculator’ appears. In the expression field as shown in the Figure 3-2 below, add slope in degrees layer by double clicking on it, multiply it by 1.570796, and then divide by 90 (whole expression will be in a bracket)→ In ‘Output raster’, browse to the folder where you want to store the files, assign a name (e.g., WB_radius_slope.tif) and save as shown in the Figure C-15 → Click **OK** → Radian slope layer is ready (Figure C-15).

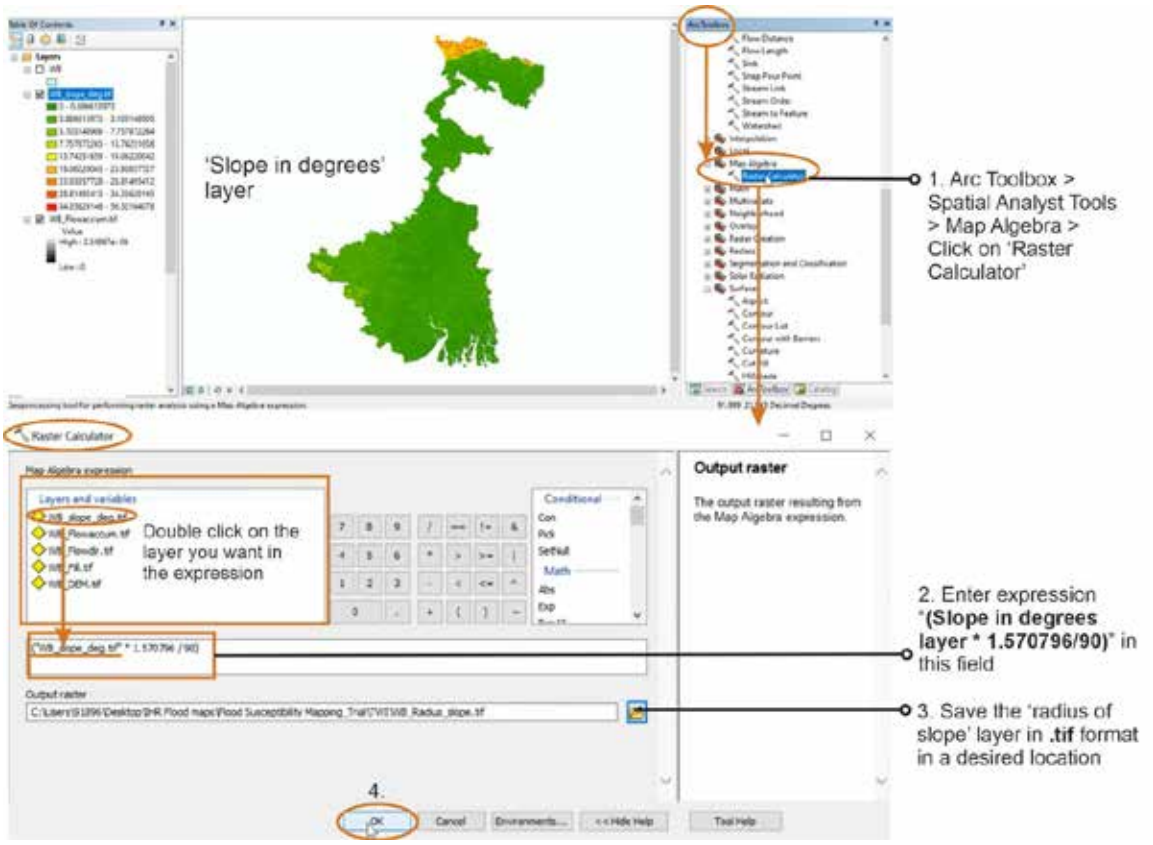


Figure C-15 Converting slope to radian

- *Tan slope layer:* Go to ‘Geoprocessing’ → Select ‘Arc Toolbox’ → Click on ‘Spatial Analyst Tools’ → Go to ‘Map Algebra’ → Click on ‘Raster Calculator.’ A dialog box for ‘Raster Calculator’ appears. In the expression field as shown in the Figure 3-3 below, add ‘Con’ by double clicking on it, enter a bracket, add radian slope layer by double clicking on it, enter “**>0**”, enter “**,**” and then add ‘Tan’ by double clicking on it. Open a bracket, add radian slope layer again by double clicking on it, close the bracket. Enter “**,**” and then enter **0.001**. Close the bracket again. The expression is now complete → In ‘Output raster’, browse to the folder where you want to store the files, assign a name (e.g., WB_tanslope.tif) and save → Click **OK** → Tan slope layer is ready (Figure C-16).

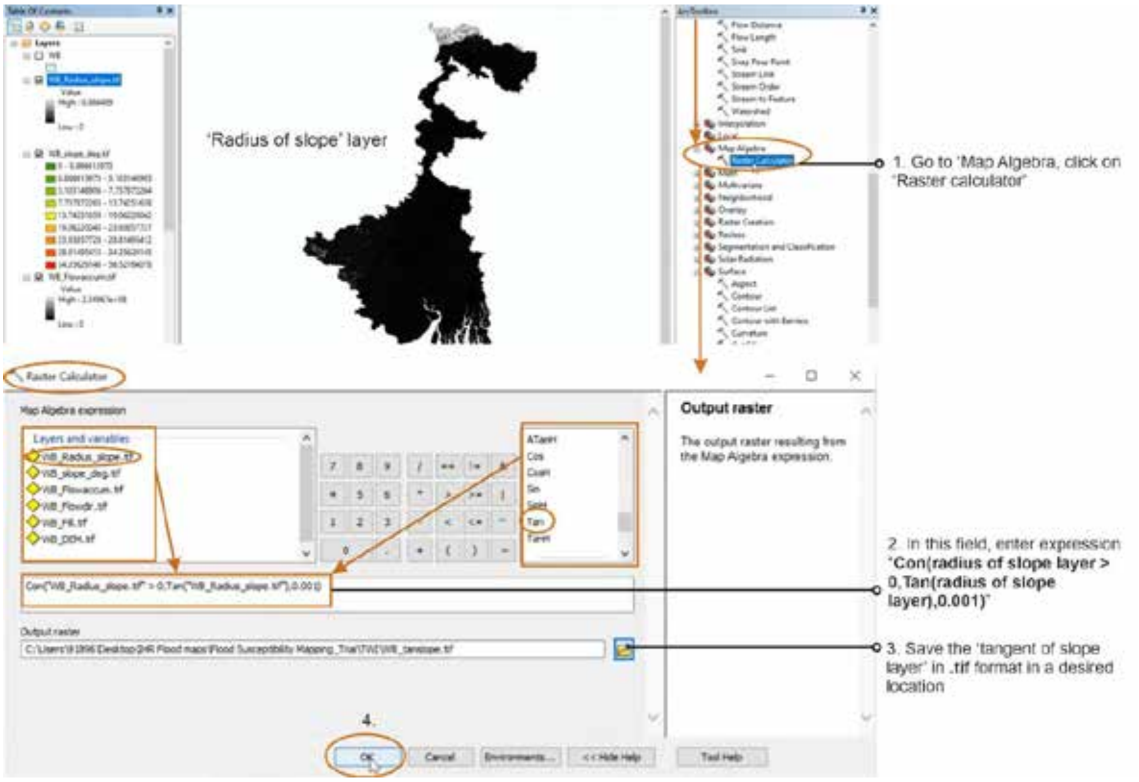


Figure C-16 Calculation of Tan slope

- *Scaled flow accumulation layer:* Go to 'Geoprocessing' → Select 'Arc Toolbox' → Click on 'Spatial Analyst Tools' → Go to 'Map Algebra' → Click on 'Raster Calculator.' A dialog box for 'Raster Calculator' appears. In the expression field as shown in the Figure C-17 below, open a bracket, add flow accumulation layer of the state by double clicking on it, enter "**+1**" and then add close the bracket → Right click on 'flow accumulation' layer of the state in table of contents section → Click on 'Properties' → In 'Layer Properties', Go to 'Source' → In 'Cell Size', copy the cell size (in this case, it is 0.00083333333) as shown in the Figure C-17→ Paste this cell size in the expression field of the 'raster calculator' and multiply it by the expression in brackets that was entered earlier → The expression is now complete as shown in the Figure C-18→ In 'Output raster', browse to the folder where you want to store the files, assign a name (e.g., WB_scaled_flowacc.tif) and save as shown in the Figure C-18 → Click **OK** → Scaled flow accumulation layer is ready.

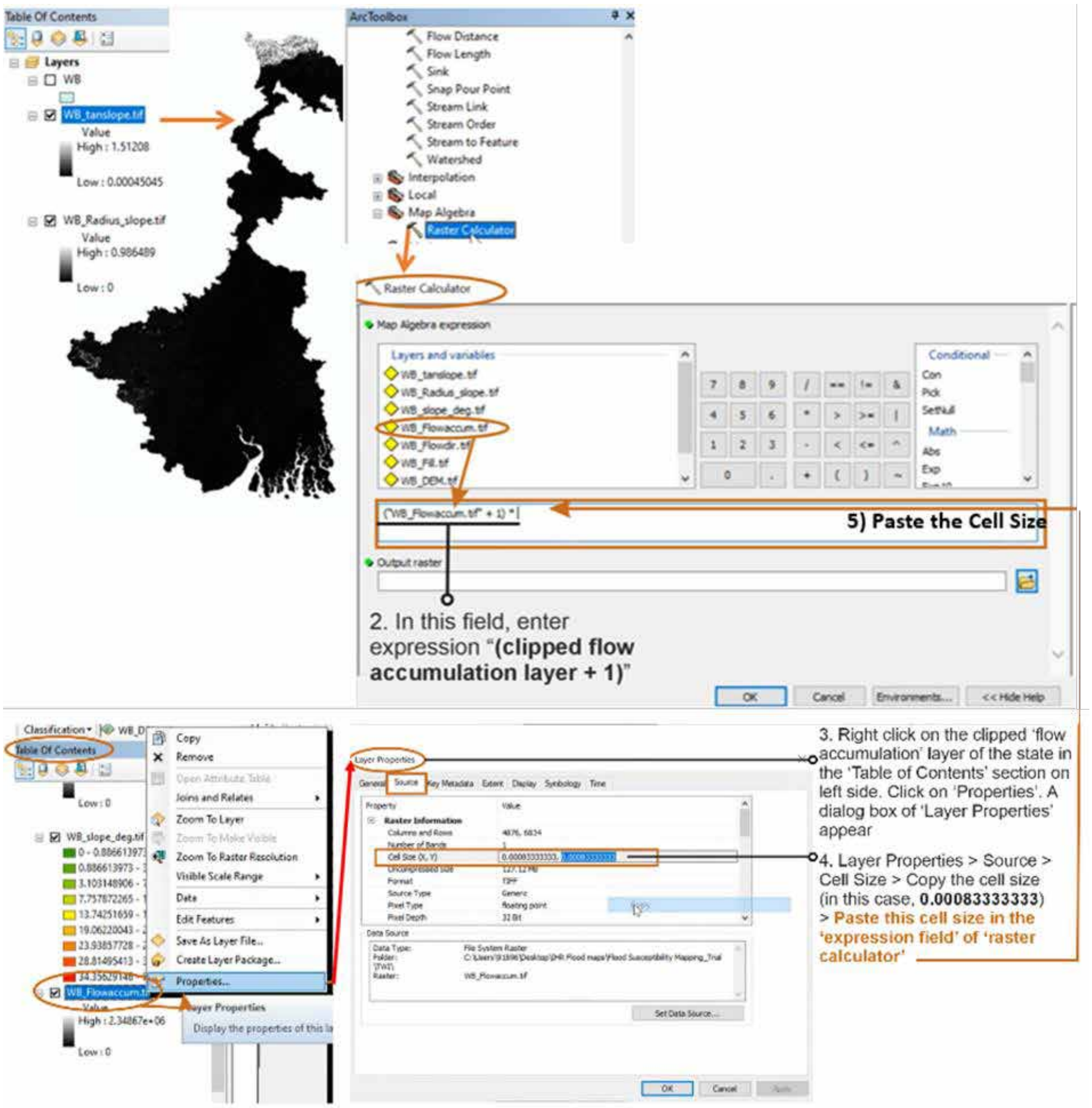


Figure C-17 Insert formula for scaled flow accumulation layer

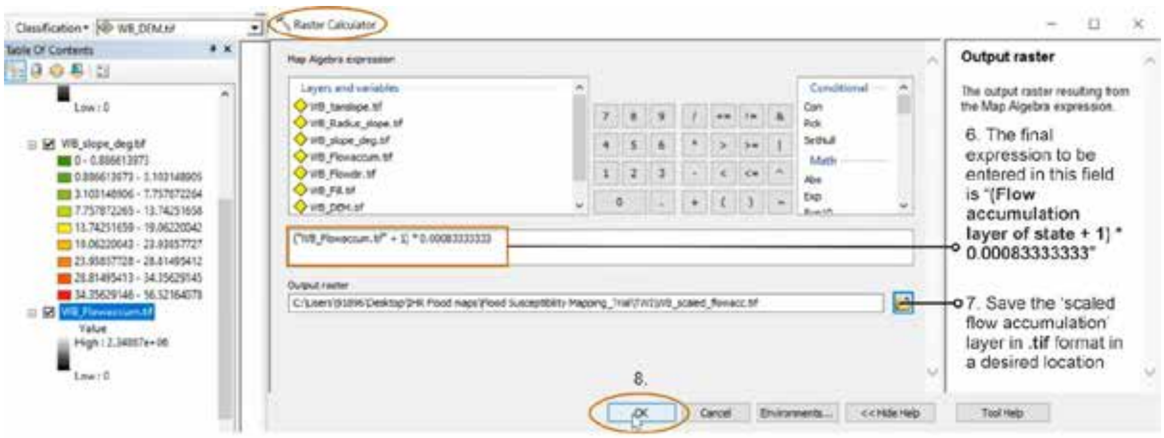


Figure C-18 Final scaling of flow accumulation layer

- *TWI layer:* Go to ‘Geoprocessing’ → Select ‘Arc Toolbox’ → Click on ‘Spatial Analyst Tools’ → Go to ‘Map Algebra’ → Click on ‘Raster Calculator.’ A dialog box for ‘Raster Calculator’ appears. In the expression field as shown in the Figure C-19 below, add ‘**Ln**’ by double clicking on it, open a bracket, add ‘scaled flow accumulation’ layer by double clicking on it and **divide** it by the ‘tan slope’ layer after adding it too. Close the bracket. The expression is now complete → In ‘Output raster’, browse to the folder where you want to store the files, assign a name (e.g., WB_TWI.tif) and save → Click OK → TWI layer is ready.

Figure C-19 Calculation of TWI layer using formula Ln (scaled flow accumulation layer / tan slope layer)

- *Changing colour of TWI layer:* Click on the ‘grey colour bar’ present under ‘TWI’ layer in the ‘Table of Contents’ section which is on extreme left as shown in the Figure C-20 → In the ‘color Ramp’, select the desired colour palette from the dropdown menu → Click OK → Colour of TWI layer is changed (Figure C-21).

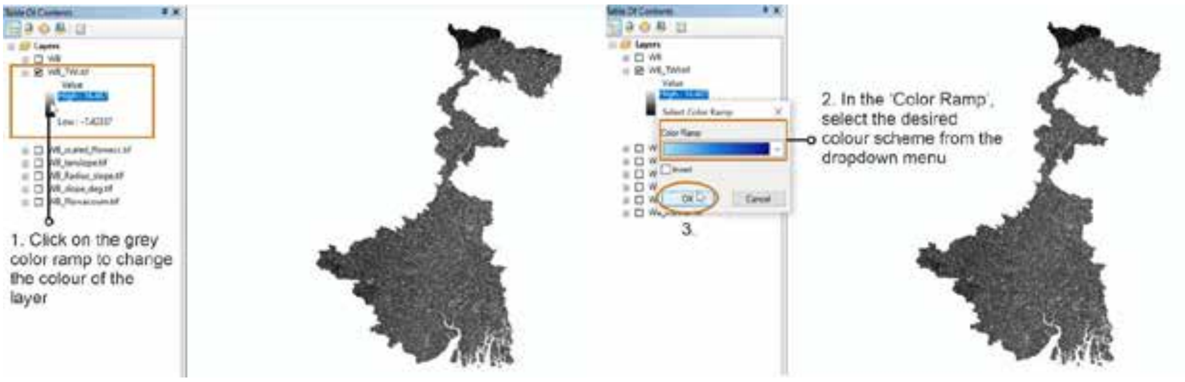


Figure C-20 Change colour of TWI layer for proper visualization

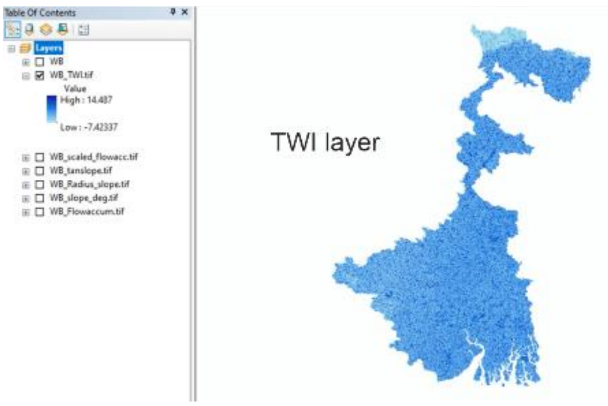


Figure C-21: Result of TWI layer

- *Reclassifying TWI layer:* Go to 'Geoprocessing' → Select 'Arc Toolbox' → Click on 'Spatial Analyst Tools' → 'Go to 'Reclass' → 'Click on 'Reclassify' → In ' Input raster', select the 'TWI' layer from dropdown menu → Click on 'Classify' → Select 'Natural Breaks' in the method → Select '5' in the classes and click OK → In 'Output raster', browse to the folder where you want to store the files, assign a name (e.g., WB_TWI_reclass.tif) and save as shown in the Figure C-22 → Click OK. TWI layer of the state is now reclassified into 5 classes. Based on their flood control/susceptibility properties low TWI values will belong to very low (1) and high TWI will be in very high (5) class and reclassified.

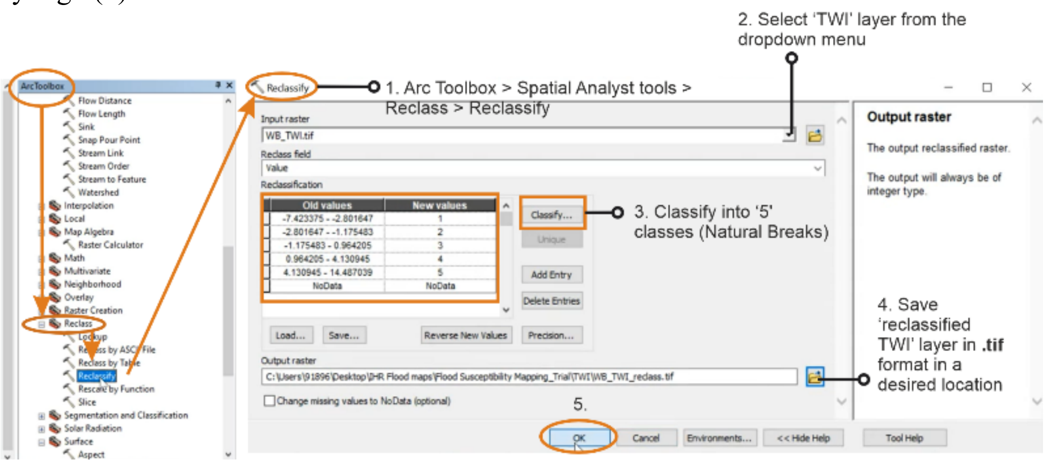


Figure C-22 Reclassification of TWI layer

- *Changing the colour scheme of reclassified TWI layer:* Right click on 'reclassified TWI' layer in the 'Table of Contents' section → Click on 'Properties → A dialog box of 'Layer Properties' appear → Click on 'Symbology' → In 'Unique values' section, select a desired color palette in 'Color Scheme' → Click OK (Figure C-23).
-

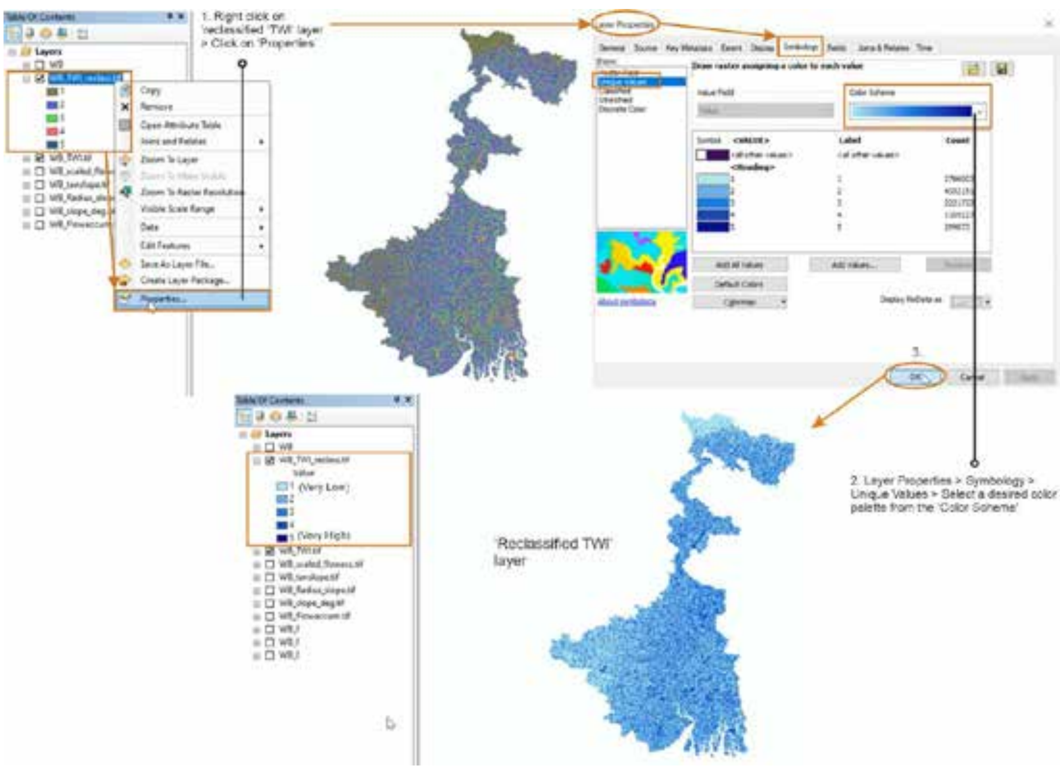


Figure C-23 Assign a colour scheme to the reclassified TWI layer

4. Geomorphology

Fluvial geomorphological processes result in different erosional and depositional landforms that may influence the generation and behaviour of floods in an area to varying degrees. For instance, low lying floodplain areas or coastal plains are generally more susceptible to flooding than structural hills. The geomorphological data of the study area was obtained from the Geological Survey of India's **Bhukosh** database available at 1:250,000 resolution. Please see link: https://bhukosh.gsi.gov.in/Bhukosh/MapViewer.aspx[1]. The different geomorphological landforms are reclassified into very low, low, moderate, high, and very high categories (class 1 to 5) depending upon their control or susceptibility to floods in a given area.

- *Preparing the geomorphology layer:* Open GIS platform and add the downloaded geomorphology shapefile for the concerned state to the interface (Figure C-24B). The image on the right (C-24A) shows the map for an area extending beyond the boundary of the study state - WB[2]. Hence, it has to be clipped to the shape of the study area or area of interest (AOI).

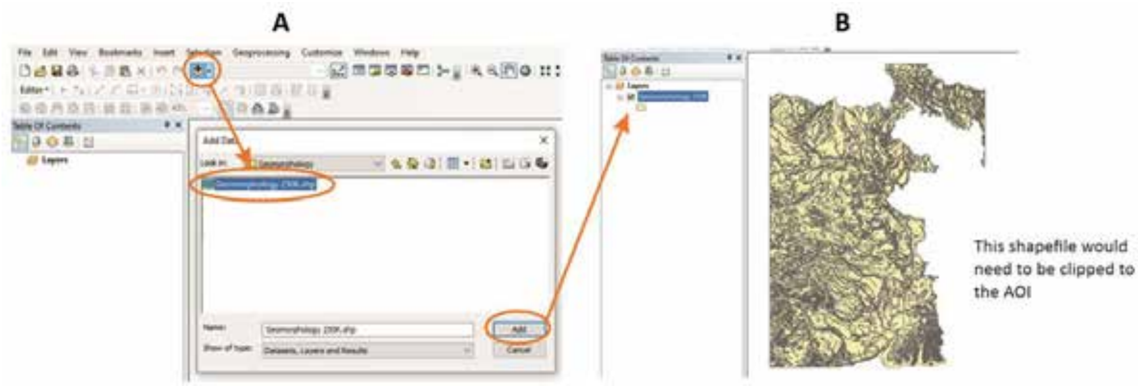


Figure C-24 Add geomorphological shapefile to GIS

- *Clip to study area:* Add shapefile of the state (state boundary downloaded from Survey of India website) to Layers (Figure C-25A)→ Go to 'Geoprocessing' → select the 'Clip' tool (Figure C-25B)→ → In the 'Input Features', select the geomorphology layer (which contains the dataset to be clipped) from the dropdown menu (Figure C-25C)→ → In the 'Clip features' box, select the layer containing your AOI (the study state 'WB' boundary shapefile in this case) → In the 'Output Feature Class' browse to the folder where you want to store the files, assign a name (e.g., WB_geom_clip.shp) and save → Click OK, when done (overall step shown in Figure C-25).

[1] You will need to register as a user in the website in order to be able to download the required dataset.
[2] Dummy state used as an example for this manual.

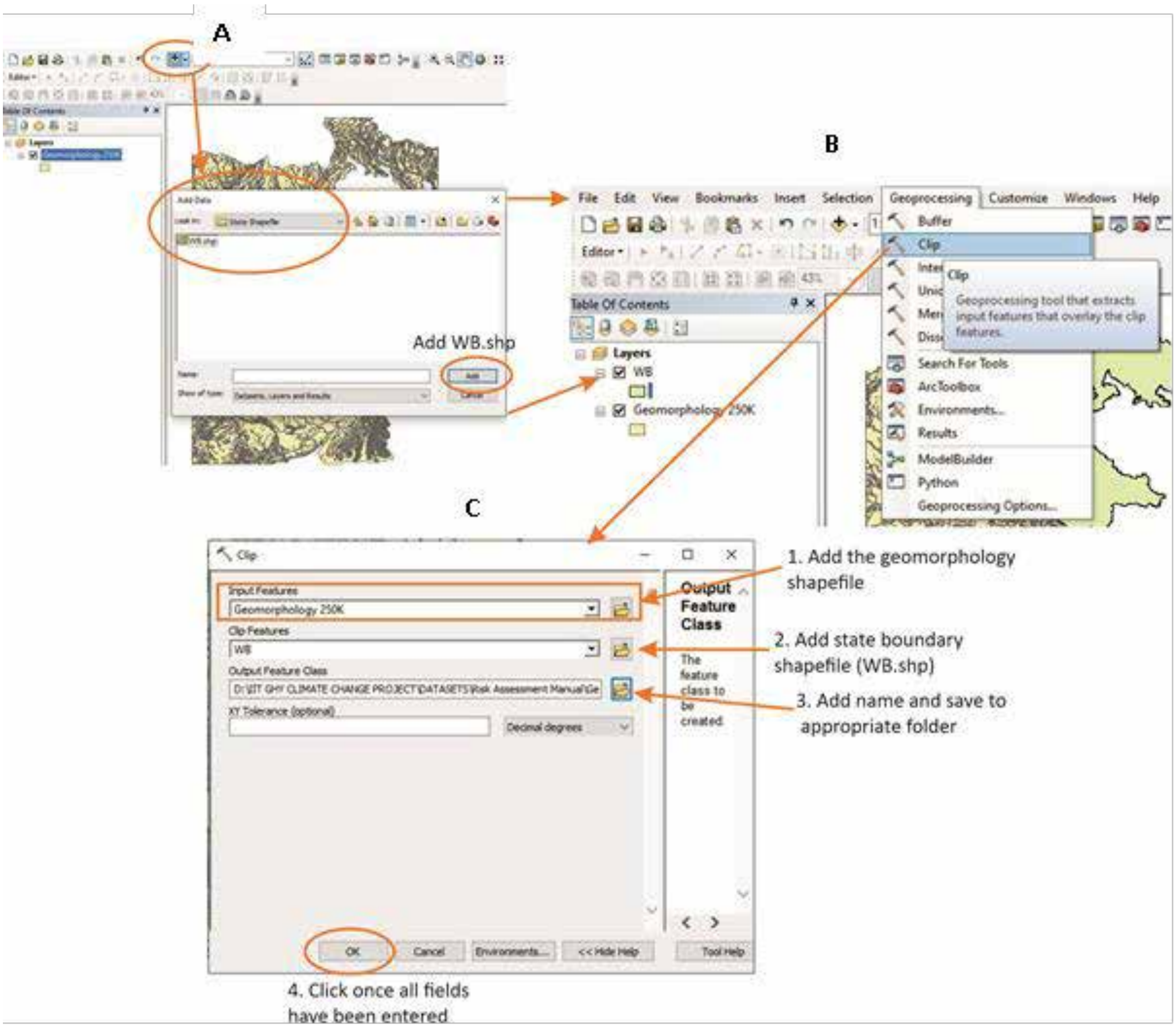


Figure C-25 Clip geomorphological shapefile to AOI

- Uncheck/Turn off all layers other than the clipped AOI as shown in Figure C-26.

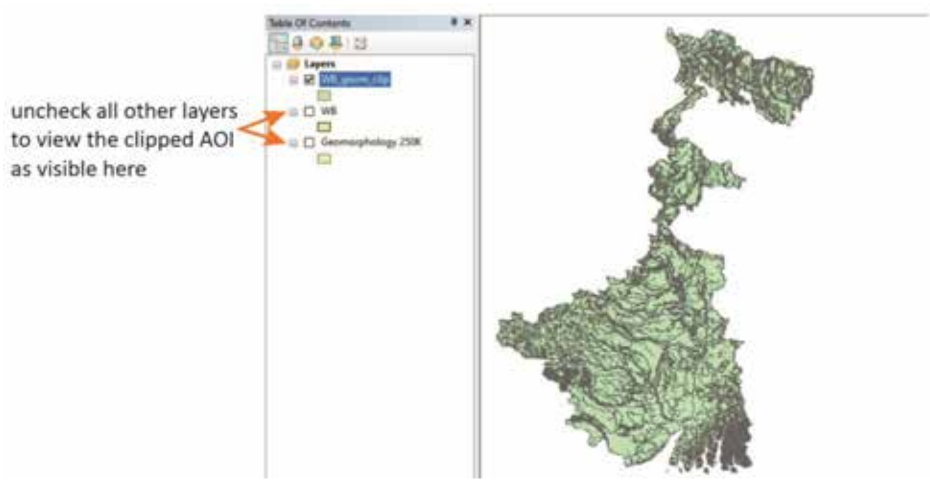


Figure C-26 Visualization of clipped geomorphology shapefile

- Explore the different landforms within the AOI using the steps illustrated below. The output would look similar to (Figure C-27).

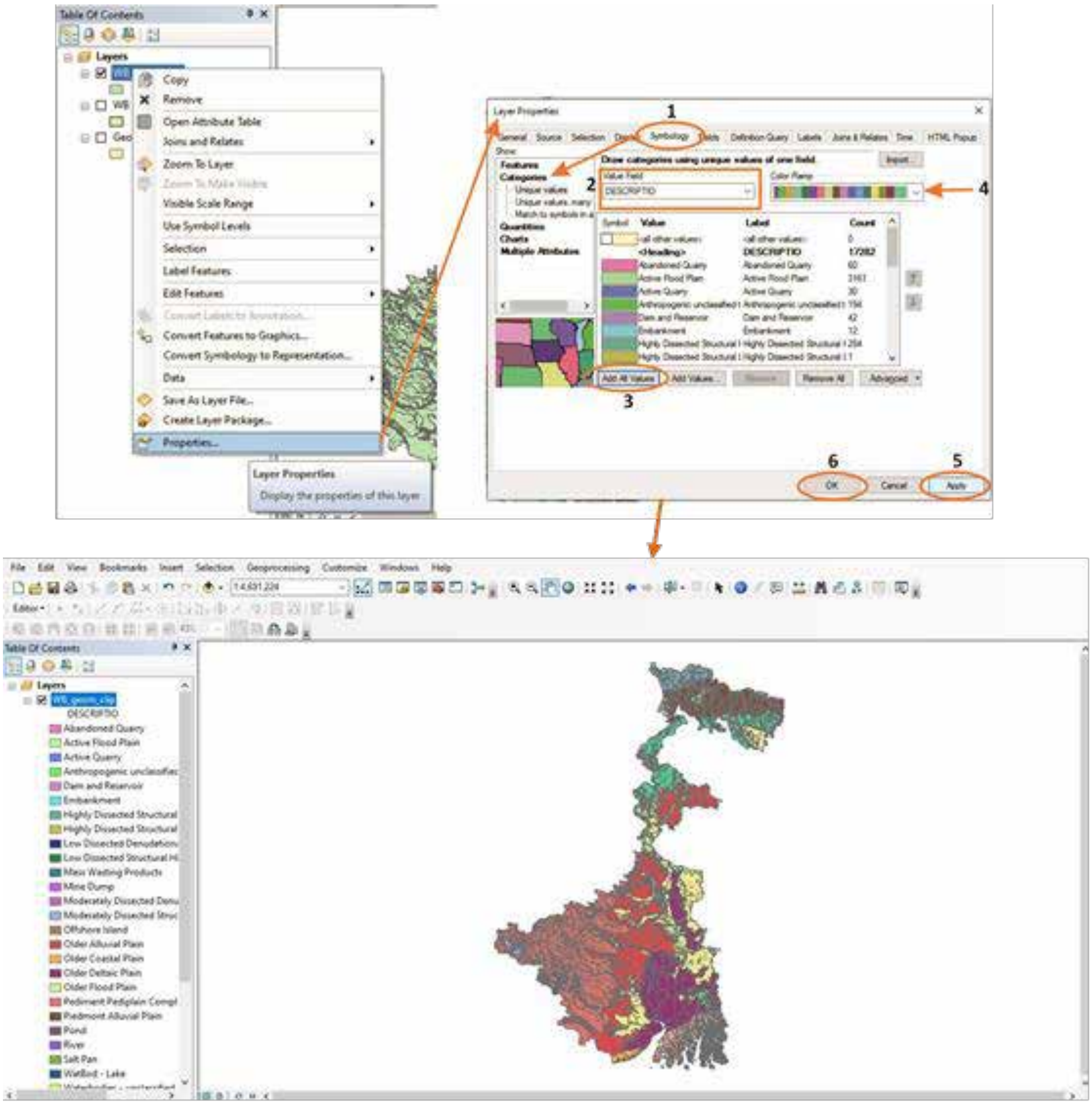


Figure C-27 Visualize geomorphology shapefile based on description classes

- Details of the different landform classes can be viewed in the 'Attribute Table'. As shown below (Figure C-28), the field 'DESCRIPTION' contains a more elaborate description of the geomorphological class, while field 'LEGEND_SHORT' contains the same information in a concise manner. Example: 'Active Floodplain' and 'Older Floodplain' classes in the former are categorized as the common class of 'Floodplain' in the latter.

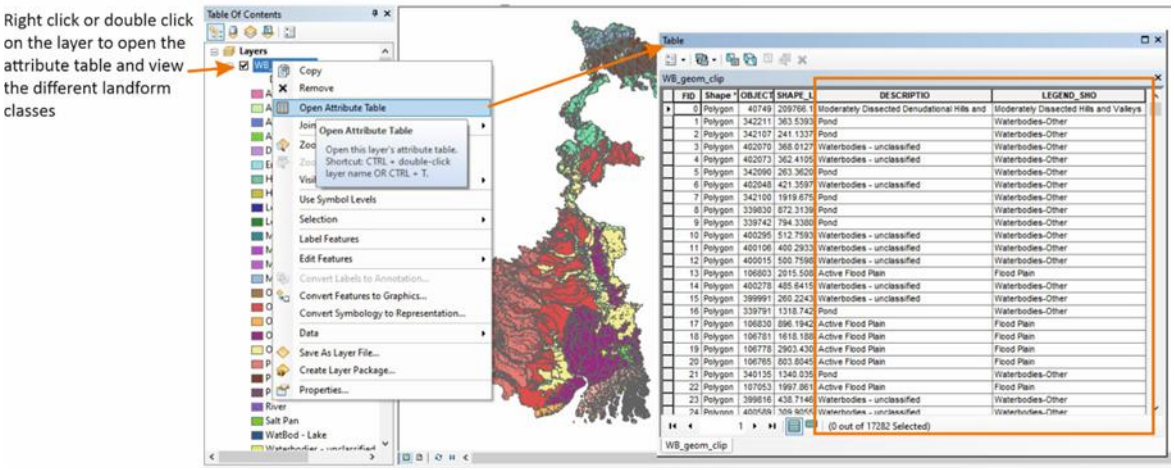


Figure C-28 Visualize elaborate description of the geomorphology class

- Combine the multiple polygons under the same landform feature (common atrribute value) using the 'Dissolve' tool under 'Geoprocessing', as displayed below in Figure C-29. Go to Geoprocessing → Dissolve → In the Input Features, select the shapefile 'WB_geom_clip' → Assign a name (e.g., WB_geom_clip_dissolve.shp) and save to the same folder as the previous files in Output Feature Class-->In 'Dissolve_Field(s)', select either the 'DESCRIPTION' field or the 'LEGEND_SHORT', based on which the combination would take place → OK.

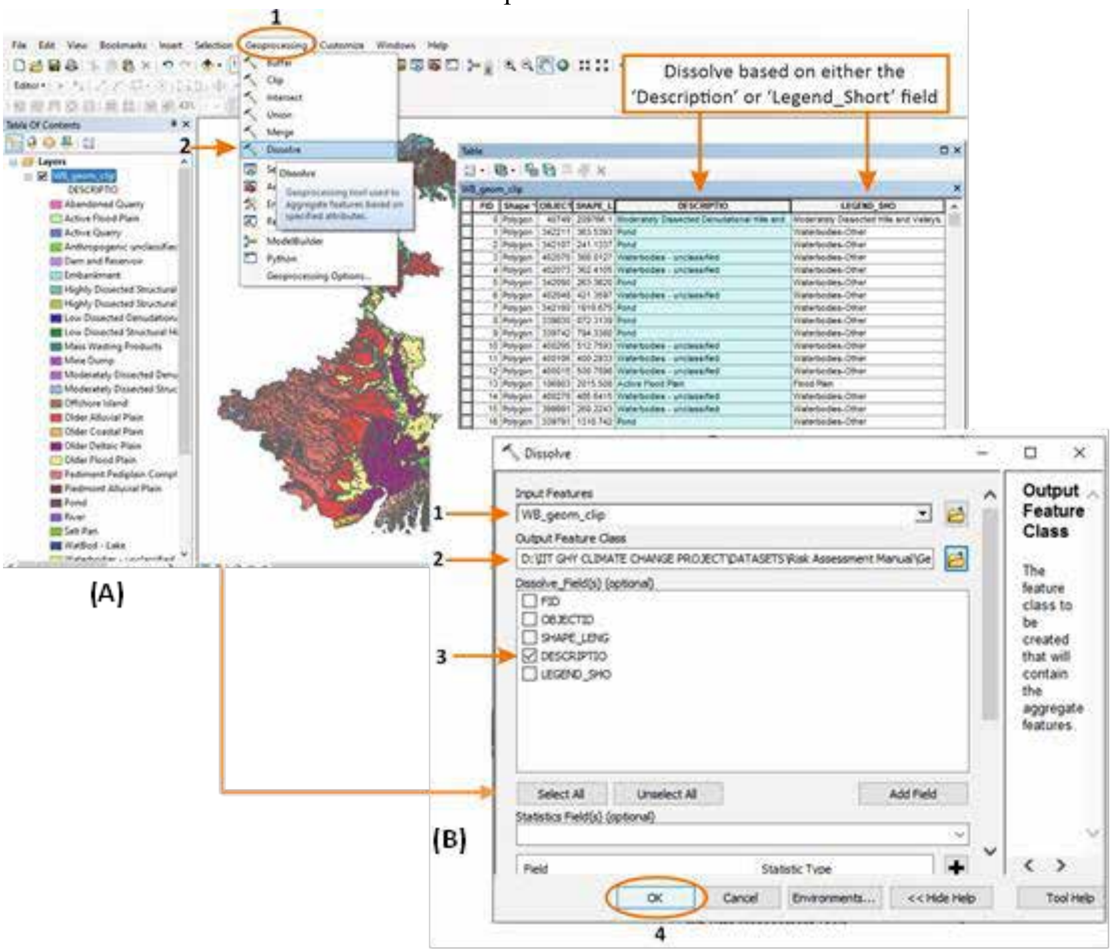


Figure C-29 Dissolve geomorphology layer based on description classes

- The dissolved output (Figure C-30A) can be explored by adding the unique values in 'Symbology' and selecting the relevant 'Value Field' as 'DESCRIPTION'. The color ramp can be adjusted to view the layer as per user preference. The steps to be followed are similar to Figure C-27. The attribute table displayed in shows the Figure C-30B different landform types present in the sample AoI displayed here.

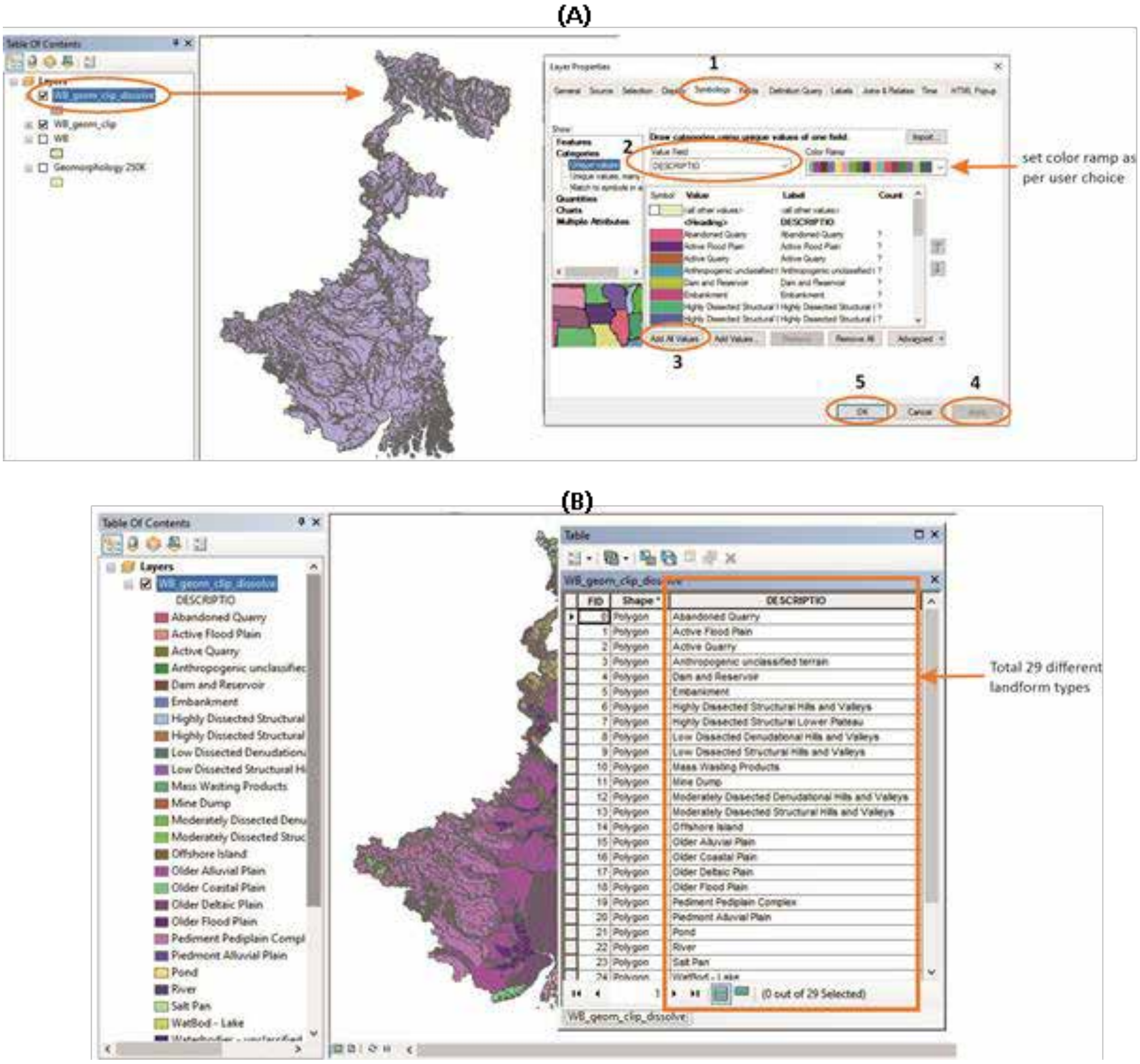


Figure C-30 Check description of the dissolved geomorphology class

- *Conver to raster:* In order to rate and reclassify these landforms according to their susceptibility to flooding, the shapefile needs to be converted to a raster file. Figure C-31 given below describes the steps to be followed for achieving this. In ArcToolbox, go to Conversion Tools → Raster → Polygon to Raster → Select 'WB_geom_clip_dissolve' in Input Features → Select 'DESCRIPTION' in Value Field → Name the Output Raster Dataset (e.g., WB_geom_polytoraster.tif) and save in relevant folder → In 'Cellsize', select the DEM file of the study area → click OK once done. The output raster would appear as shown in Figure C-31 (bottom).

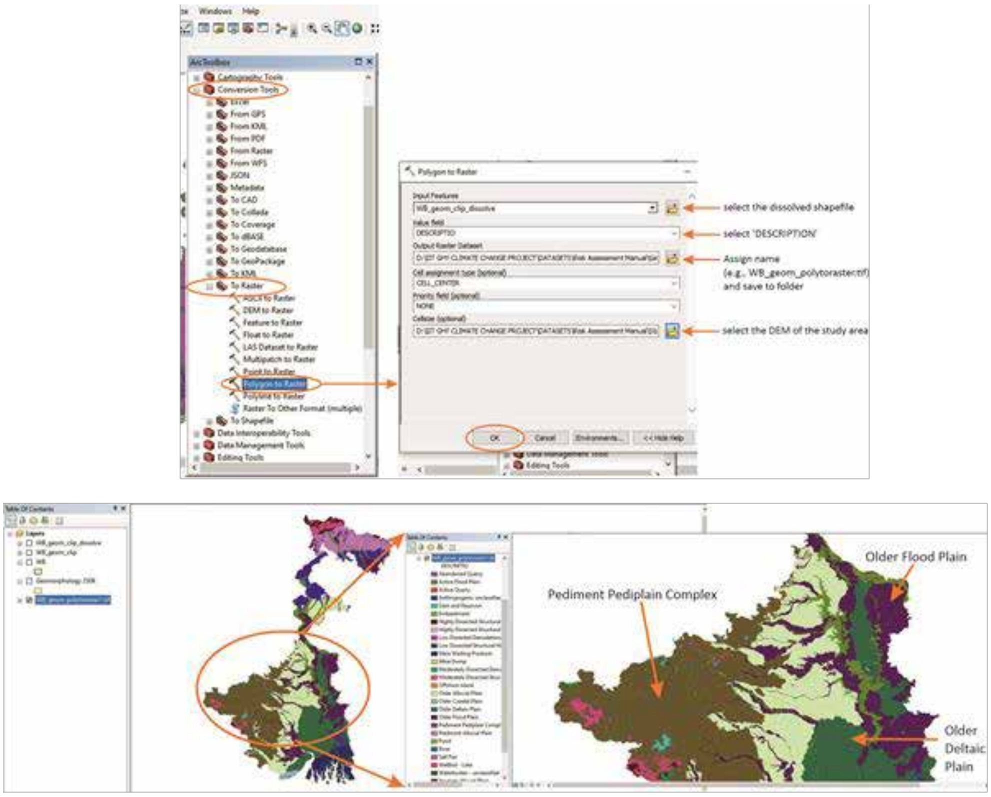


Figure C-31 Convert dissolved geomorphological shapefile to raster

- *Reclassify:* Different landforms influence flood occurrence in any given area in different forms and degree. Based on expert opinion and geomorphological knowledge of the study area, the various landform classes have to be rated from 1 to 5, signifying flood characteristics and reclassified for the final overlay. The steps to be followed are displayed in Figure C-32: Go to 'Spatial Analyst Tools' in ArcToolbox → Reclass → Reclassify → In the window that appears, select the raster file that needs to be reclassified in 'Input raster', i.e., WB_geom_polytoraster → Select 'DESCRIPTION' in 'Reclass field' → Assign the flood susceptibility rating in 'New values' → Click OK after saving the output raster in the required folder. The final reclassified geomorphology layer would be obtained as shown below in. Figure C-33.

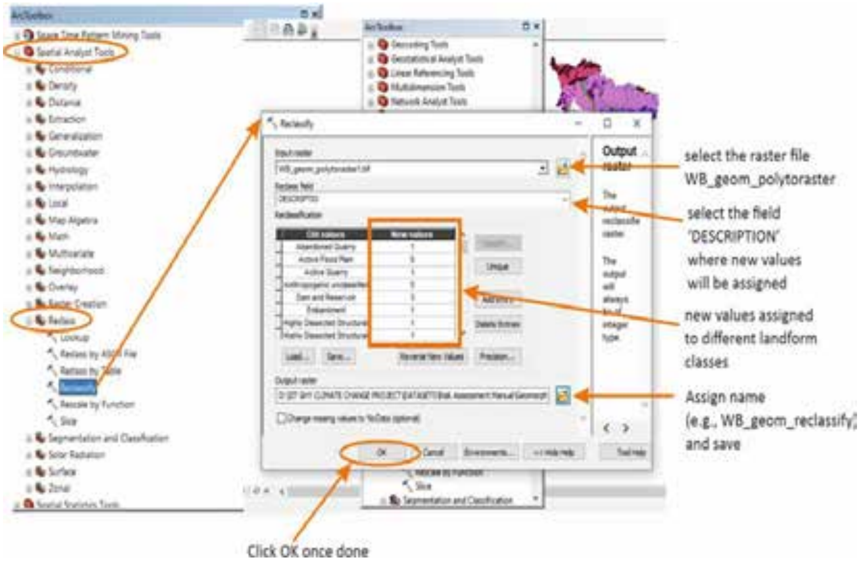


Figure C-32 Reclassification of geomorphology layer

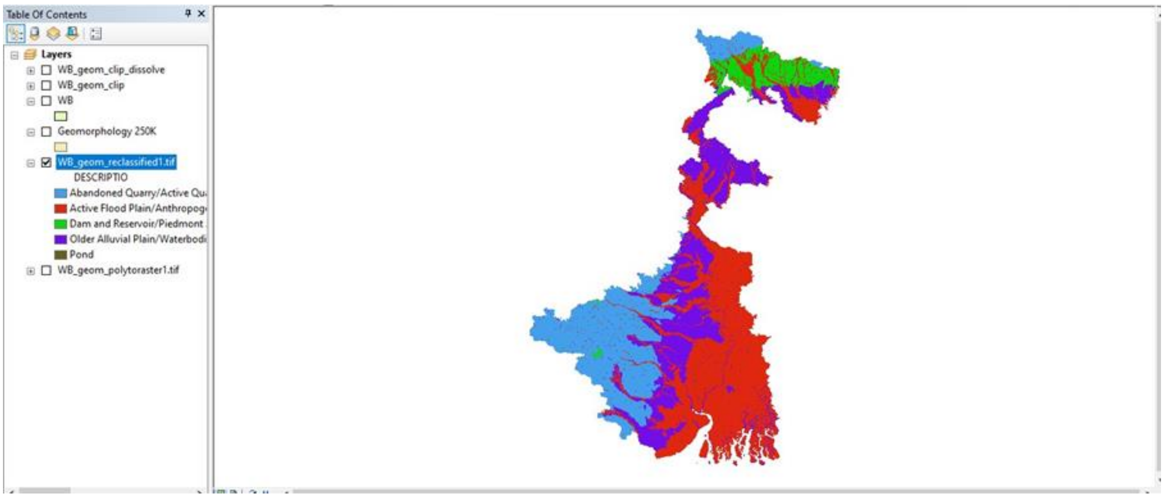


Figure C-33 Reclassified geomorphology layer

- In order to display it according to the reclassified values, go to Layer Properties → Symbology → Unique Values → Select 'Value' in Value Field instead of 'DESCRIPTION' → select a color scheme of choice (here we have used the blue ramp) → Add All Values → Apply → OK (Figure C-34). The output raster would appear as shown in Figure C-35. This raster thematic layer will then be assigned a weight based on the AHP analysis and overlaid with the eight other FCFs to obtain the composite FSM of the AOI.

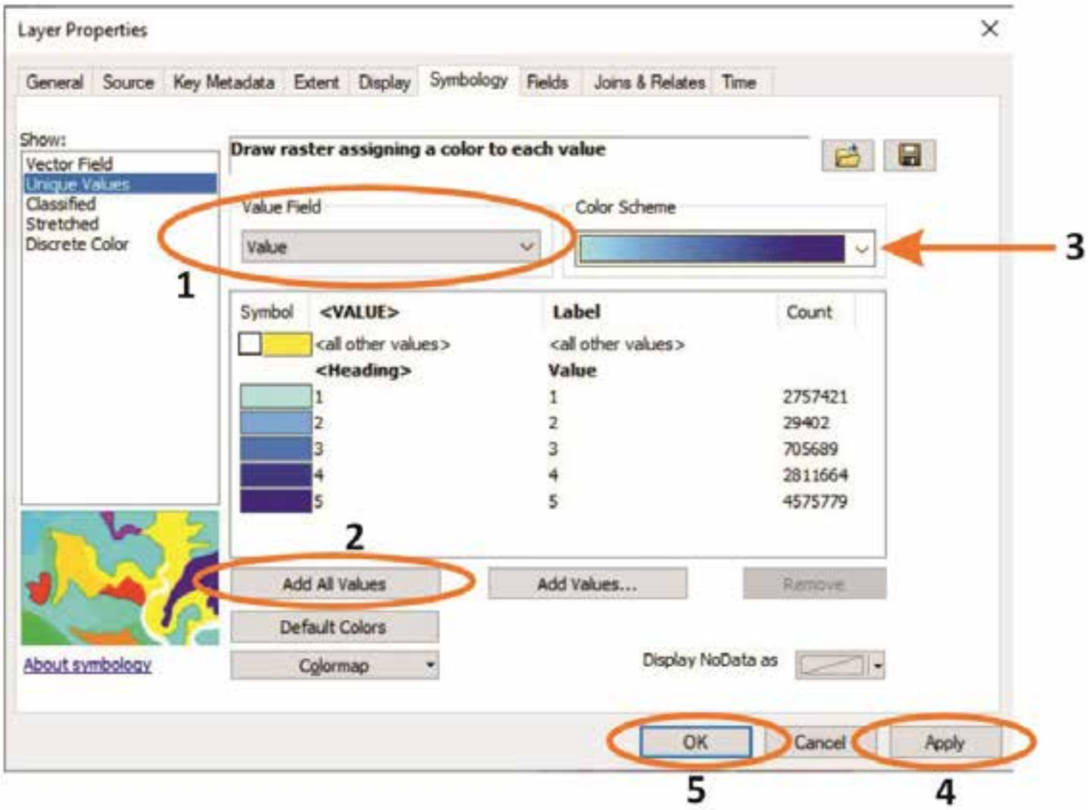


Figure C-34 Assign a colour scheme to the reclassified geomorphology layer

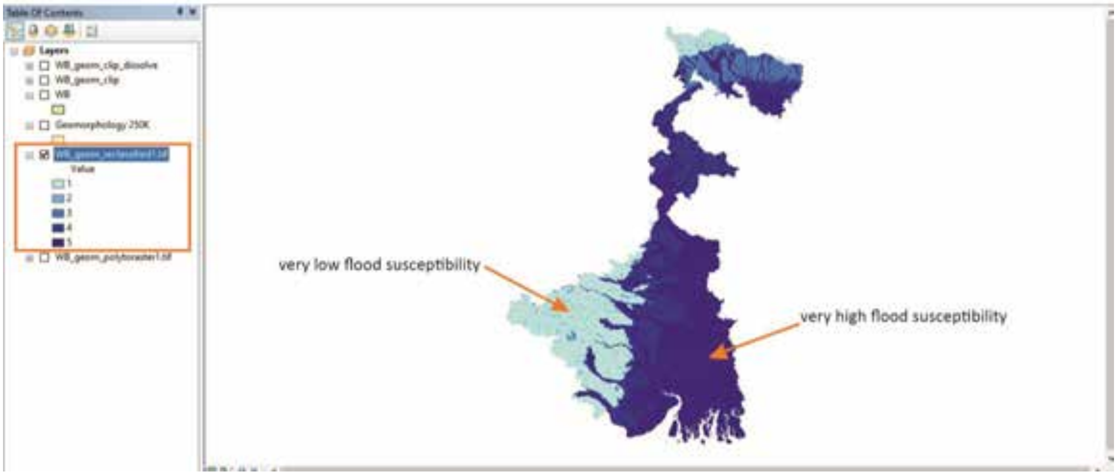


Figure C-35 Output result of reclassified geomorphology layer with colour scheme

5. Soil Texture

The soil data was obtained from the Food and Agricultural Organization of the United Nations (FAO) and classified into five classes based on its properties and relation to water holding capacity. Given is the link for downloading the vector dataset (Digital Soil Map of the World) at 1: 5000000 scale: https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/faounesco-soil-map-of-the-world/en/ and https://data.apps.fao.org/map/catalog/srv/eng/catalog.search#/metadata/446ed430-8383-11db-b9b2-000d939bc5d8.

Steps for preparing the Soil Texture layer for FSM:

- Add the Digital Soil Map of the World (DSMW) to the GIS interface as shown below (Figure C-36A). Once the layer has been added, you can change the symbology (Figure C-36B) to view the map in terms of the DOMSOI value field, which is the code for the dominant soil unit (covering 40% of the mapping unit). The output would appear as shown in Figure C-37.

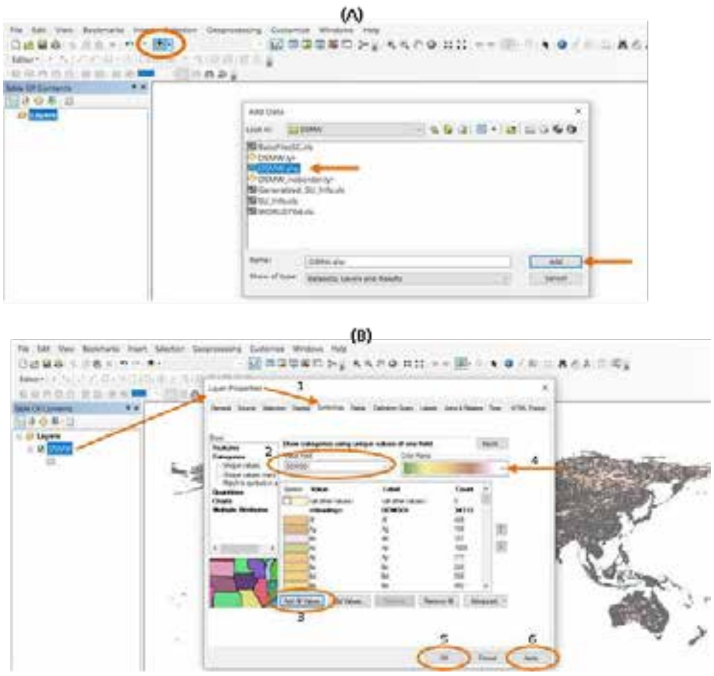


Figure C-36 Add the Digital Soil Map of the World (DSMW) to the GIS

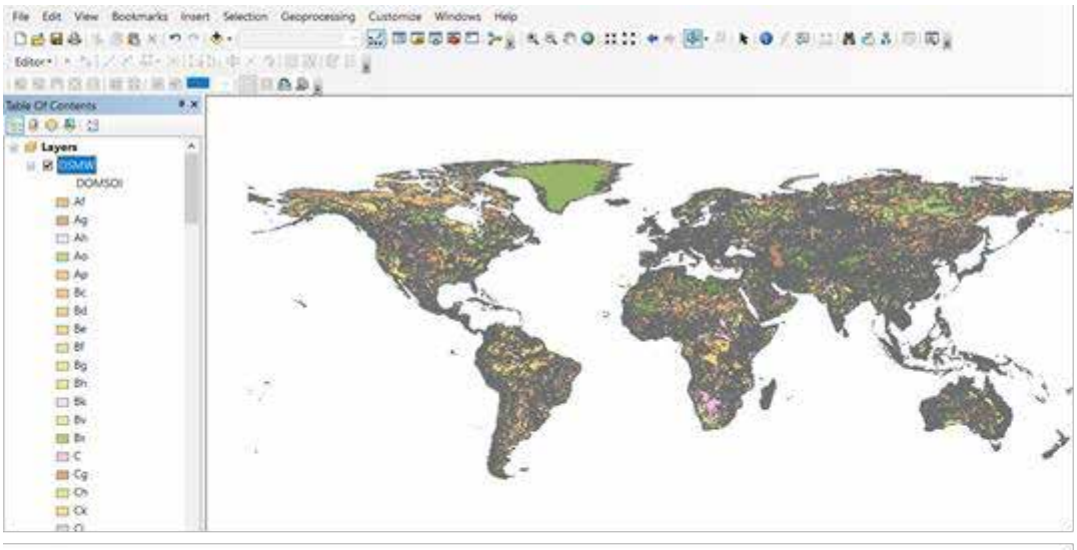


Figure C-37 Digital Soil Map of the World (DSMW) of world

- *Define projection for 'DSMW'* - The DSMW shapefile in Figure C-37 will show 'unknown spatial reference'. So, to define a projection. Go to Arc Toolbox → Click Data Management Tools → Click on Projections and transformation → Click Define Projection → 'Define Projection' window will pop-up → In 'Input Dataset or Feature Class' browse and select the Soil files 'DSMW' → In Coordinate System (Figure C-38) → 'Spatial Reference Properties' window will popup → Select 'Geographic Coordinate System' → Select 'World' → Select 'WGS 1984' → Select 'OK' (GCS_WGS_1984) → Select 'OK'.

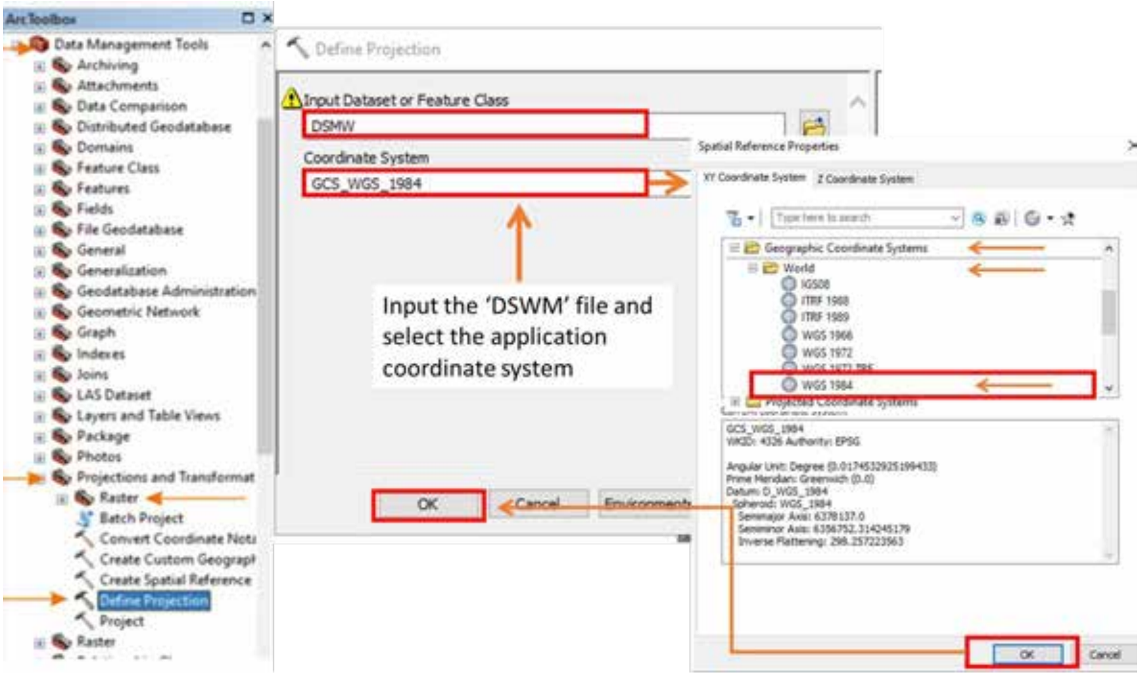


Figure C-38 Define projection for Digital Soil Map of the World shapefile

- *Clip to Soil Map for India:* Add shapefile of the all-India boundary (India boundary downloaded from Survey of India website) to Layers → Go to 'Geoprocessing' → select the 'Clip' tool (also shown in Figure C-25). → In the 'Input Features', select the 'Soil' layer (which contains the dataset to be clipped 'DSWM') from the dropdown menu → In the 'Clip features' box, select the layer containing your country boundary shapefile (the country boundary shapefile in this case

‘India_wgs1984.shp’) → In the ‘Output Feature Class browse to the folder where you want to store the files, assign a name (e.g., India_FAOSoil.shp) and save → Click OK (show in Figure C-39).

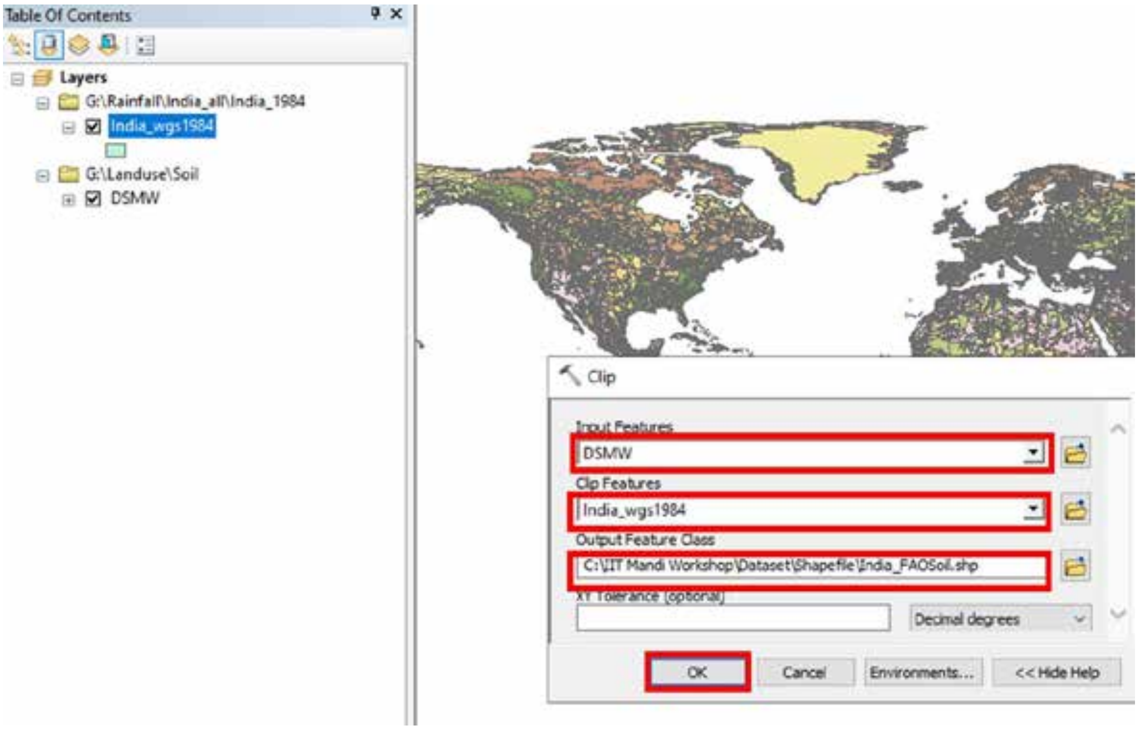


Figure C-39 Clip India soil layer from world soil layer

- *Clip for the required AOI (study state/district/block)* – Using the shapefile of the dummy state ‘WB_State’, the ‘India_FAOSoil’ dataset will need to be clipped to the AOI. The clip tool can be accessed directly from the ‘Geoprocessing’ tab present at the top of the interface (also shown in Figure C-25). In the ‘Input Features’, select the clipped India soil layer (eg, ‘India_FAOSoil.shp’) from the dropdown menu → In the ‘Clip features’ box, select the layer containing your AOI (the study state boundary shapefile in this case ‘WB_state.shp’) → In the ‘Output Feature Class browse to the folder where you want to store the files, assign a name (e.g., WB_FAOSoil.shp) and save → Click OK, when done (this step will be similar to the step shown in Figure C-39) Once the AOI has been clipped from the larger dataset, the map for the dummy state would look like Figure C-40A) given below (categorized according to the DOMSOI value field in ‘Symbology’). The Legend in Figure C-40 B shows the names for the DOMSOI units[3] in WB.

[3] The names of the DOMSOI units are available in the map legend of the Digital Soil Map of the World (pdf file).

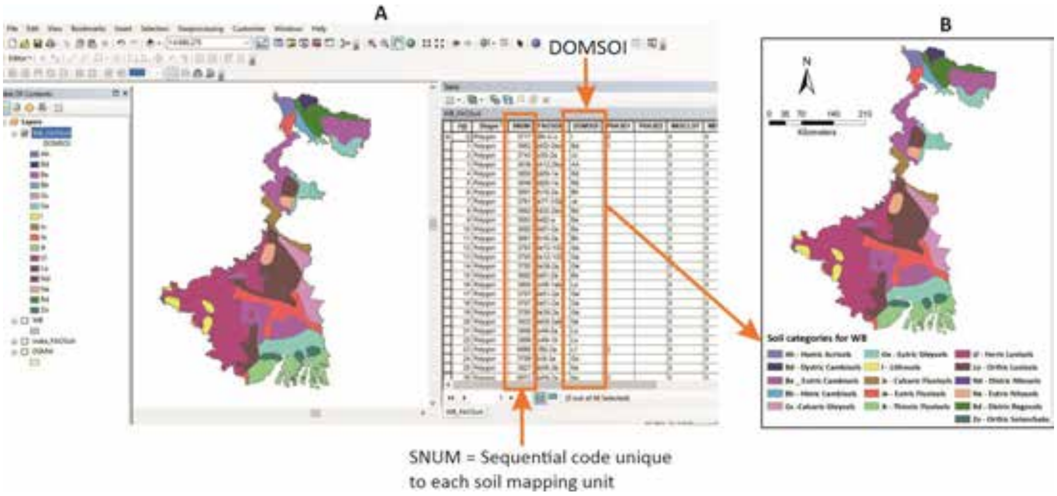


Figure C-40 Visualize soil categories based on DOMSOI value field

- Through expert opinion and literature review, these soil units can be rated from very low to very high flood control characteristics according to their texture, infiltration, and run-off properties. The raster format of the soil map for the AOI can then be reclassified into five classes signifying the flood susceptibility.
- Alternately, these soil units can further be categorized based on their texture (percentage composition of sand, silt, and clay) as 'clay/loam/sandy loam/clay loam' etc., which would be rated and reclassified for the final overlay. The textural classes to the FAO soil mapping units can be assigned based on the 'usersoil' excel file of the SWAT soil database (Figure C-41). This SWAT dataset contains detailed characteristics, including texture, hydrological group, percentage of sand, silt, and clay etc., of different soil units.

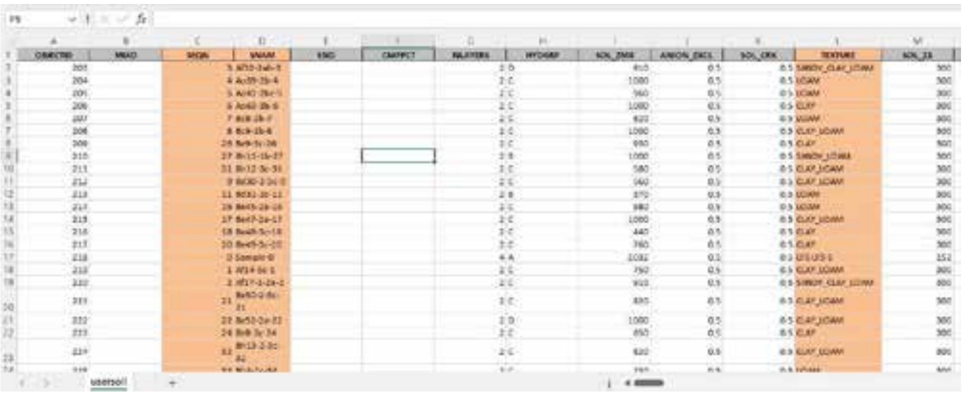


Figure C-41 SWAT 'usersoil' classification

However, to join the SWAT 'usersoil' table with the attribute table of the FAO soil map, further processing is required as explained below.

- From the attribute table in Figure C-41, it can be seen that there are around 65 different polygons representing the soil mapping units in WB. The next step would be to aggregate the features based on specified attributes using the Dissolve function. The SNUM field in the attribute table represents sequential code unique for each soil Mapping Unit (see Figure C-41). Therefore, to aggregate the similar soil mapping units, go to Geoprocessing → Dissolve → Select 'WB_FAOSoil' in Input Features → Assign a name (WB_FAOSoil_dissolve.shp) and save to related folder in Output

Feature Class → Select the 'SNUM' field in Dissolve_Field(s) (Optional) → OK Figure C-42). The output and its attribute table would be similar to Figure C-43 after adjusting the symbology and assigning a color ramp.

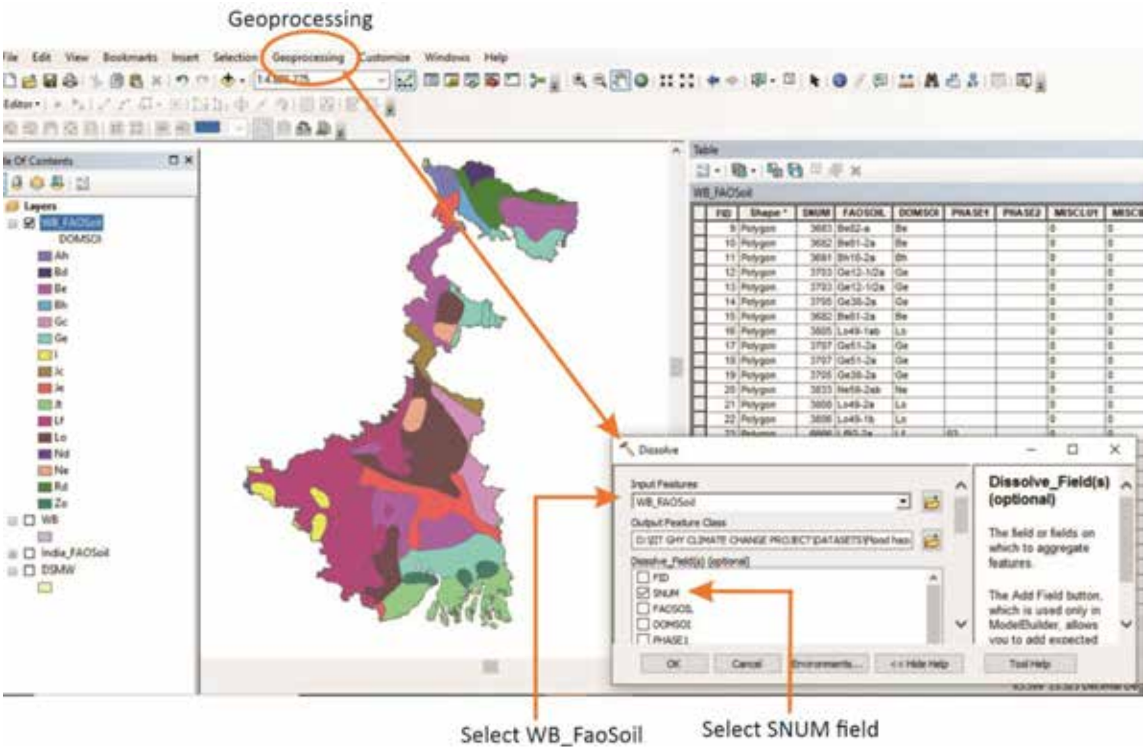


Figure C-42 Dissolve soil layer based on SNUM classes

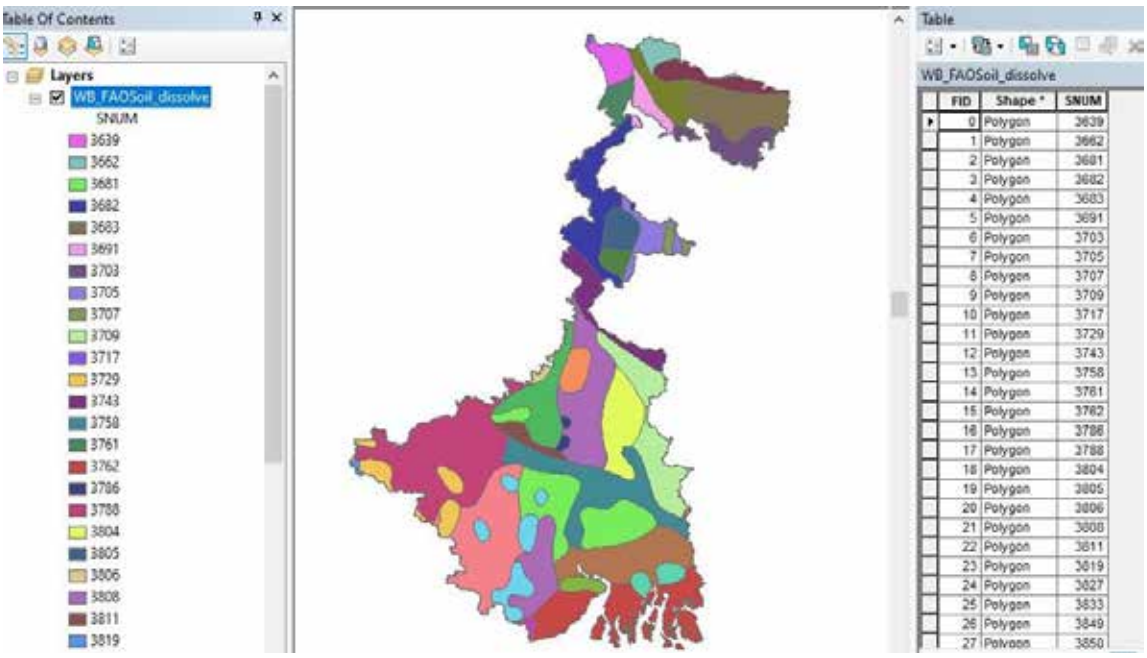


Figure C-43 Visualize dissolve soil layer based on SNUM classes

- *Joining of 'usersoil' table to attribute table of the dissolved layer (WB_FAOSoil_dissolve):* Add 'usersoil' excel sheet to the interface (Figure C-44).

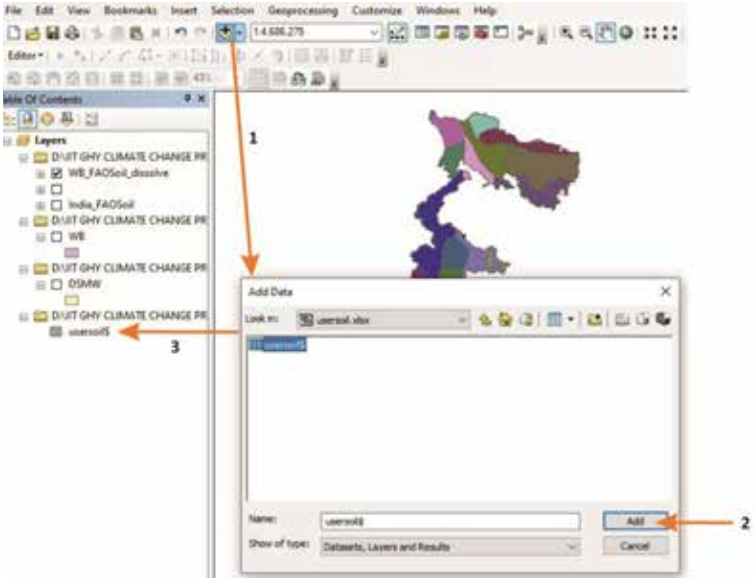


Figure C-44 Add usersoil excel sheet to GIS

- Next, as shown in Figure C-45, right click on WB_FAOSoil_dissolve layer → Joins and Relates → Join → In the window that appears, select 'Join attributes from a table' from the drop-down menu under 'What do you want to join to this layer?' → select SNUM in '1.' → choose 'usersoil$' sheet in '2.' → choose 'SEQN' in '3.' → Check 'Keep all records in 'Join Options' → Validate Join → OK. Thus, the join will be based on the field 'SNUM' of the FAO Soil data table and 'SEQN' field of the SWAT usersoil sheet, which match each other and is unique and common to each soil unit of both datasets. The resultant attribute table of WB_FAOSoil_dissolve post joining will appear as shown in Figure C-46.

Figure C-45 Joining of 'usersoil' table to attribute table of the dissolved soil layer

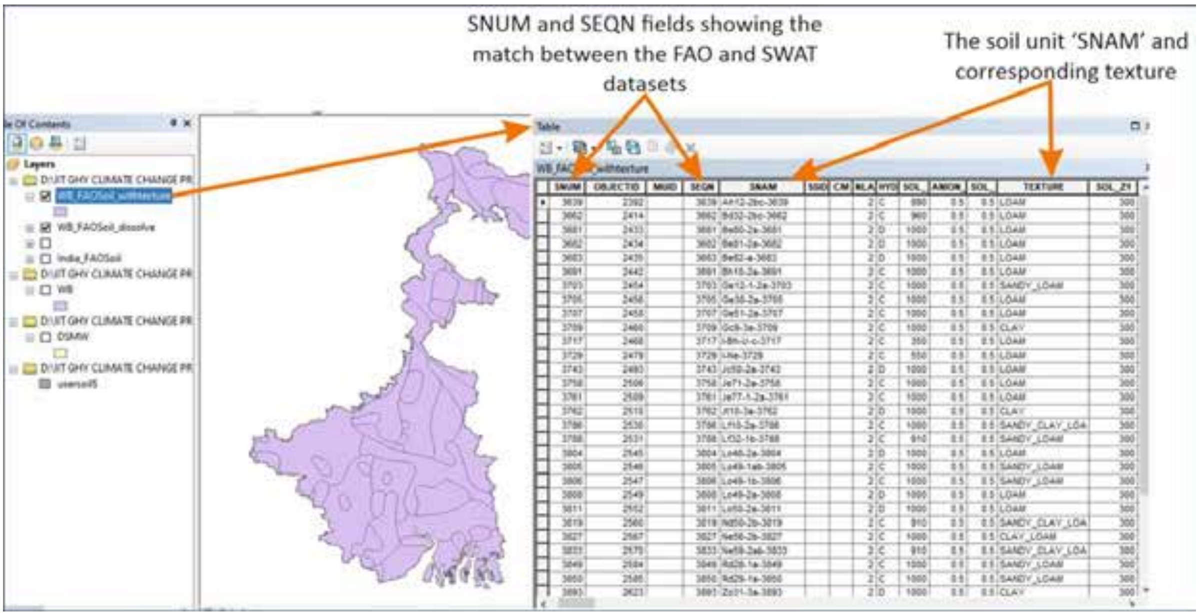


Figure C-46 Visualize joined 'usersoil' sheet in soil layer attribute table

- *Export as a new shapefile:* Once the join has been executed, export the data as a new shapefile. Right click on WB_FAOSoil_dissolve → Data → Export Data → Select 'All features' in 'Export:' → Save as a new shapefile in 'Output feature class' (E.g., WB_FAOSoil_withtexture) → OK (Figure C-47). The new output shapefile 'WB_FAOSoil_withtexture.shp' would contain the combination of all properties as described in the DSMW dataset and the SWAT database. The resultant attribute table would appear as shown below in Figure C-48. The soil texture types present in the study area can be viewed by changing the 'value field' under Symbology (in Layer properties) to 'Texture' as given in Figure C-49. Based on their flood control/susceptibility properties determined by their run-off characteristics, the different soil textural types will be rated between very low (1) and very high (5) and reclassified.

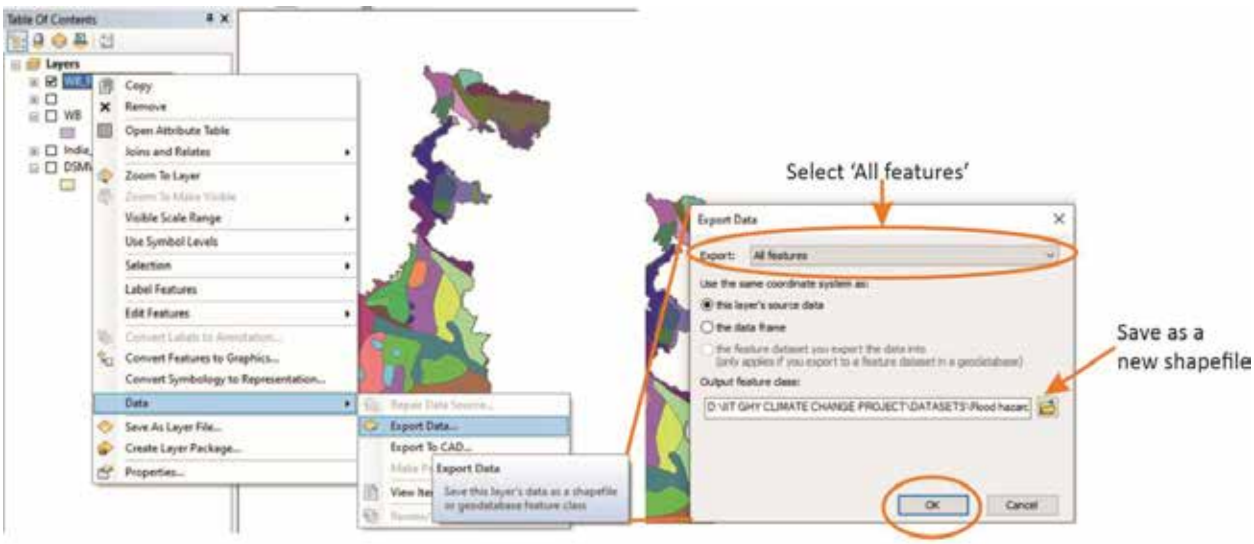


Figure C-47 Export soil layer to new shapefile

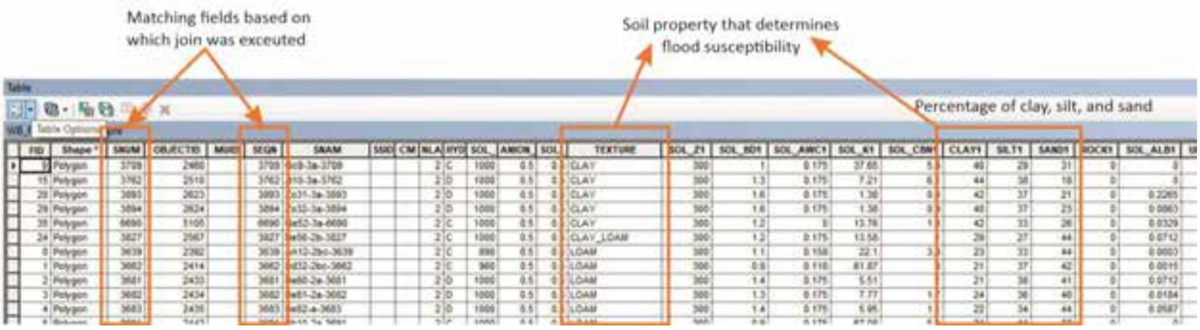


Figure C-48 Soil property and its flood susceptibility

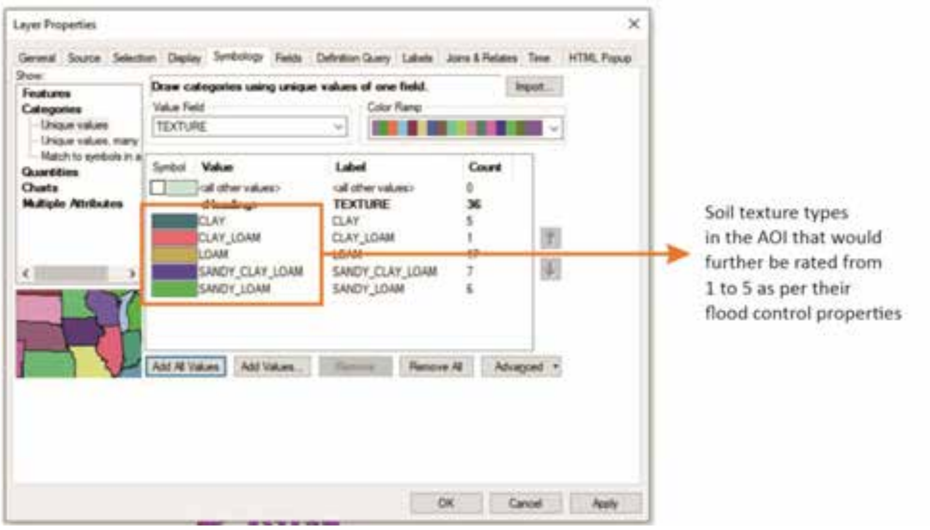


Figure C-49 Visualize soil layer based on texture property of soil

- *Polygon to raster:* To rate and reclassify the soil texture, the shapefile 'WB_FAOSoil_withtexture', will need to be converted to raster format. Figure C-50 given below describe the steps to be followed for achieving this. In ArcToolbox, go to Conversion Tools → Raster → Polygon to Raster → Select 'WB_FAOSoil_withtexture' in Input Features → Select 'Texture' in Value Field → Name the Output Raster Dataset (e.g., WB_texture.tif) and save in relevant folder → In 'Cellsize', select the DEM file of the study area → click OK. The converted file (WB_texture.tif) would appear as displayed below in Figure C-51.

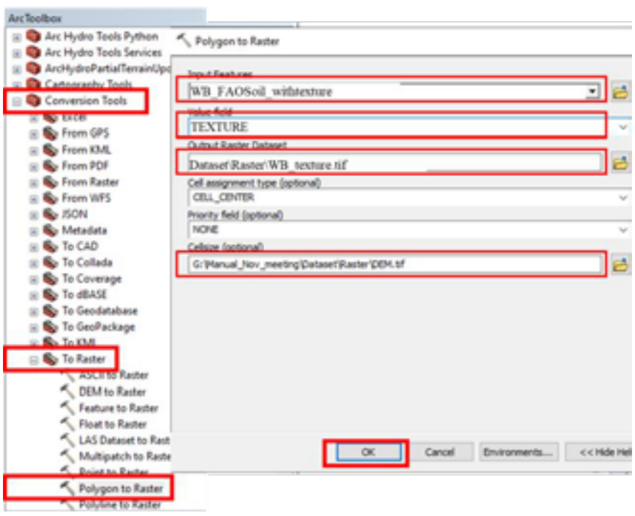


Figure C-50 Convert soil shapefile to raster based on soil texture

- *Reclassify:* Go to ArcToolbox → Spatial Analyst Tools → Reclass → Reclassify → Select WB_texture.tif in Input raster → 'Texture' in Value Field → Add the ratings (between 1 and 5) as New Values → Click OK after saving the output raster (WB_texture_reclassify.tif) in the required folder as the one shown in Figure C-51. The final reclassified soil texture layer would be obtained as the one shown in Figure C-52. This raster would then be assigned a weight based on the AHP analysis and overlaid with the eight other FCFs to obtain the composite FSM of the AOI.

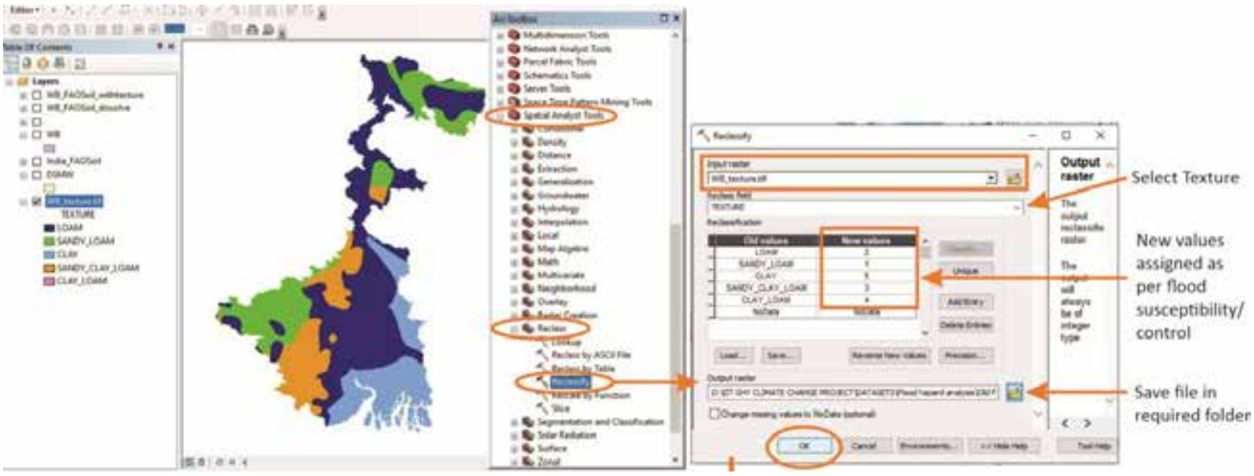


Figure C-51 Reclassification of soil layer

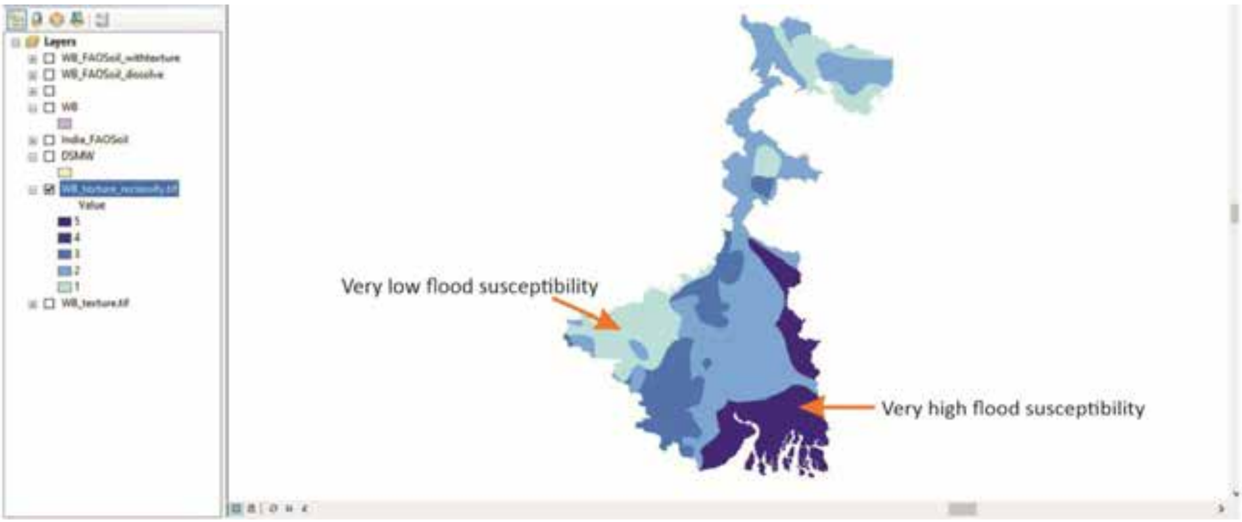


Figure C-52 Output result of reclassified soil layer with colour scheme

6. Distance from River (DR)

In this indicates the major pathways of flood discharge and its spread. Generally, areas adjacent to rivers are more vulnerable to inundation as water overflows and spreads laterally, than those located further away from the banks. The River Network data of the study area was obtained from the Hydrosheds database available at https://www.hydrosheds.org/products/hydrorivers[1]. In this study, DR was calculated using the 'Euclidean distance' tool in GIS and classified into five classes (5, 4, 3, 2, 1) based on natural breaks/jenks. The class with the lowest range of distance from the river was classified as 5, indicating 'very high' flood susceptibility, and the range with the largest DR as 1, indicating 'very low' susceptibility.

- *Add shapefile of the AOI state* (state boundary downloaded from Survey of India website) to Layers → To Add data click → Add data Box will appear → click to connect dataset folder →Select location to '\Dataset'→ Click **OK (**displayed below in Figure C-53)

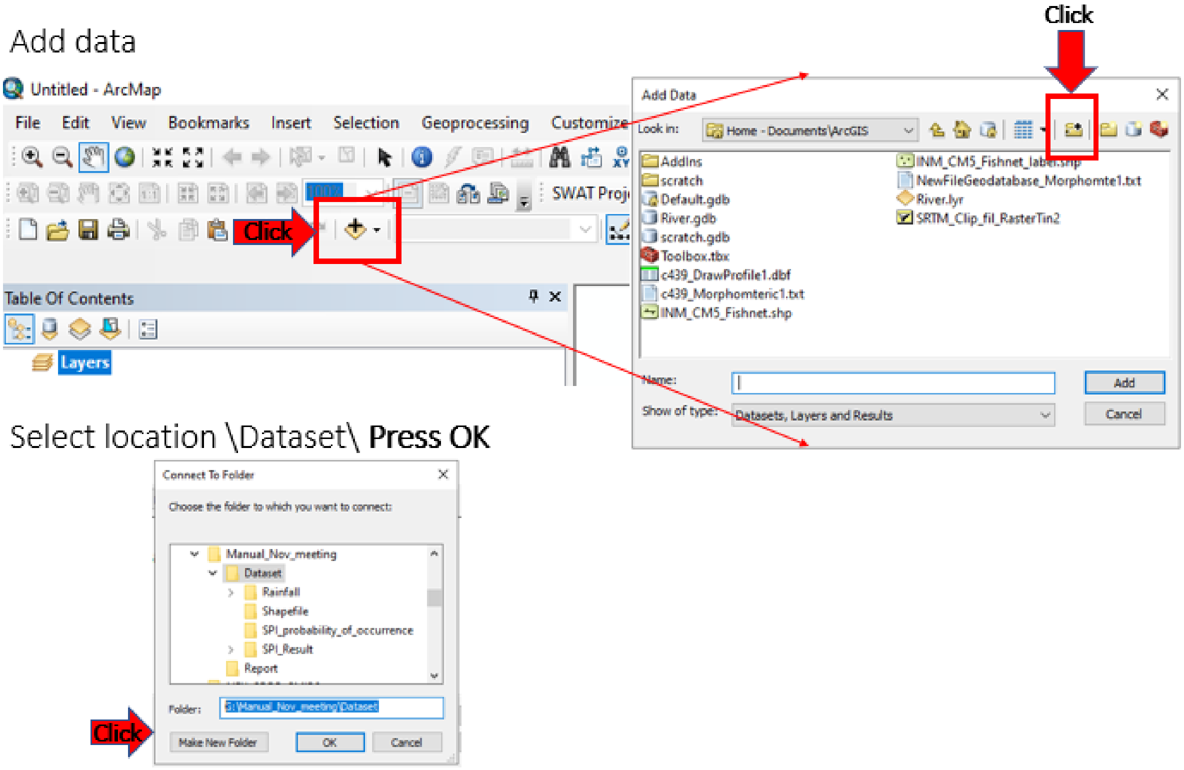


Figure C-53 Connect dataset folder

- To Add the SOI District shapefile → Double click on **Shapefile** folder → click on State boundary shapefile ('**WB_State')** → Click **ADD (**displayed below in Figure C-54).

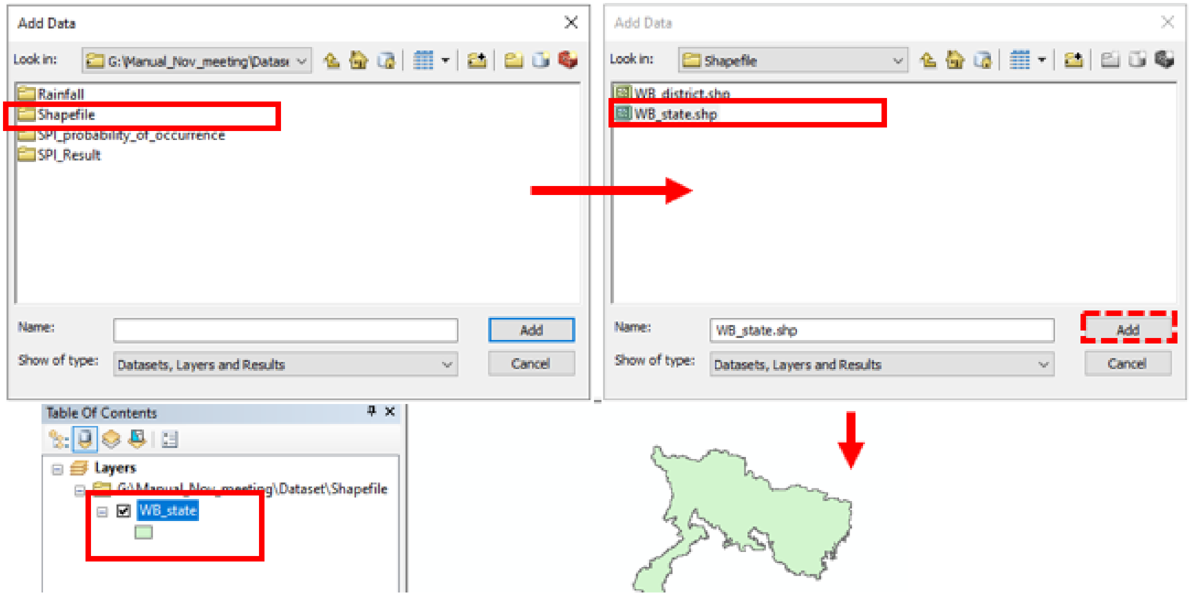


Figure C-54 Add the AOI / state boundary shapefile

- To *Add the Hydroshed Rivers network shapefile* → Double click on **Shapefile** folder → click on Hydrosheds database network shapefile (**'India_HydroRivers.shp')** → Click **ADD** (displayed below in Figure C-55)

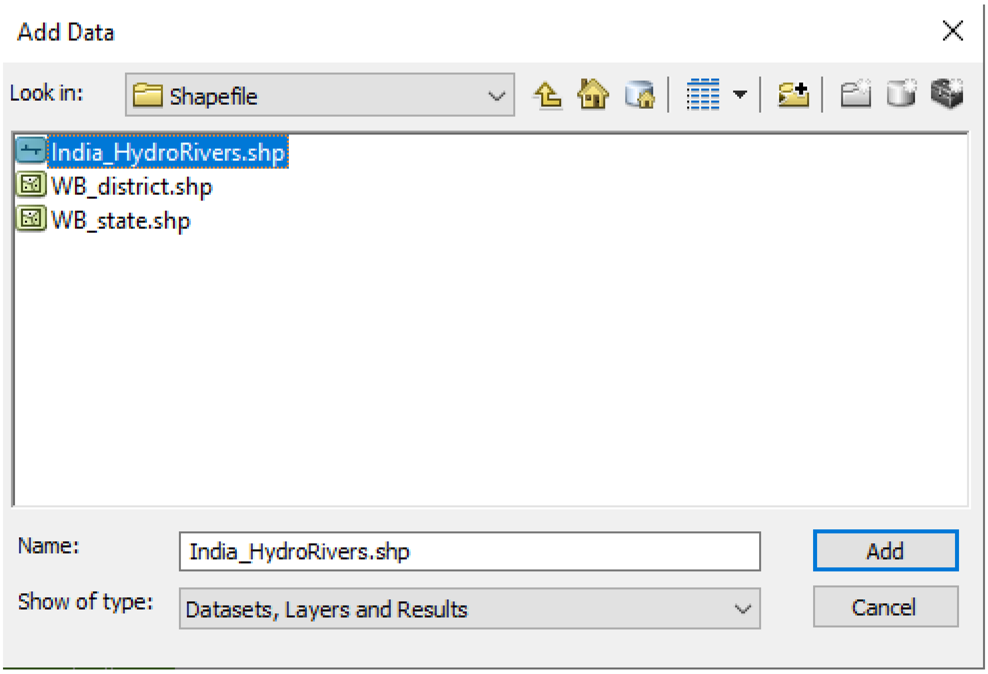


Figure C-55 Add the Hydroshed Rivers network shapefile

- *Clip to study area:* In ArcToolbox, go to 'Analysis Tools' → select the 'Extract' → select the 'Clip' tool → In the 'Clip features' window, select the 'Input Features', India_HydroRivers layer (which contains the dataset to be clipped) from the dropdown menu → In the 'Clip features', select the layer containing state boundary shapefile ('WB_state') → In the 'Output Feature Class' browse to the folder where you want to store the files, assign a name (e.g., Dataset\Raster\Distance from River\WB_HydroRiver.shp) and save → Click **OK**. **(**displayed below in Figure C-56)

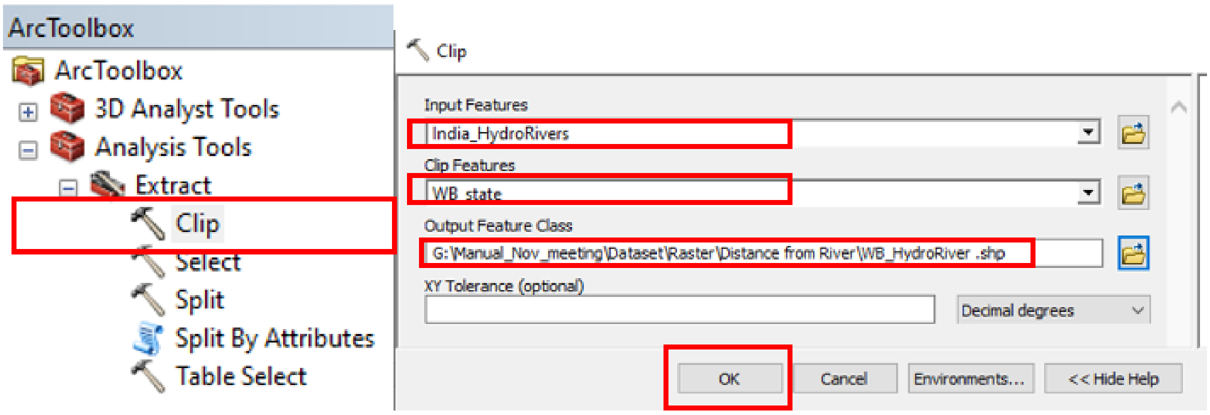


Figure C-56 Clip Hydroshed Rivers network shapefile for AOI

- *Extract Major River Network:* Mainly the flood causes in the main river therefore consider only the high order streams.
- In Table of Contents, right click Clipped River network shapefile ('WB_HydroRiver') → Click Open Attribute Table → In 'Table' window go to ORD_STRA column **Double Click** (To sort column double Click) **(**displayed below in Figure C-57)

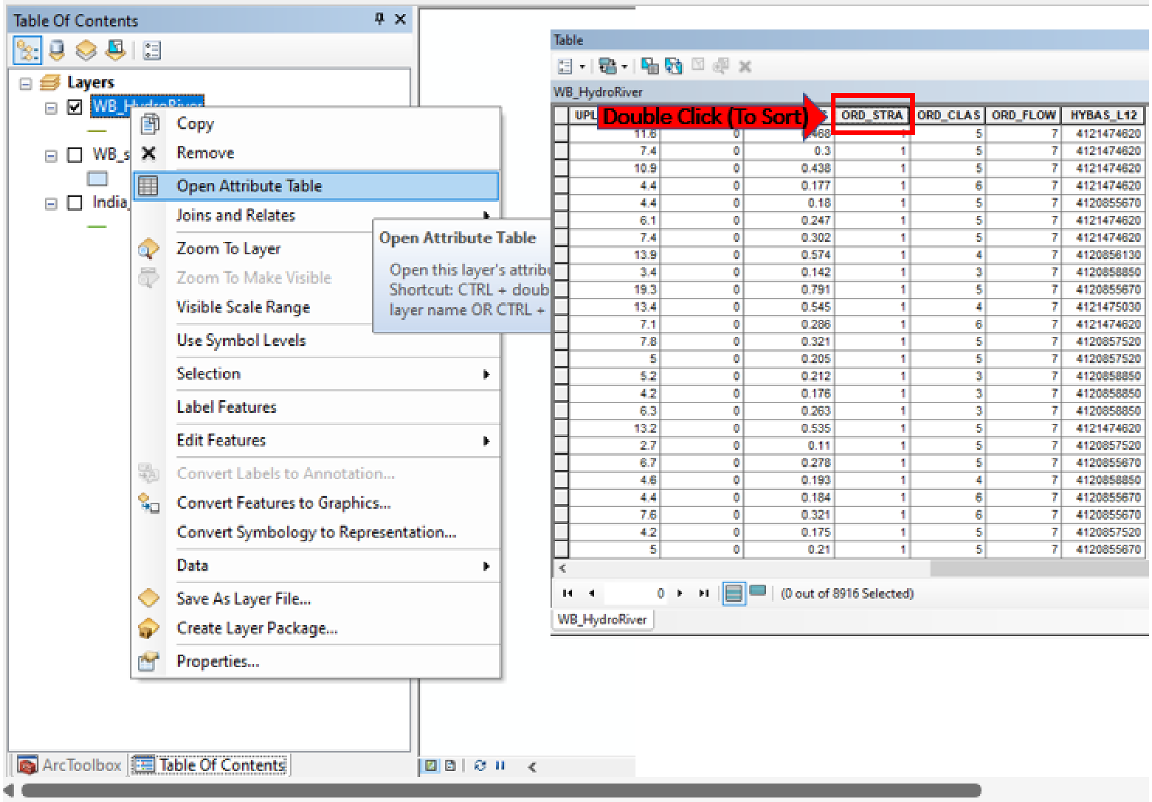


Figure C-57 Sort attribute table having stream order Strahler

- Select all row where ORD_STRA is more than '4' (main river network is present in all stream order more than 4) → Go to Table of Contents, right-click shapefile 'WB_HydroRiver' → Click 'Data' → Click 'Export Data' → 'Export Data' window will pop-up, Name the Output Raster Dataset (e.g., 'Dataset\Raster\Distance from River\WB_River_4_8.shp') and save in relevant folder → click **OK** →'ArcMap' window will pop-up to ask do we want to add export layer in to map, to add click **Yes. (**displayed below in Figure C-58)

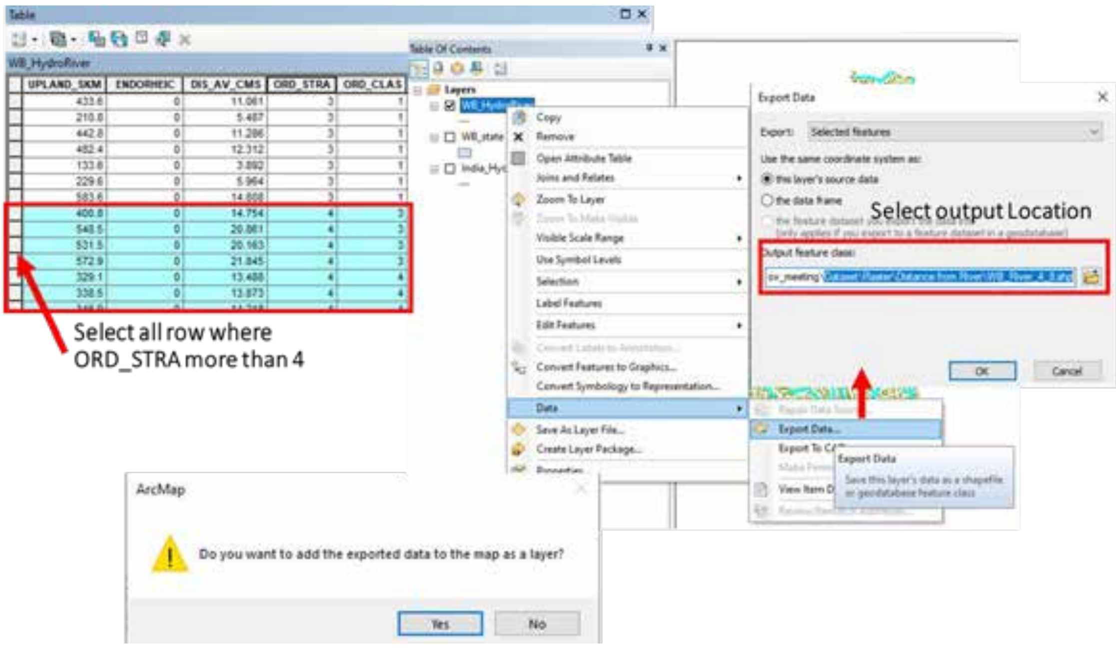


Figure C-58 Extract main river network having stream order more than 4

- *Distance from River Network:* In ArcToolbox, go to 'Spatial Analysis Tools' → Select the 'Distance' → Select the 'Euclidean Distance' tool → In the 'Euclidean Distance' window, select the 'Input raster or features', which contains the Extract Major River Network ('WB_River_4_8 layer') from the dropdown menu → In the 'Output Distance Raster' browse to the folder where you want to store the files, assign a name (e.g., Dataset\Raster\Distance from River\WB_DR.tif) and save → In 'Output cell size', select the DEM file of the study area ('Dataset\Raster\DEM.tif) '→click '**Environment Settings**' → In 'Processing Extent' Select the layer containing state boundary shapefile of AOI ('WB_state') → In 'Mask' select the DEM file of the study area ('Dataset\Raster\DEM.tif')→ click **OK** → click **OK (**displayed below in Figure C-59).

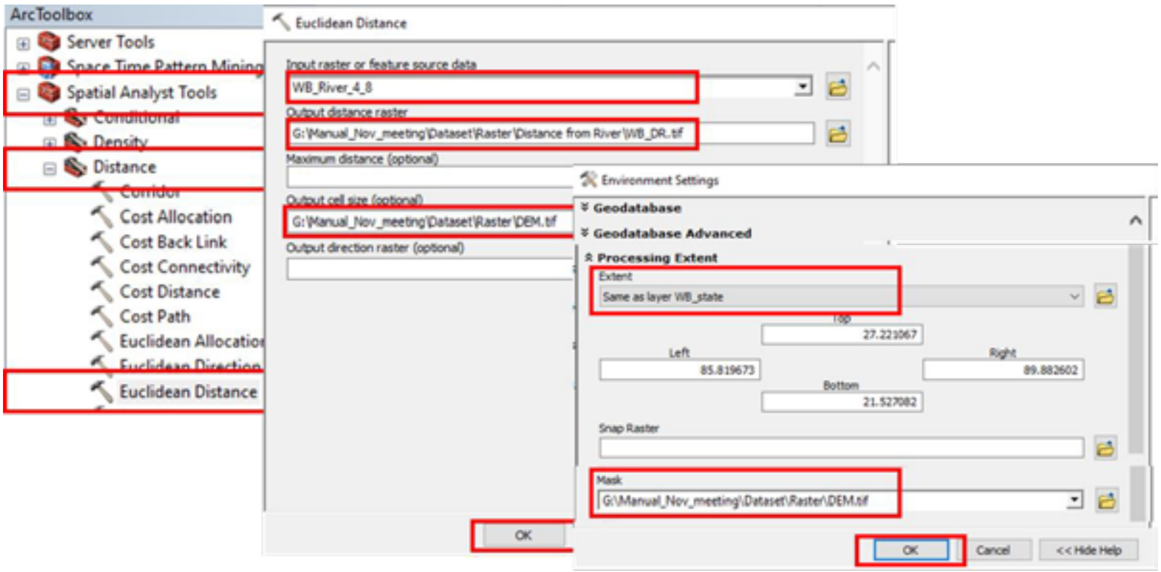


Figure C-59 Calculate Euclidean distance for the river network

- *Reclassify*: The class with the lowest range of distance from the river was classified as 5, indicating 'very high' flood susceptibility, and the range with the largest DR as 1, indicating 'very low' susceptibility. In ArcToolbox, go to 'Spatial Analyst Tools' → Select the 'Reclass' → Select the 'Reclassify' → 'Reclassify' Window will pop-up, select the output of Euclidean Distance ('WB_DR.tif') in 'Input raster' → Click **Classify** → Classification Window will pop-up, Select 'Natural Break' in 'Classification Method' → Select '5' in 'Classes → click **OK** → Change Reclassification 'New Values' as per below figure (Near to river will get higher value '5' and far away from river will get less value '1') → In 'Output Raster' select relevant folder and assign file name ('Dataset\Raster\Distance from River\WB_DR_reclassify.tif') → Click ☑ in 'change missing values to No Data'→ click **OK**. **(**displayed below in Figure C-60).

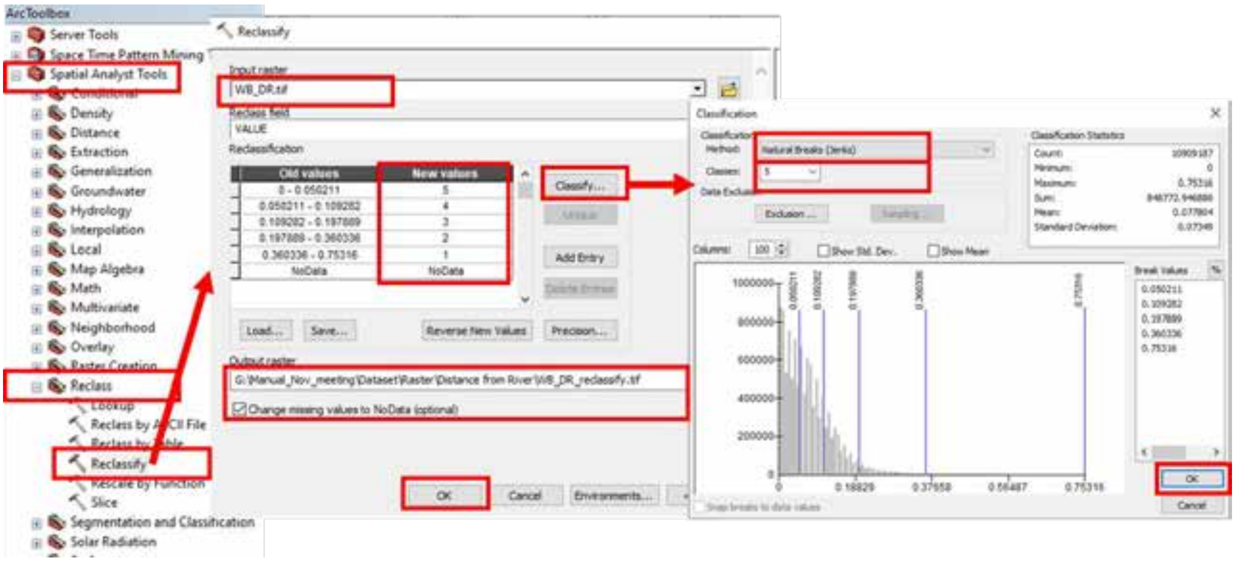


Figure C-60 Reclassified distance from river layer

- *Changing the colour scheme of reclassified DR layer:* Repeat same step as followed in previous section of changing the colour scheme of reclassified layer. Result of DR is shown in Figure C-61.

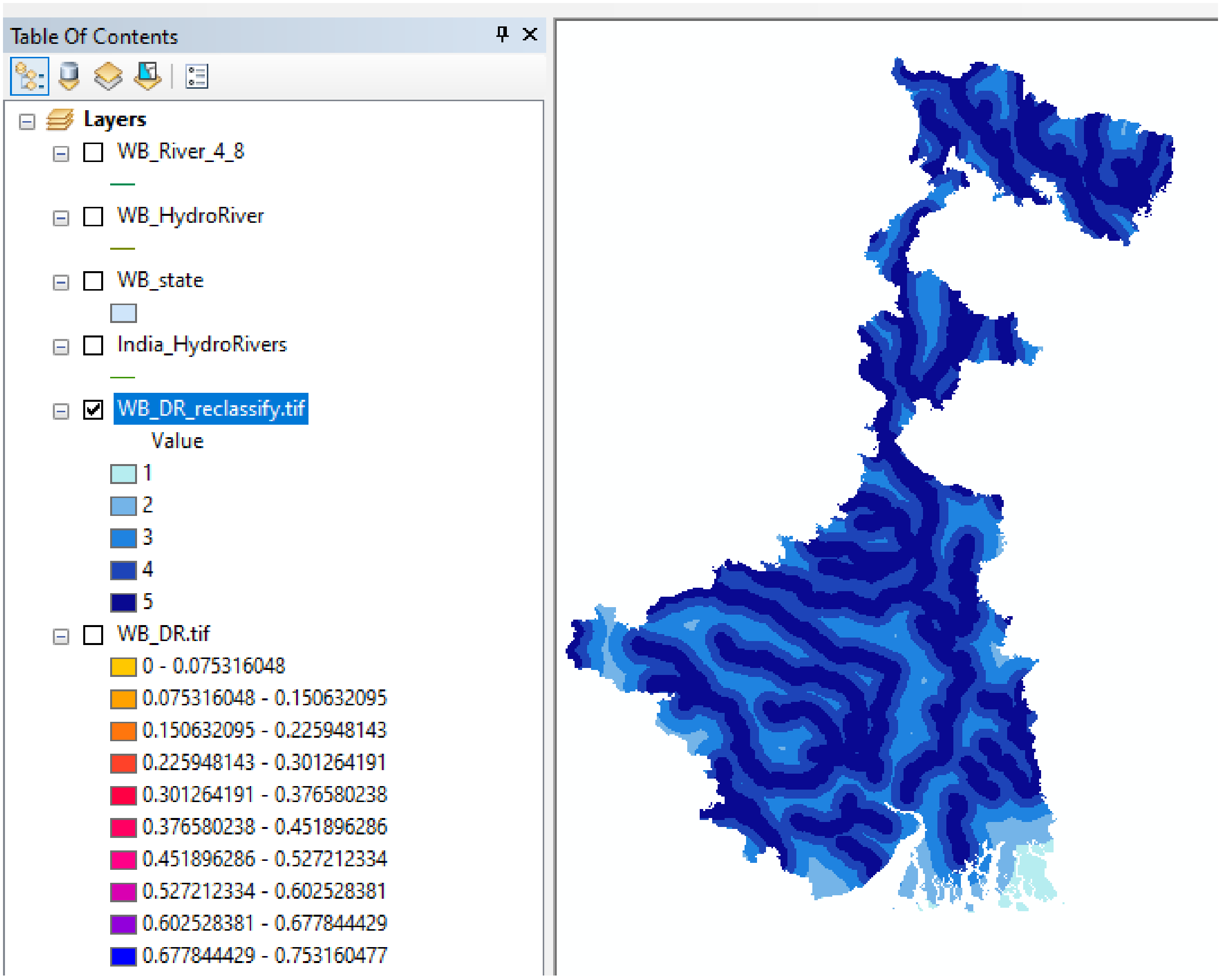


Figure C-61 Output result of reclassified distance from river layer with colour scheme

7. Land use/land cover (LULC)

The land use/land cover data of the study area was obtained from the Sentinel-2 10m Land Use/Land Cover Timeseries layer database available at 10 m resolution or any other product can also be use. For downloading Sentinel-2 10m Land Use/Land Cover Timeseries layer for year 2019 please see link: https://www.arcgis.com/home/item.html?id=fc92d38533d440078f17678ebc20e8e2 [4]. The data is classified in to 9 classes. The classes are Water Areas, Trees (any significant clustering of tall (~15-m or higher) dense vegetation), flooded vegetation areas (flooded area that is a mix of grass/shrub/trees/bare ground), Crops (Human planted/plotted cereals, grasses, and crops not at tree height; examples: corn, wheat, soy, fallow plots of structured land), Built Area (human made structures), bare ground areas (rock or soil with very sparse to no vegetation), Snow/Ice Large, Clouds (no land cover information due to persistent cloud cover), rangeland (open areas covered in homogenous grasses)

The different land use/land cover are reclassified into very low, low, moderate, high, and very high categories (class 1 to 5) depending upon their control or susceptibility to floods in a given area.

Download Land Use /Land cover data: Open Link https://www.arcgis.com/home/item.html?id=fc92d38533d440078f17678ebc20e8e2 (as shown in Figure C-62)→ Select the Tiles and the location of AOI / State → Window will pop-up, 'Download Scene by year' select the year '2019' → The file will be start downloading (as shown in Figure C-63). If the AOI / State is located in a manner that requires downloading multiple tiles. So based on AOI / State download the land use land cover map.

Figure C-62 Land Use /Land cover data portal.

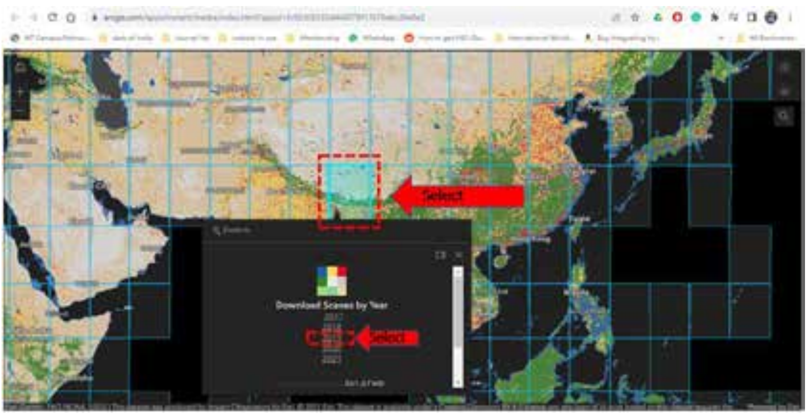


Figure C-63 Download Land Use /Land cover data

[4] You will need to register as a user in the website in order to be able to download the required dataset.

- *Add shapefile of the state* (state boundary downloaded from Survey of India website) to Layers → To Add data click → Add data Box will appear → click to connect dataset folder →Select location to add and store file ('\Dataset')→ Click **OK**(as shown in Figure C-64)

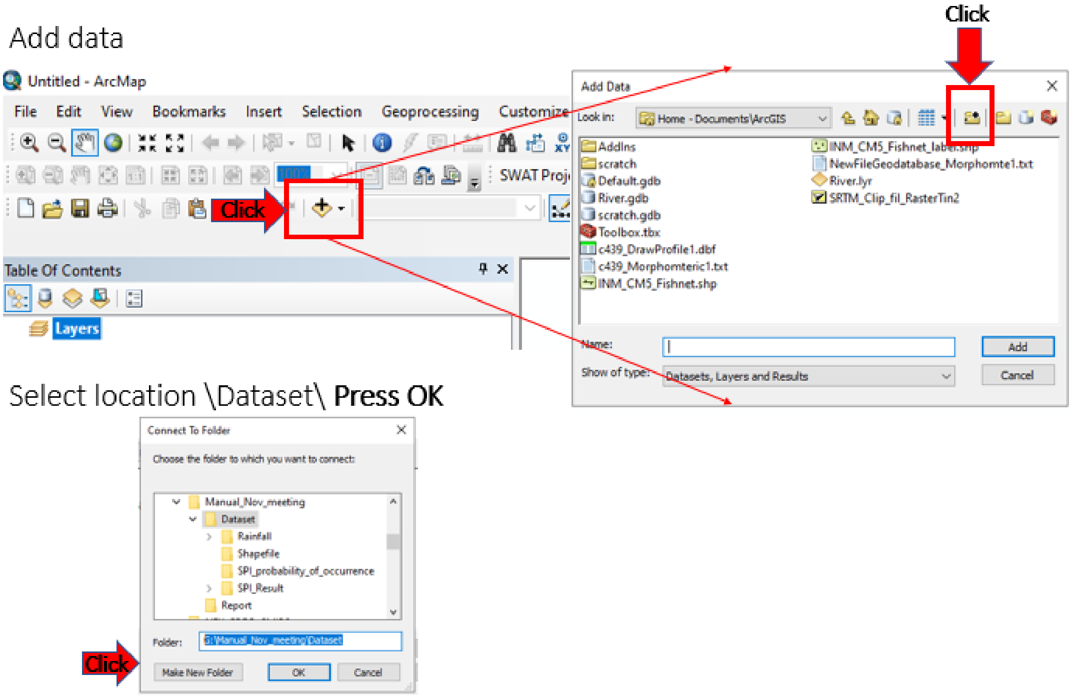


Figure C-64 Connect dataset folder

- To Add the SOI District shapefile of AOI → Double click on **Shapefile** folder → click on State boundary shapefile ('**WB_State'**) → Click **ADD**(as shown in Figure C-65)

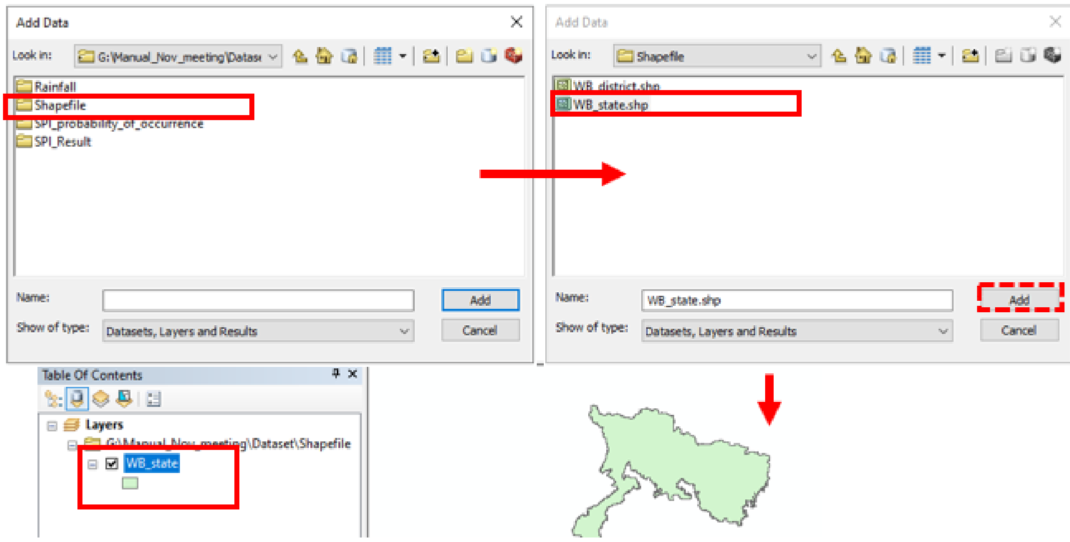


Figure C-65 Add the AOI / State shapefile

- To Add *Land Use /Land cover* → Double click on **Raster** folder → Double click on **Landuse** folder → Double click on **Raw** folder → select all raster file for AOI (both files) → Click **ADD**(as shown in Figure C-66) (For example AOI/state, the AOI/State is situated in a way that two land-use tiles cover the extent of the AOI/State).

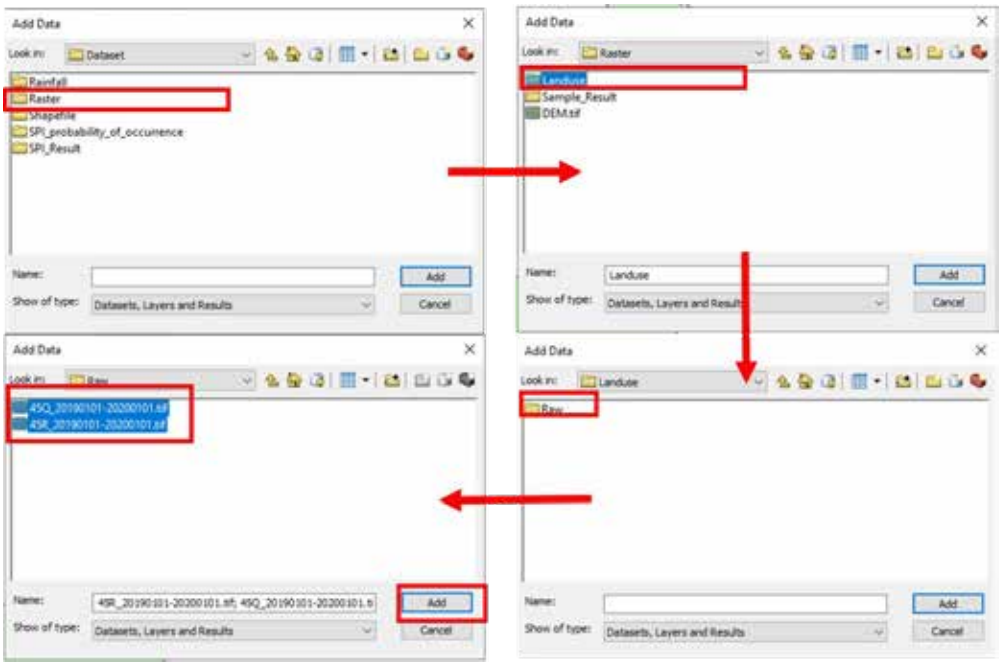


Figure C-66 Adding the Land Use /Land cover data to GIS

- *Define projection* for '*Land Use /Land cover*': This step needs to be performed for all the tiles download for AOI. In ArcToolbox, go to 'Data Management Tools' → Select the 'Projection and Transformation' → Select the 'Raster' → Select 'Project Raster' → 'Project Raster' Window will pop-up → Select 'Input Raster' as Landuse raster file for AOI ('45R_20190101-20200101.tif') → Input file name the 'Output Raster Dataset' (e.g., 'Dataset\Raster\Landuse\ 45R_20190101-20200101_GCS.tif') and save in relevant folder → Select 'Output Coordinate System' as 'GCS_WGS_1984' → click **OK** (as shown in Figure C-67).

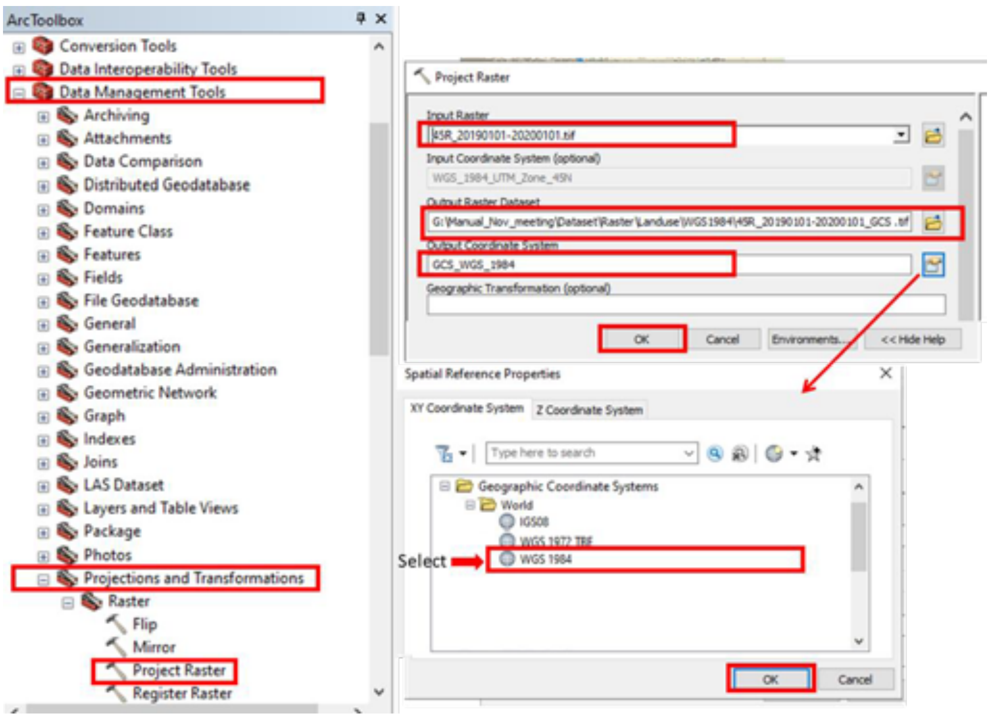


Figure C-67 Projecting Land Use /Land cover raster

- (If you have a single tile for your AOI/State, then you need to skip this step.) *Repeat Define projection* for all the tiles raster file: In ArcToolbox, go to 'Data Management Tools' → Select 'Projection and Transformation' → Select 'Raster' →'Project Raster' Window will pop-up → Select 'Input Raster' as land use raster file for AOI ('45Q_20190101-20200101.tif') → Input file name the 'Output Raster Dataset' (e.g., 'Dataset\Raster\Landuse\ 45Q_20190101-20200101_GCS.tif') and save in relevant folder → Select 'Output Coordinate System' as 'GCS_WGS_1984' → click **OK** (If you have multiple tile for your AOI/State than you have to repeat the step for all tiles)

- *Clip for the required AOI (study state/district/block)* – Using the state boundary shapefile of the AOI ('WB_State') and add the projected Landuse raster file ('45Q_20190101-20200101_GCS.tif' & '45R_20190101-20200101_GCS.tif') dataset will need to be clipped to the AOI. In ArcToolbox, go to 'Data Management Tools' → Select the 'Raster' → Select the 'Raster Processing' → Select the 'Clip' →'Clip' Window will pop-up → Select projected landuse raster file ('45Q_20190101-20200101_GCS.tif' OR '45R_20190101-20200101_GCS.tif') in the 'Input Raster' → Select 'Output Extent' as the state boundary shapefile of the AOI ('WB_state')→ Check Mark Use 'Input Feature for Clip Geometry' → and to save in relevant folder Select 'Output Raster Dataset' as ('Dataset\Raster\Landuse\Clip\' '45Q_20190101-20200101_GCS_C.tif' OR '45R_20190101-20200101_GCS_C.tif') → click **OK** (as shown in Figure C-68 for 45Q and Figure C-69 for 45R) (If you have more than two tiles for your AOI/State, repeat the step for each tile).

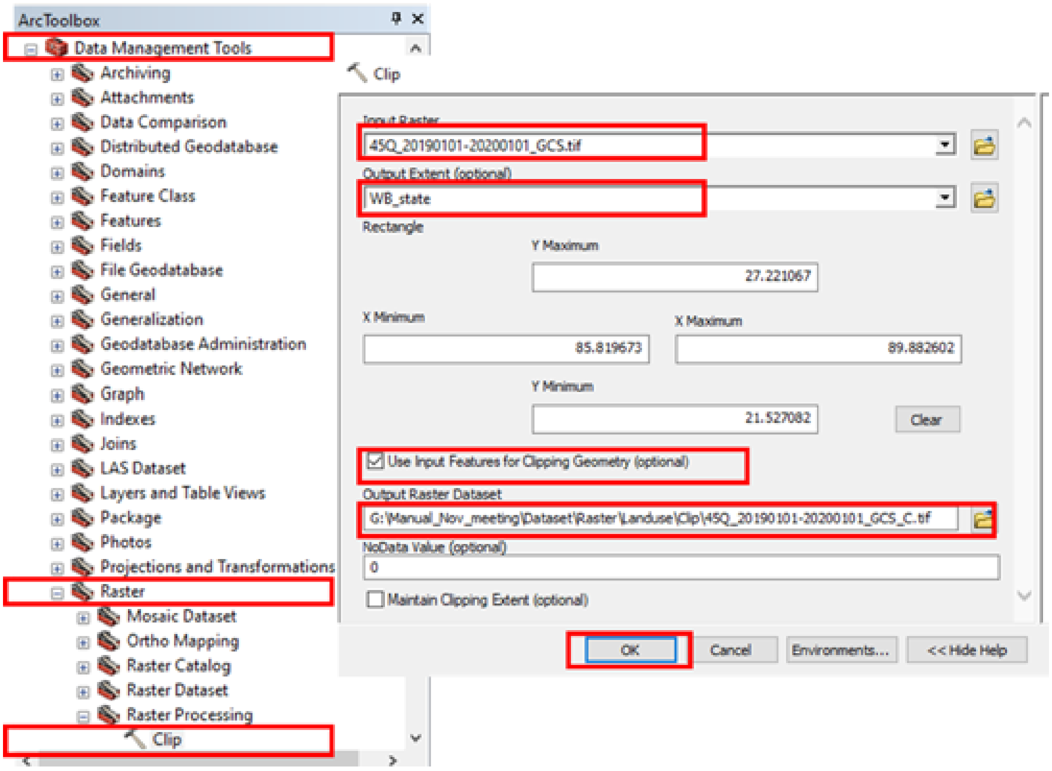


Figure C-68 Clip Land Use /Land cover raster 1 to AOI

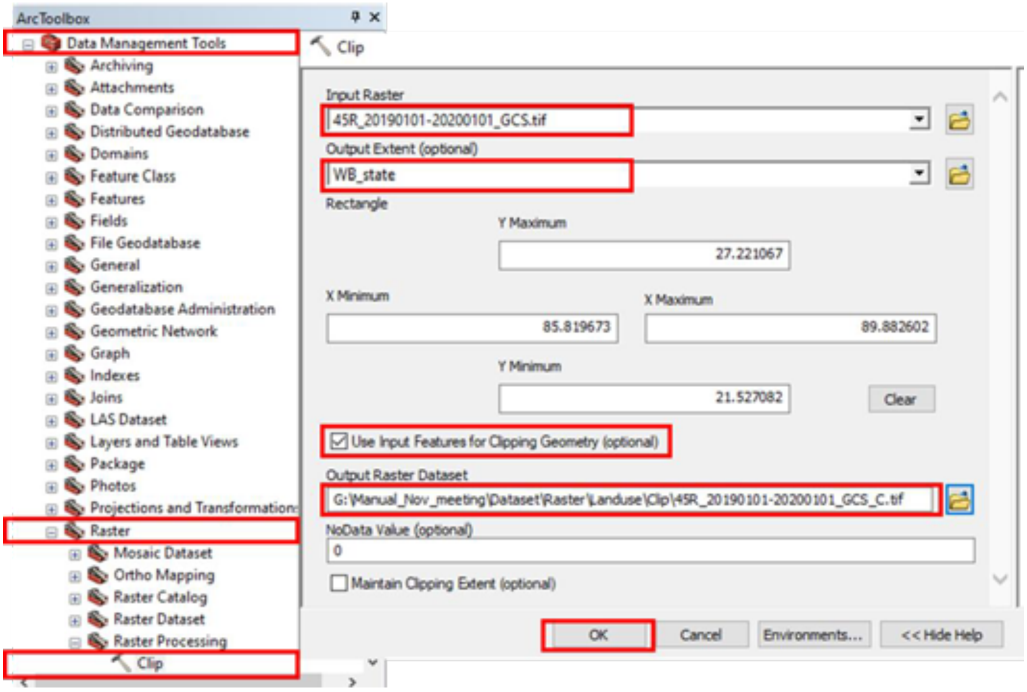


Figure C-69 Clip Land Use /Land cover raster 2 to AOI

- *Combine the cliped multiple Raster file*: Go to 'Data Management Tool' → Select the 'Raster' → Select the 'Raster Dataset'→ Select the 'Mosaic to New Raster' → In the 'Input Raster', select all the Projected cliped raster file of land use ('45Q_20190101-20200101_GCS_C.tif' & '45R_20190101-20200101_GCS_C.tif') → Select relevant folder ('Dataset\Raster\Landuse\') in 'Output Location' → 'Assign a Raster Dataset name with Extension (e.g., 'WB_LULC.tif') → Select 'Number of Bands' as '1' → **OK**. as shown in Figure C-70.
- If you have a single tile for your AOI/State, skip this step.

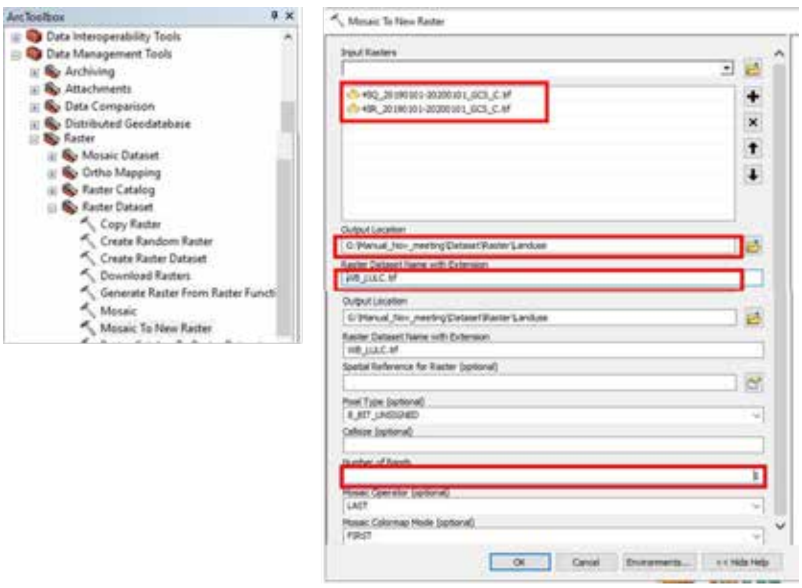


Figure C-70 Mosaic multiple raster file to single raster file

- *Reclassify*: The different land use/land cover are reclassified into very low, low, moderate, high, and very high categories (class 1 to 5) based on the property. In ArcToolbox, go to 'Spatial Analyst Tools' → Select the 'Reclass' → Select the 'Reclassify' → Window will pop-up, select the Mosaic Land use raster file ('Dataset\Raster\Landuse\WB_LULC.tif') in 'Input raster' → Click on **Unique**

→ In 'Reclassify' Select New Values Based on below window → In 'Output Raster' select relevant folder and assign file name ('Dataset\Raster\Landuse\WB_LULC_reclassify.tif)→ click **OK**. as shown in Figure C-71. (Variations in land use, land cover, and flood susceptibility across different regions are quite common. So, the classification of land use classes varies with respect to flood susceptibility classes, indicating that different types of land use exhibit distinct levels of flooding. This variability could be attributed to factors such as land cover, topography, and urban development, which influence how different areas respond to and are impacted by flood events. So based on you AOI we need to reclassify this flood susceptibility classes. Example for our AOI is shown in Table C-1)

Table C-1: Example for reclassification of land use, land cover, and flood susceptibility classes

Flood Susceptibility class	Land use class
1	Clouds (10), Snow/Ice (9)
2	Trees (2)
3	Crops (5), Rangeland (11)
4	Flooded vegetation (4), Built Area (7)
5	Water (1), Bare ground (8)

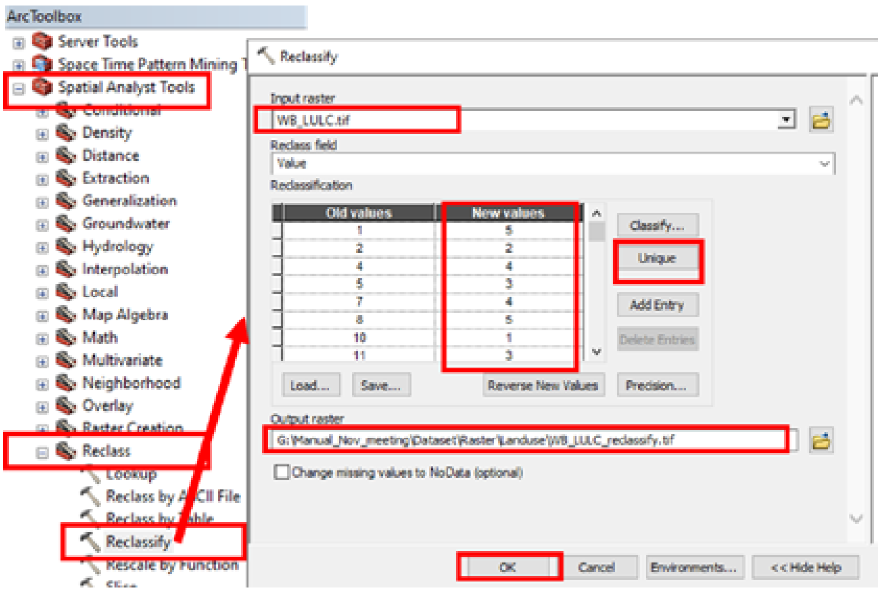


Figure C-71 Reclassification of land use, land cover layer

- *Changing the colour scheme of reclassified LULC layer:* Repeat same step as followed in previous section of changing the colour scheme of reclassified layer. Result of LULC is shown in Figure C-72

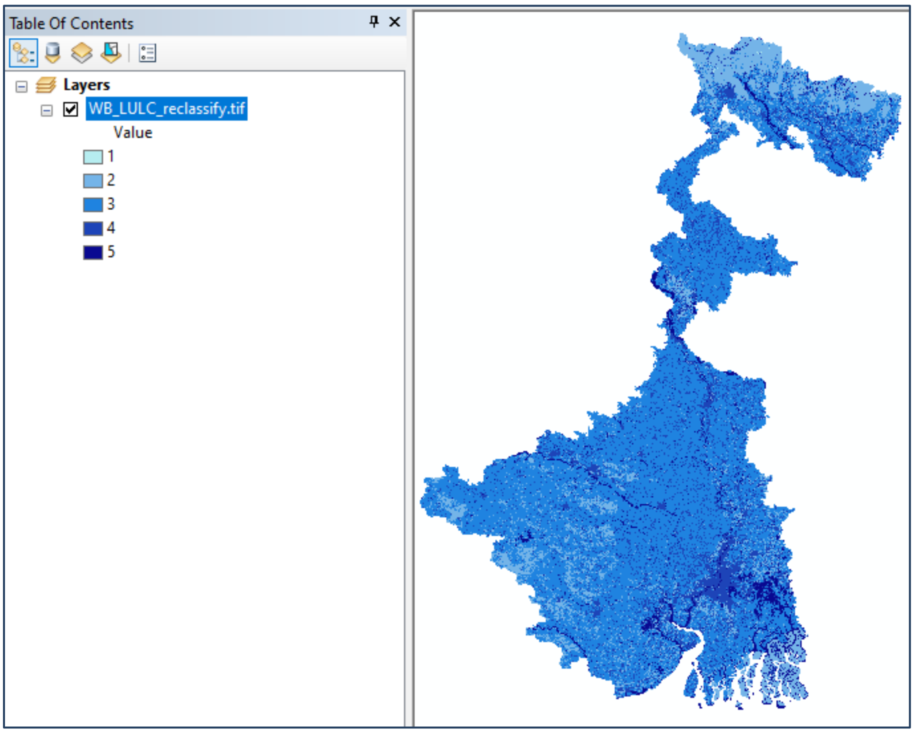


Figure C-72 Output result of reclassified land use land cover layer with colour scheme

8. Standardized Precipitation Index (SPI)

The states will receive the district-level monthly precipitation data (50 years, tentatively) from the Project Team (in an excel format) for both Observed, and RCP scenarios.

- Download SPI generator from the following link and run the application after extracting all the files: https://drought.unl.edu/Monitoring/SPI/SPIProgram.aspx
- The application requires MicrosoftNET 4.0 framework and can be compiled as a 32- or 64-bit executable. The application consists of two files: a vb.net 4.0 application and a c#.net 4.0 DLL.
    - 'SPIGenerator.exe' – the Windows console application.
    - StandardPrecipitationIndex.dll – the SPI DLL.
- The application reads in precipitation data and supports different time scales and data types (weekly, monthly). It outputs SPI data and, optionally, frequency and drought period data. In addition to executing as a Windows GUI (Graphical User Interface) it can also execute from the command line.
- Running the application as a Windows application or command line produces the same program flow:
    i. Retrieve and verify input parameters
    ii. Parse input file
    iii. Aggregate data
    iv. Calculate SPI
    v. Write results to file.
- Execution of SPI as Windows GUI (Figure C-73):

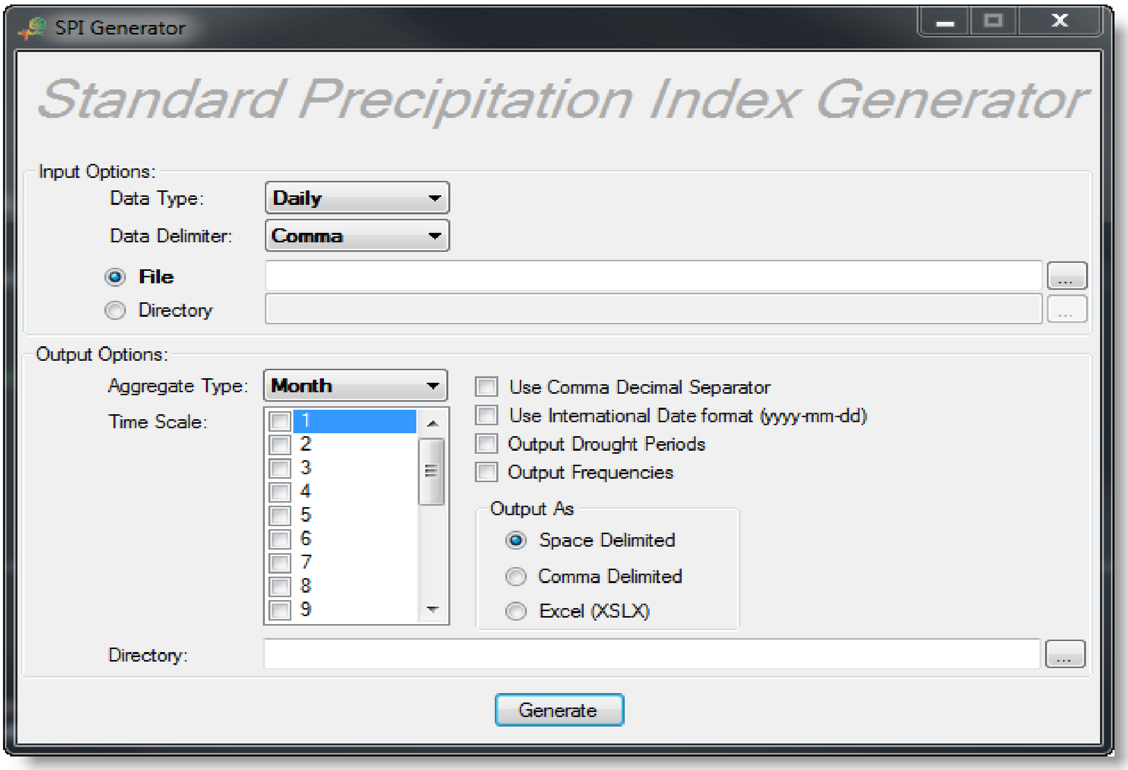


Figure C-73 SPI Generator user interphase

- The application will output data to a space-delimited, comma-separated, or Excel file. The file format is the same using either the Windows GUI or command line.
- Select Data delimiter based on your input file (Comma or Space). (Figure C-74). Check Input File if its “Comma” or “Space” separated).

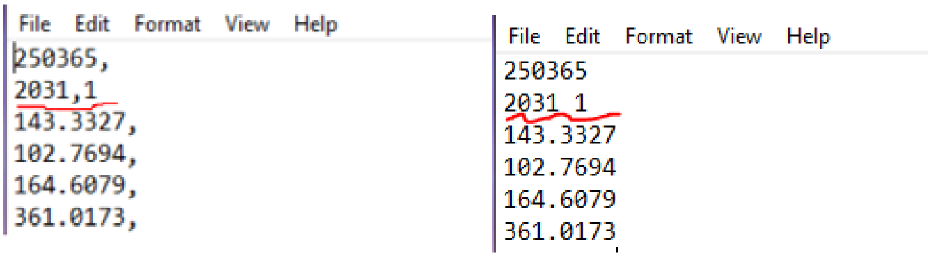


Figure C-74 Format of input file

- Select Data Type Monthly
- Select Data delimiter (Comma).
- Select File Sample file for Rainfall data. (Example dataset is available for area of interest (West Bengal) Observed Climate (1970 to 2019) (Folder Location: ‘Dataset/Rainfall/His/DistrictName’).
- Select Time Scale: 6 Month (For SPI 6)
- Create output Directory. (For example dataset: select file Observed Climate (1970 to 2019) (Folder Location: ‘Dataset\SPI_Result\WB_SPI_Output_His’(Figure C-75).

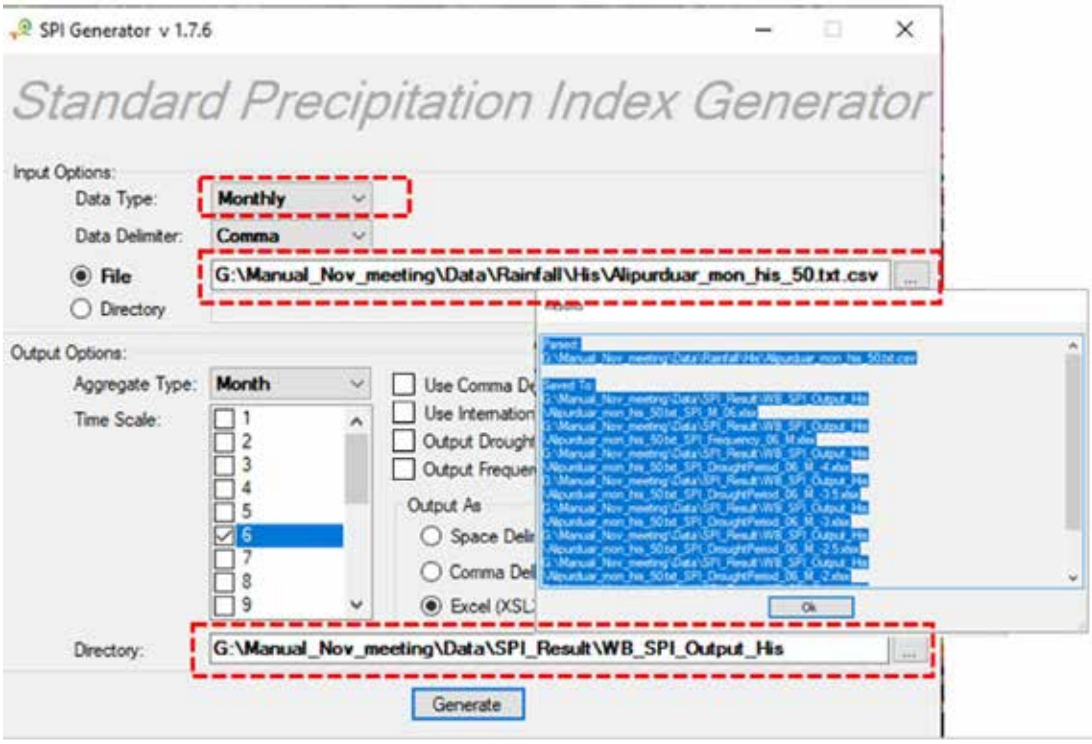


Figure C-75 Example input for SPI generator

- The calculated SPI 6 values are compared with SPI values corresponding to moderate, severe, and extreme dry/wet events (refer to Table C-2 below).

Table C-2 SPI index classification

SPI VALUE	CLASSIFICATION
≥ 2.0	Extremely wet
1.5 to 1.99	Very wet
1.0 to 1.49	Moderately wet
-0.99 to 0.99	Near Normal
-1.0 to -1.49	Moderately Dry
-1.5 to -1.99	Severely Dry
-2 and less	Extremely Dry

- The probability of occurrence of dry/wet events could then be expressed as the number of severe + extreme events (as per SPI value), divided by the total number of events (595) **[SPI 6 is calculated on a monthly basis for a moving window of 6 months, that's why we have -99 values for first 5 months. Delete these first five null values]**.[5]
- **The output of this assessment is in percentage, representing the probability for a hazard to occur.** The probability of occurrence of dry or wet events could be expressed as the number of events of a given type and the severity of hazard.

[5] **Important note:** Delete the first five "-99" values and then calculate spi6 for dry and wet events.

- Sample Results for observed Climate for 'Alipurduar' is shown in excel file Folder: 'Dataset\SPI_probability_of_occurrence\Alipurduar_mon_his_50.txt_SPI_M_06.xlsx'. (Included with formula for calculation) (Figure C-76).

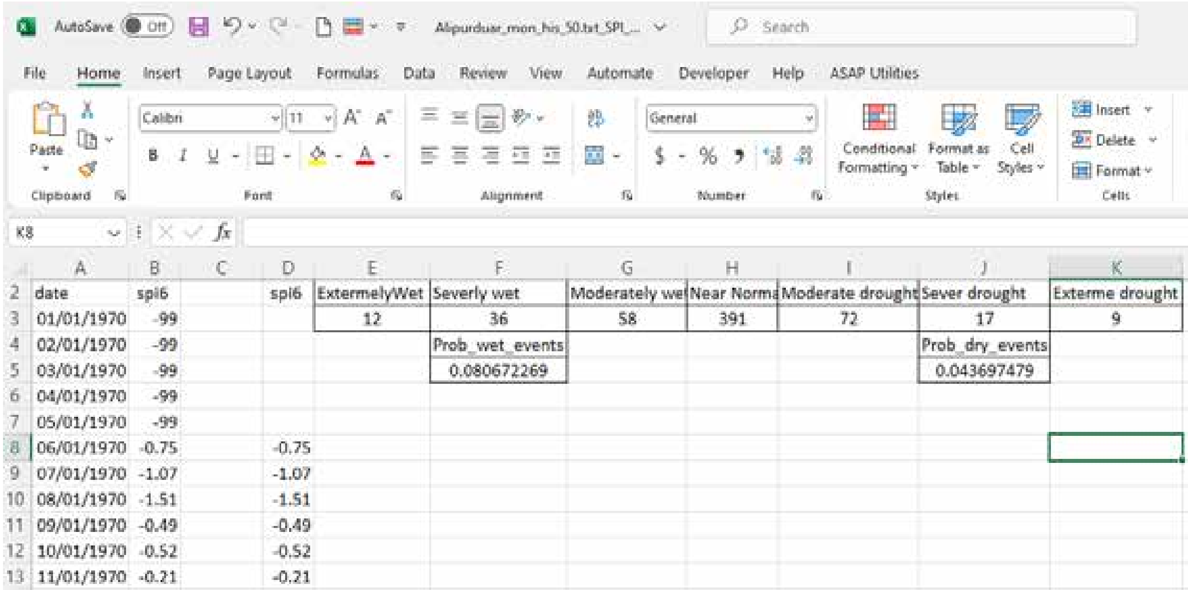


Figure C-76 Sample results for probability of occurrence of dry/wet events

- Similarly, summary of probability of occurrence of dry or wet events for all the district of West Bengal in Observed Climate ('SPI_WB_HIS'), sample calculated, and result is stored in Location: 'Dataset\SPI_probability_of_occurrence\'.
- *Preparing the SPI layer:* Open GIS platform, connect dataset folder, and add the SOI shapefile for the concerned AOI (West Bengal state to the interface '\Dataset\Shapefile\WB_district.shp').
- To add data, click → Add data Box will appear → click to connect dataset folder → Select location to '\Dataset' → Click **OK** (Figure C-77).

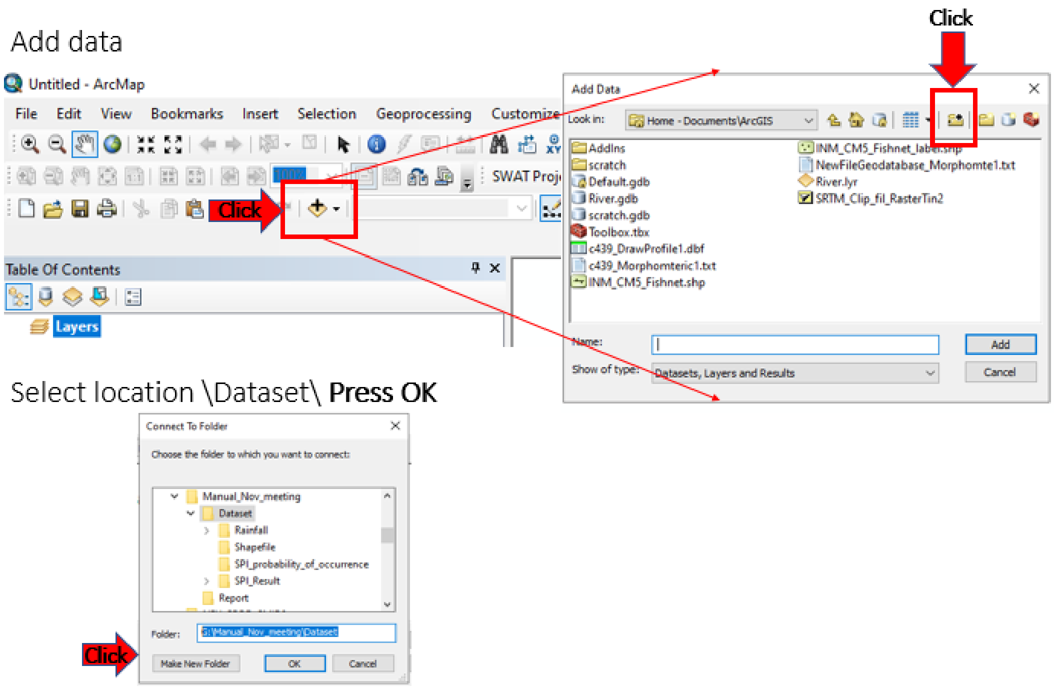


Figure C-77 Connect dataset folder

- To Add the SOI District shapefile → Double click on **Shapefile** folder → click on File AOI district shapefile (the study state **WB_district** shapefile in this case) → Click **ADD** (Figure C-78).

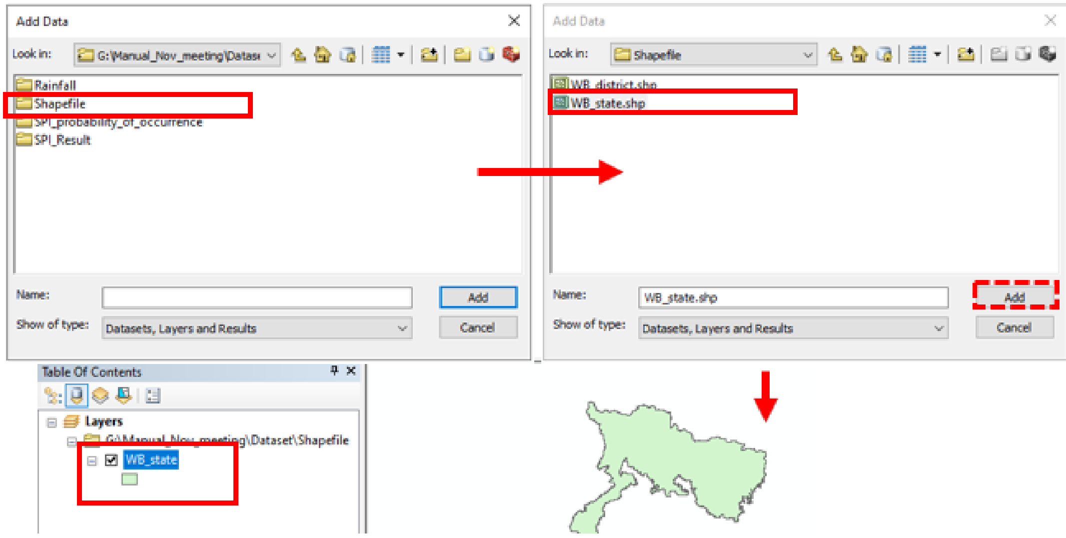


Figure C-78 Add the AOI / District shapefile

- *Prepare File to connect SPI value of District with AOI (WB_district) district shapefile:*
In the 'Table of Contents' layer → Right Click on shapefile → Click on Open Attribute Table →Use FID and District name to relate with Excel file where SPI values (Figure C-79) → probability of occurrence of dry or wet events for all the district of AOI (West Bengal) in Observed Climate ('SPI_WB_HIS') result is stored in Location: 'Dataset\SPI_probability_of_occurrence\'.

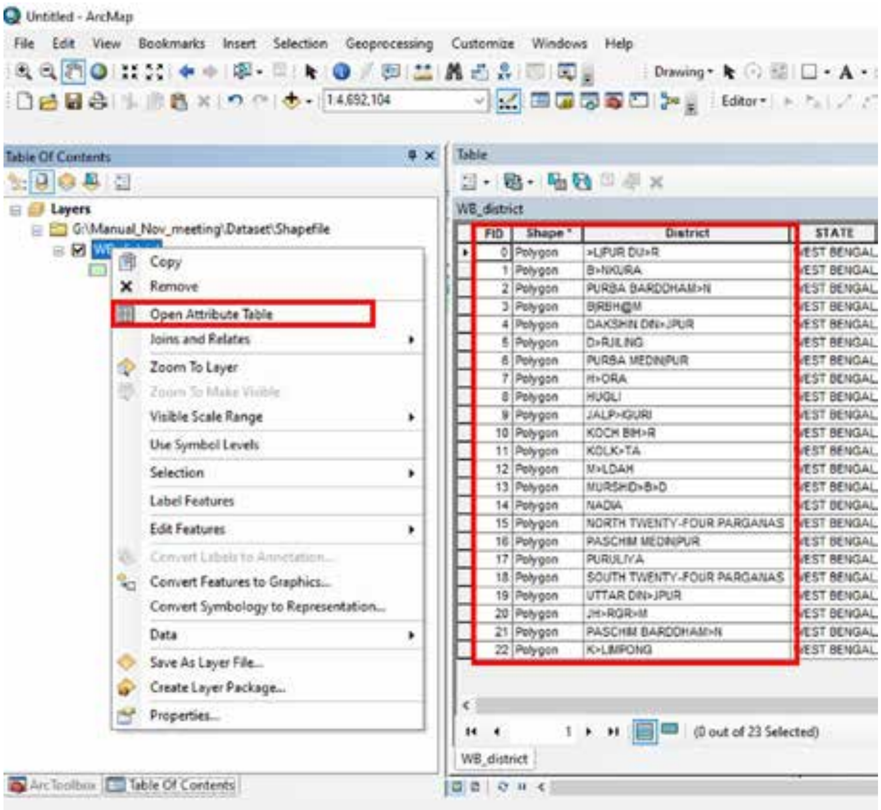


Figure C-79 Get FID and district name from attribute table

- As shown in Figure C-80, select All Row of Table → Right Click → Click on Copy Selection → Open Excel Sheet

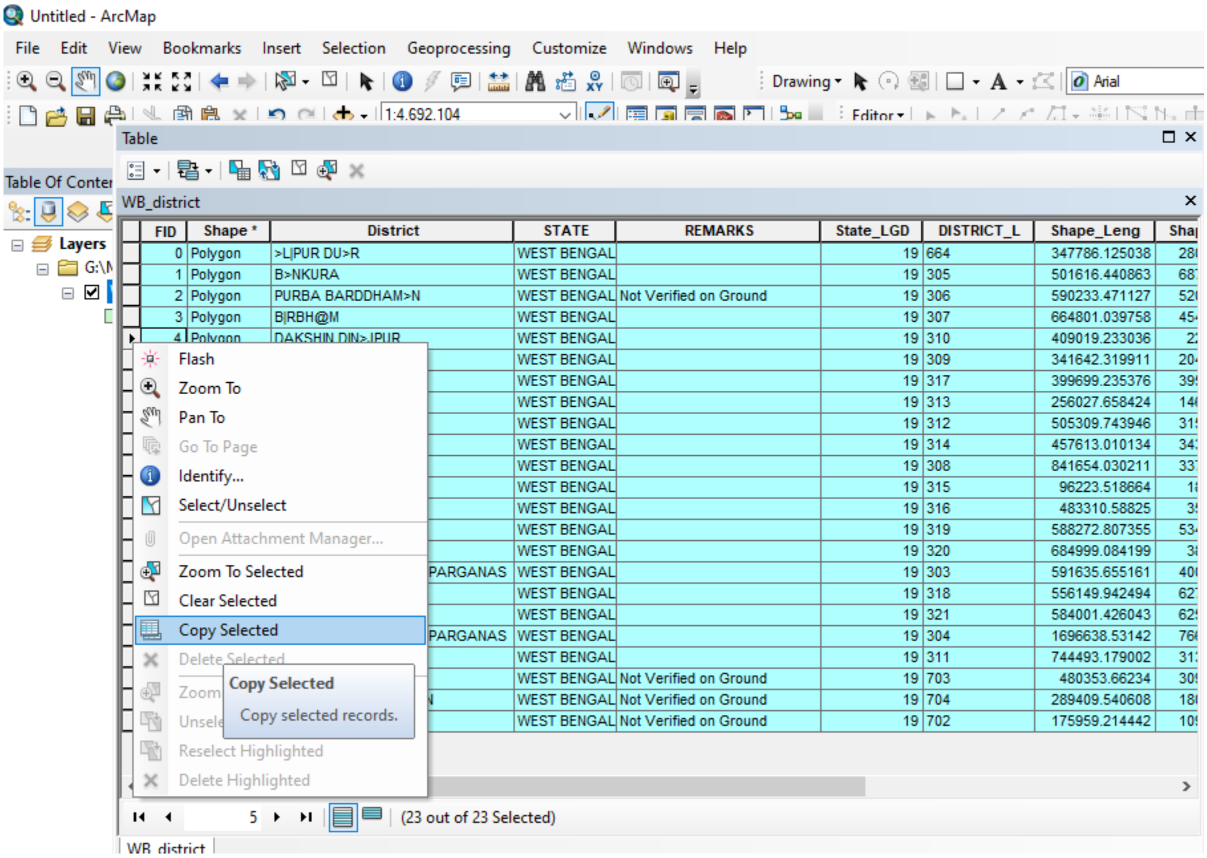
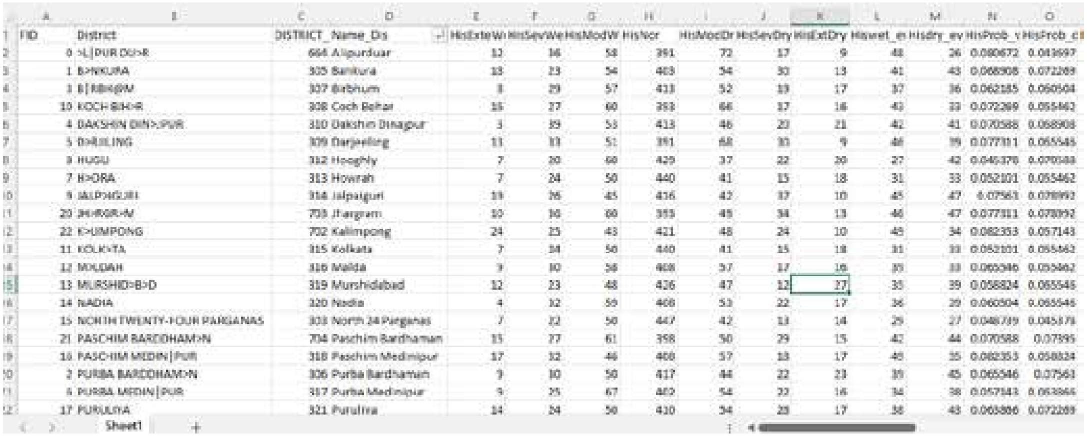


Figure C-80 Extract detail from attribute table

- *Prepare Excel Sheet (Figure C-81):* Paste the copied attribute table to new excel sheet. → And also Paste the probability of occurrence of dry or wet events for all the district of AOI (the district of West Bengal) in Observed Climate ('SPI_WB_HIS') → Sample file is located in: 'Dataset\ SPI_probability_of_occurrence\SPI_Joint_His.csv'.



FID	District	DISTRICT_Name_Dis	HisExteWe	HisSevWe	HisModW	HisNor	HisModDr	HisSevDry	HisExtDry	Hiswet_e	Hisdry_ev	HisProb_	HisProb_d
0	>L|PUR DU>R	664 Alipurduar	12	16	58	391	72	17	9	48	26	0.080672	0.043697
1	B>NKURA	305 Bankura	13	23	54	403	54	30	13	41	43	0.068908	0.072269
3	B|RBH@M	307 Birbhum	8	29	57	413	52	19	17	37	36	0.062185	0.060504
10	KOCH BIH>R	308 Coch Behar	16	27	60	393	66	17	16	43	33	0.072269	0.055462
4	DAKSHIN DIN>JPUR	310 Dakshin Dinajpur	3	39	53	413	46	20	21	42	41	0.070588	0.068908
5	D>RJILING	309 Darjeeling	11	33	51	391	68	30	9	44	39	0.077311	0.065546
8	HUGLI	312 Hooghly	7	20	60	429	37	22	20	27	42	0.046378	0.070588
7	H>ORA	313 Howrah	7	24	50	440	41	15	18	31	33	0.052101	0.055462
9	JALP>IGURI	314 Jalpaiguri	19	26	45	416	42	17	10	45	47	0.07563	0.078992
20	JH>RGR>M	703 Jhargram	10	36	60	393	45	34	13	46	47	0.077311	0.078992
22	K>LIMPONG	702 Kalimpong	24	25	43	421	48	24	10	49	34	0.082353	0.057143
11	KOLK>TA	315 Kolkata	7	24	50	440	41	15	18	31	33	0.052101	0.055462
12	MOLDAH	316 Malda	9	30	58	408	57	17	16	39	33	0.065546	0.055462
13	MURSHID>B>D	319 Murshidabad	12	23	48	426	47	12	27	35	39	0.058824	0.065546
14	NADIA	320 Nadia	4	32	59	408	53	22	17	36	39	0.060504	0.065546
15	NORTH TWENTY-FOUR PARGANAS	303 North 24 Parganas	7	22	50	447	42	13	14	29	27	0.048739	0.045378
21	PASCHIM BARDDHAM>N	704 Paschim Bardhaman	15	27	61	398	50	29	15	42	44	0.070588	0.07395
16	PASCHIM MEDIN|PUR	318 Paschim Medinipur	17	32	46	408	57	13	17	49	35	0.082353	0.058824
2	PURBA BARDDHAM>N	306 Purba Bardhaman	9	30	50	417	44	22	23	39	45	0.065546	0.07563
6	PURBA MEDIN|PUR	317 Purba Medinipur	9	25	67	402	54	22	16	34	38	0.057143	0.063866
17	PURULIA	321 Purulia	14	24	50	410	34	23	17	38	43	0.063866	0.072269

Figure C-81 Integration of FID with probability of occurrence of wet event

- To Add data click → Add data Box will appear → click to connect dataset folder →Select location to '\Dataset\shapefile'→ Select file Prepared Excel Sheet in last step ('SPI_Joint_His.csv') → Click **ADD** (Figure C-82).

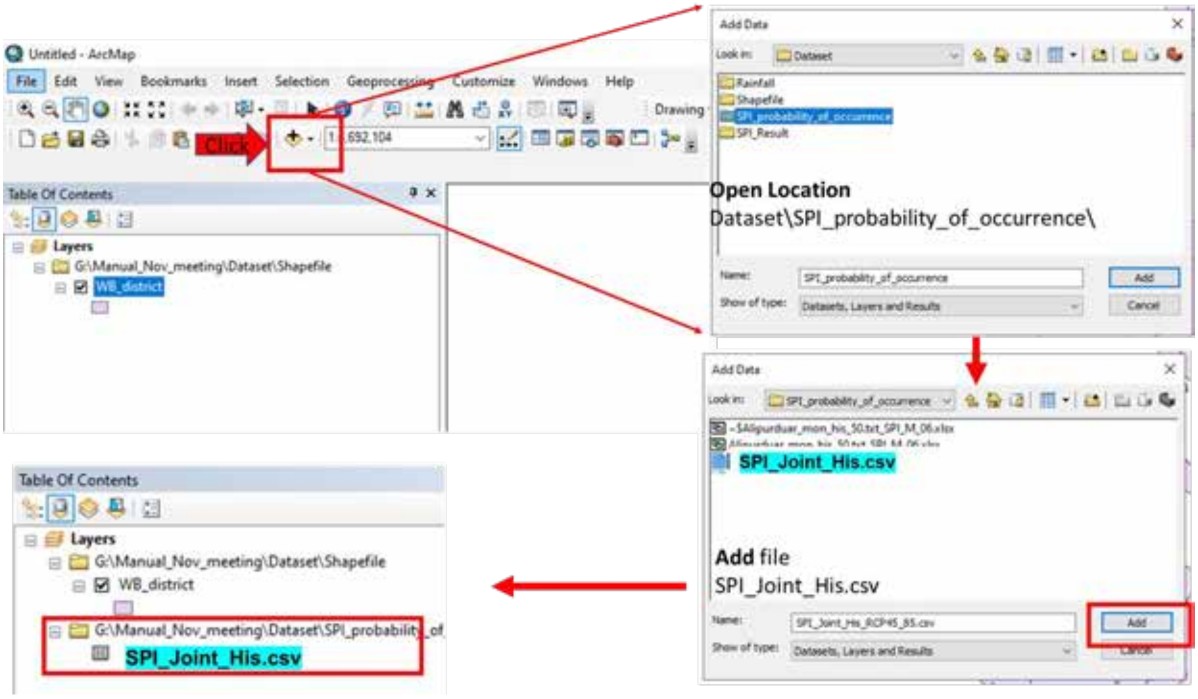


Figure C-82 Add CSV file to GIS

- Go to Table of Contents layer → Right Click on district shapefile of AOI (‘WB_district’) → Click on Join and Relates →Click on **Join** →Join Data Box will pop-up→ 1st Choose the field in this layer that the join will be based on: Select **FID** → 2nd Choose the table to Join to the Layer Select Prepared Excel Sheet (‘SPI_Joint_His.csv’) → 3rd Choose the field in the table to base the Join on: Select **FID** → Click on Validate Join → Click **OK** (Figure C-83).

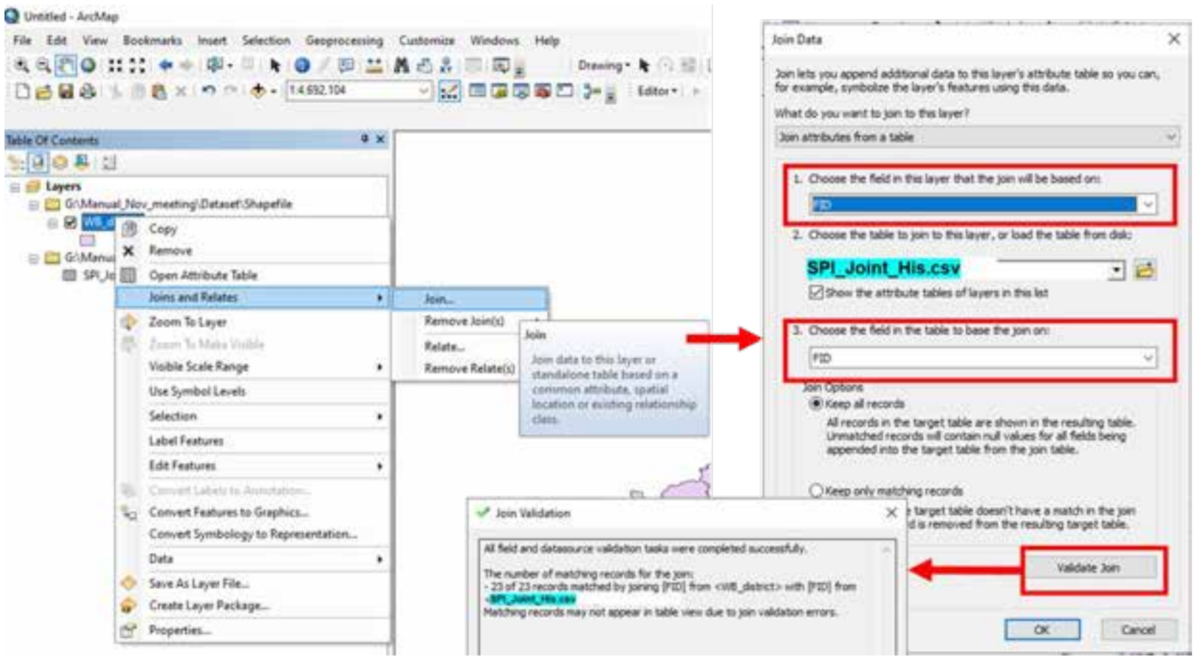


Figure C-83 Joins and relates added CSV to AOI / District shapefile

- Go to Table of Contents layer → Right Click on shapefile → Click on Open Attribute Table → Check all Joint are Joined (Figure C-84).

Table

WB_district

Name_Dls	FID	District	DISTRICT_L	Name_Dls	HisExteWet	HisSevWet	HisModWet	H
Alipurduar	0	>L|PUR DU>R	664	Alipurduar	12	36	58	
Bankura	1	B>NKURA	305	Bankura	18	23	54	
Purba Bardhaman	2	PURBA BARDDHAM>N	306	Purba Bardhaman	9	30	50	
Birbhum	3	B|RBH@M	307	Birbhum	8	29	57	
Dakshin Dinajpur	4	DAKSHIN DIN>JPUR	310	Dakshin Dinajpur	3	39	53	
Darjeeling	5	D>RJILING	309	Darjeeling	13	33	51	
Purba Medinipur	6	PURBA MEDIN|PUR	317	Purba Medinipur	9	25	67	
Howrah	7	H>ORA	313	Howrah	7	24	50	
Hooghly	8	HUGLI	312	Hooghly	7	20	60	
Jalpaiguri	9	JALP>IGURI	314	Jalpaiguri	19	26	45	
Coch Behar	10	KOCH BIH>R	308	Coch Behar	16	27	60	
Kolkata	11	KOLK>TA	315	Kolkata	7	24	50	
Malda	12	M>LDAH	316	Malda	9	30	58	
Murshidabad	13	MURSHID>B>D	319	Murshidabad	12	23	48	
Nadia	14	NADIA	320	Nadia	4	32	59	
North 24 Parganas	15	NORTH TWENTY-FOUR PARGANAS	303	North 24 Parganas	7	22	50	
Paschim Medinipur	16	PASCHIM MEDIN|PUR	318	Paschim Medinipur	17	32	46	
Puruliya	17	PURULIYA	321	Puruliya	14	24	50	
South 24 Parganas	18	SOUTH TWENTY-FOUR PARGANAS	304	South 24 Parganas	5	30	57	
Uttar Dinajpur	19	UTTAR DIN>JPUR	311	Uttar Dinajpur	10	13	61	
Jhargram	20	JH>RGR>M	703	Jhargram	10	36	60	
Paschim Bardhaman	21	PASCHIM BARDDHAM>N	704	Paschim Bardhaman	15	27	61	
Kalimpong	22	K>LIMPONG	702	Kalimpong	24	25	43	

1 (0 out of 23 Selected)

WB_district

Figure C-84 Attribute Details of the Integrated Probability of Occurrence of Wet Events - CSV File and AOI/District Shapefile

- In ArcToolbox, go to Conversion Tools → Raster → Polygon to Raster → Select district shapefile of AOI with connected excel sheet having probability of wet/ dry event ('WB_district') in Input Features → Select the column have the probability of wet event for observed climate ('SPI_Joint_His_HisProb_wet') in 'Value Field' → Name the Output Raster Dataset (e.g., 'Dataset\Raster\SPI_HIS.tif') and save in relevant folder → In 'Cellsize', select the DEM file of the AOI ('Dataset\Raster\DEM.tif) '→ click '**Environment Settings**' → select the DEM file of the AOI ('Dataset\Raster\DEM.tif ') in 'Mask' → click **OK** → click **OK** (Figure C-85).

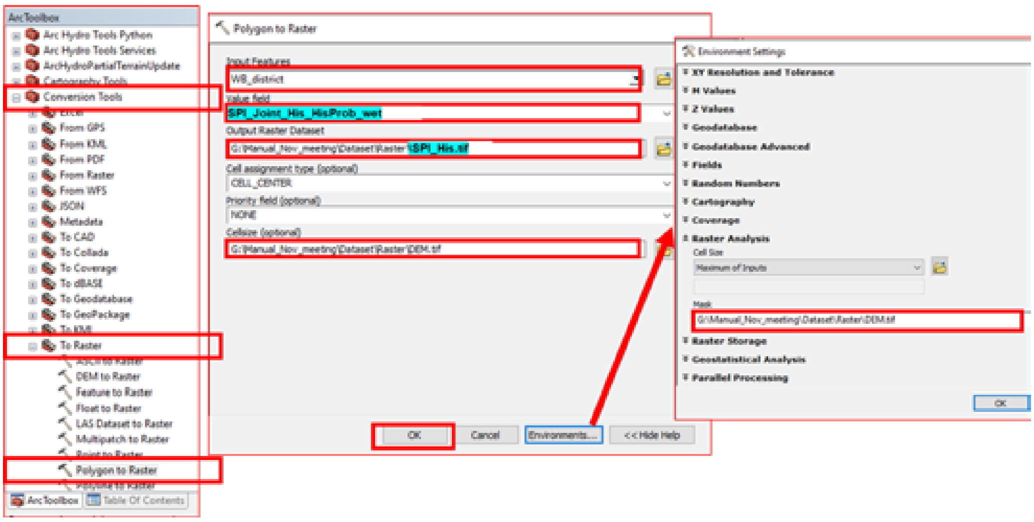


Figure C-85 Convert probability of occurrence of wet events from shapefile to raster

- *Reclassify*: Probability of occurrence of severe and extreme wet event the higher value will be more susceptible to flood. Therefore, lowest value to highest value will be reclassify in the classes have rated from 1 to 5. As shown in Figure C-86, in ArcToolbox, go to ‘Spatial Analyst Tools’ → Select the Reclass → Select the Reclassify → Window will pop-up, select the SPI layer for observed obtain in last step (‘Dataset\Raster\SPI_HIS.tif’) in ‘Input raster’ → Click **Classify** → Classification Window will pop-up, Select ‘Equal Interval’ in ‘Classification Method’ → Select ‘5’ in ‘Classes → click **OK** → In ‘Output Raster’ select relevant folder and assign file name (‘Dataset\Raster\SPI_HIS_reclassify.tif’)→ Click  in ‘change missing values to No Data’→ click **OK**. The output raster would appear as displayed in Figure C-87.

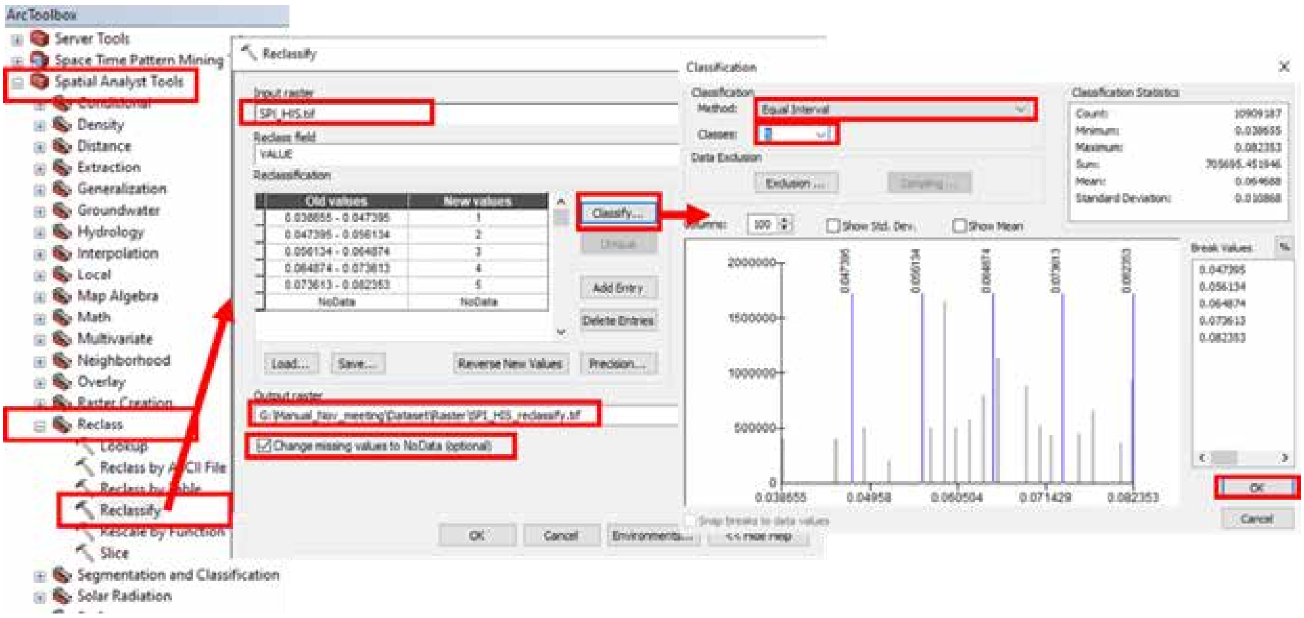


Figure C-86 Reclassified SPI layer

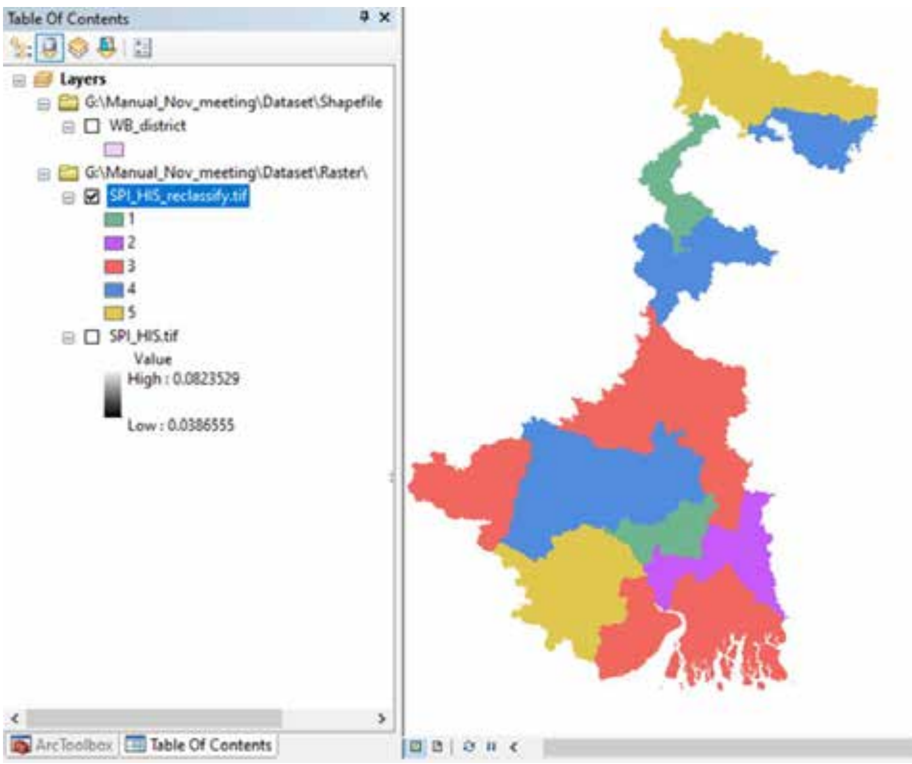


Figure C-87 Output result of reclassified SPI layer

Multi-criteria Decision Making Using the Analytic Hierarchy Process

MCDA-AHP based weightage assignment of flood conditioning factors: Within the various MCDA techniques present, the Analytical Hierarchy Process (AHP) is the most frequent and widely employed approach and has increasingly been used in determining flood risks and flood susceptibility mapping. Developed by T. L. Saaty in 1971-1975 (Saaty, 1987), the AHP is a systematic method that takes into account the subjective attributes of a complex problem involving multiple factors and decomposes it into a 'simple and subjective evaluated sub-problem hierarchy' (Gupta & Dixit, 2022; Lin et al., 2020). It is effective because it can address conflicting data and incorporate human/expert judgement. The AHP process includes selecting factors, organizing them hierarchically, determining their significance, combining priorities, and ensuring consistency. Saaty's scale of 1 to 9 (Saaty, 1987; Saaty, 2008) is used to assign scores or ranks to each FCF in a pair-wise comparison matrix based on their relative influences on flood and relative importance as shown in Tables 2 and 3, respectively.

- The AHP calculations, including the construction of the pair-wise comparison matrix and the derivation of the weights and consistency, were conducted using a web-based AHP solution tool created by Goepel (2018, https://bpmsg.com/ahp/).
- Open AHP calculations using Link: https://bpmsg.com/ahp/. (Figure C-88).

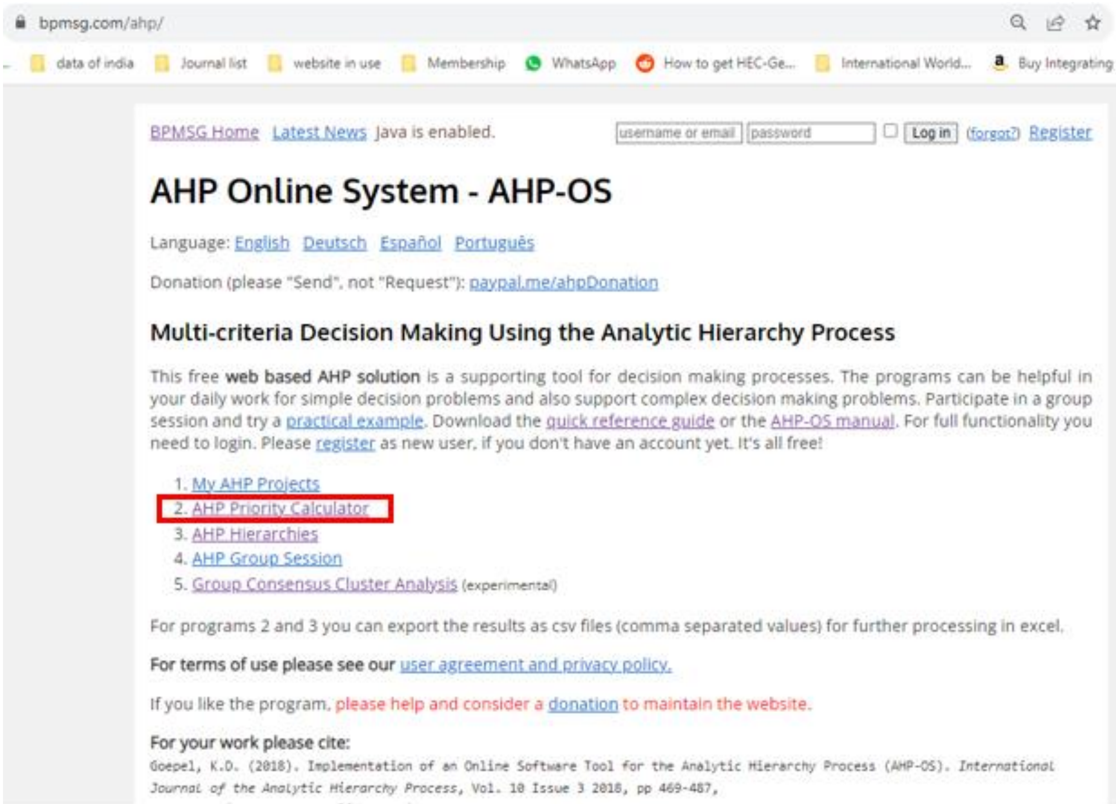


Figure C-88 AHP calculations portal

- Click On 'AHP Priority Calculator' using Link: https://bpmsg.com/ahp/ as shown in the highlighted box in Figure C-88.
- 'Input number and names' of layer insert number of layers '9' click GO as shown in Figure C-89.

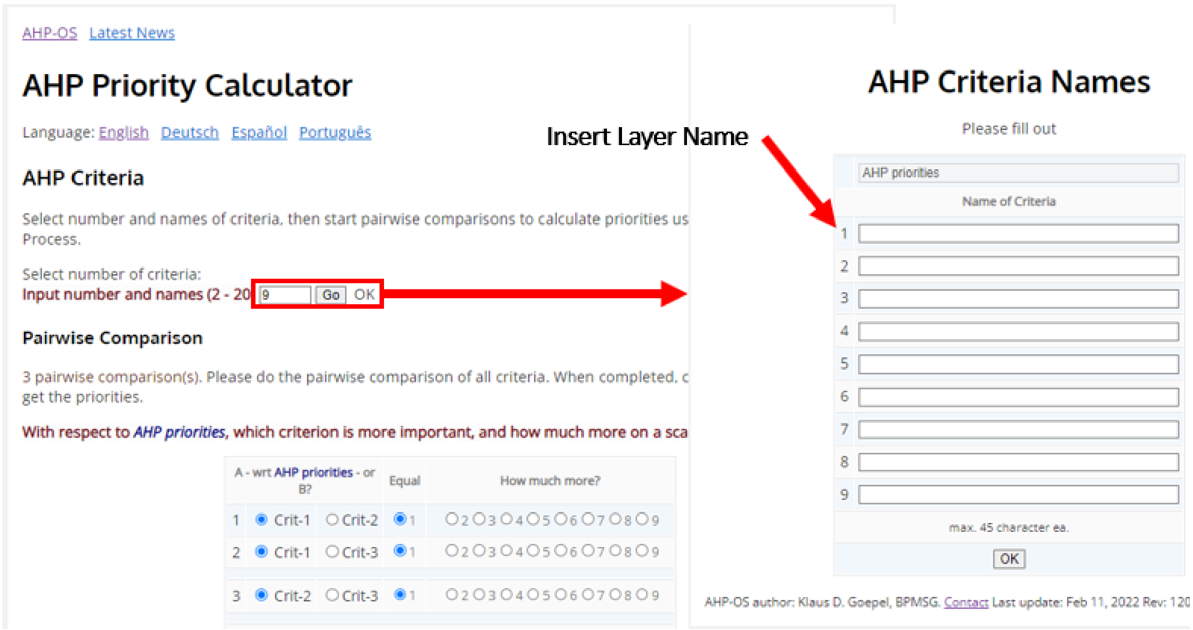


Figure C-89 Input details for flood layer

- Window will appear 'AHP Criteria Names' insert name of layer (Insert all name of layer which we have prepared) → Click OK as displayed in Figure C-89.

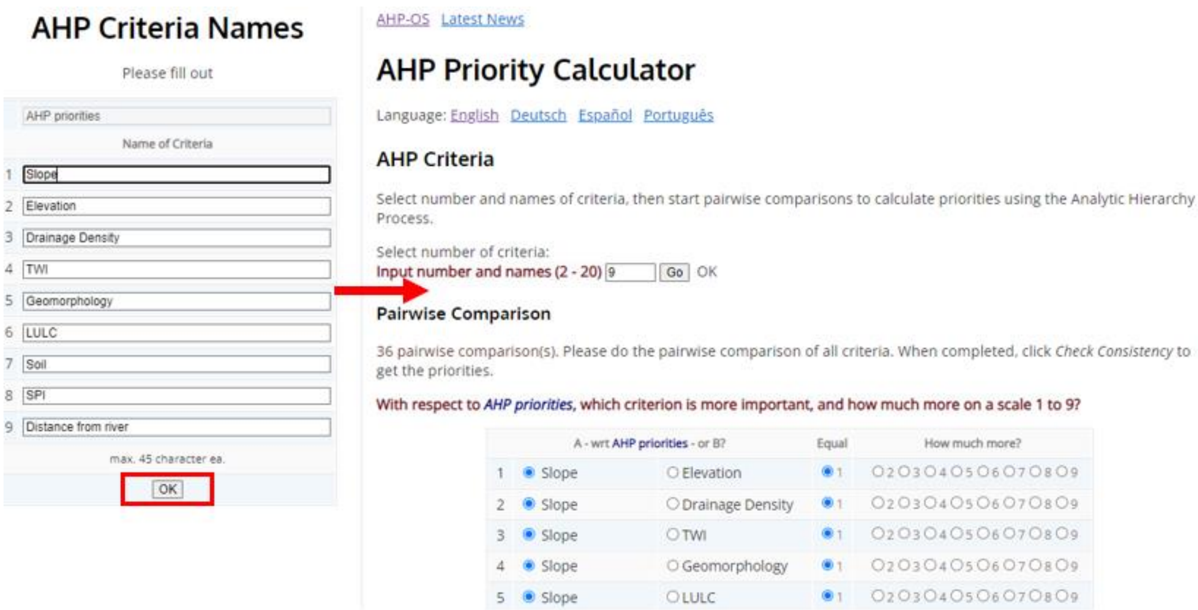


Figure C-90 AHP Priority Calculator

- Window will appear having 'AHP Priority Calculator' as displayed in Figure C-90 insert priorities of layer based on Saaty (1980) scale where pairwise comparison of each layer and its importance is defined based on Saaty scale.

- A pairwise comparison matrix of the indicators is created according to relative importance on a qualitative scale of 1 to 9 as shown in Table C-3.

Table C-3: The relative importance of each criterion based in Saaty (1980)

Scales	Numerical rating	Reciprocal
Equally importance	1	1
Equally to moderately importance	2	1/2
Moderately importance	3	1/3
Moderately to strongly importance	4	1/4
Strongly importance	5	1/5
Strongly to very strongly importance	6	1/6
Very strongly importance	7	1/7
Very strongly to extremely importance	8	1/8
Extremely importance	9	1/9

- Start pairwise comparisons (Figure C-91) → Select the layer which is more important → For example between slope and TWI, TWI is very strong important than select '7', Slope and Distance to river if you feel they are equal important than select '1'. → Complete all pairwise comparison for all 36 layers→ click calculate.

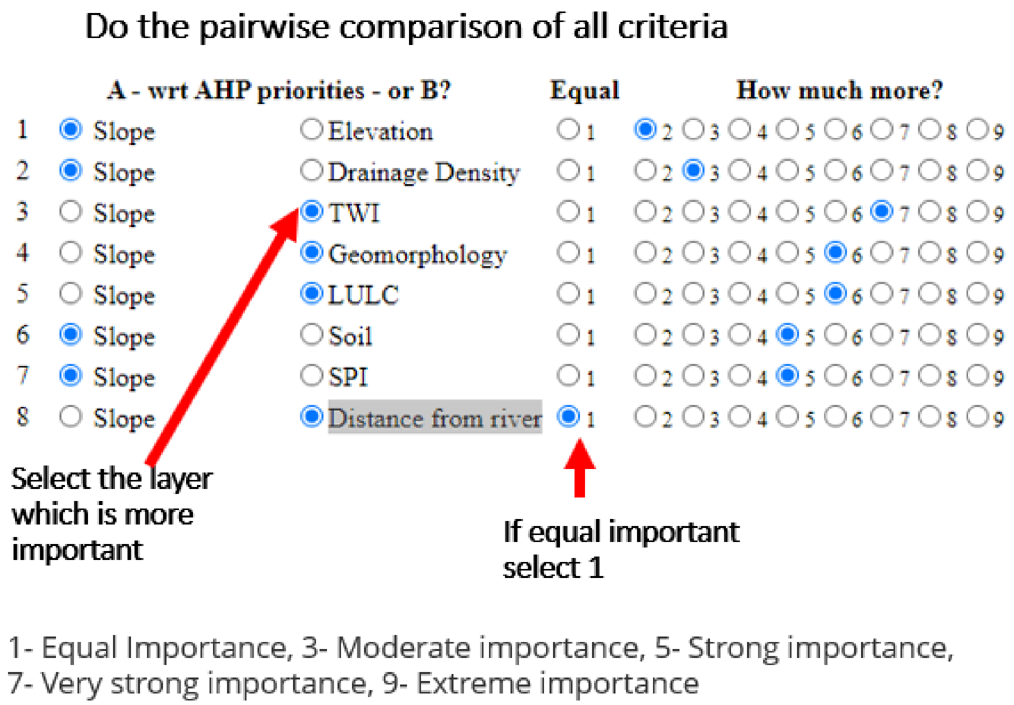


Figure C-91 Pairwise comparisons of each layer and its importance

- Click Check Consistency to get the priorities. Acceptable results are achieved if the computed consistency ratio (CR) is below 10%, as visible in the highlighted boxes in Figure C-92.

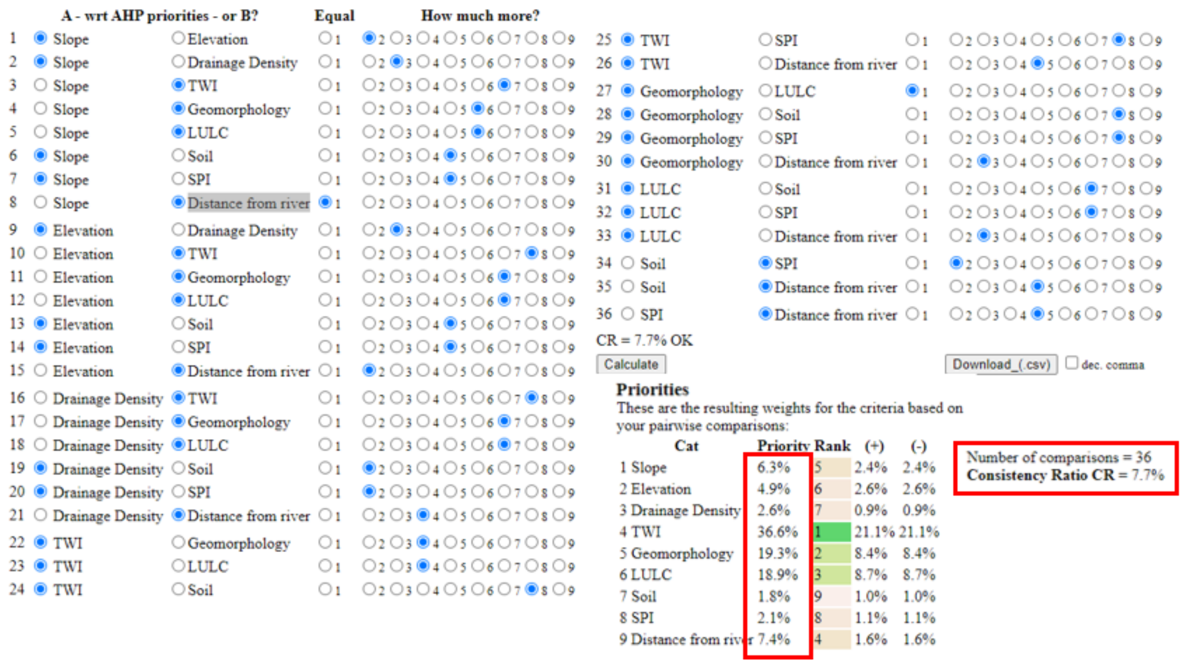


Figure C-92 Example of AHP calculation and its results

- Once the AHP based priority of each factor are obtained, the reclassified and weighted thematic layers are overlaid and combined using the 'Weighted Overlay".
- *Preparing the Weighted Overlay:* Open GIS platform, connect dataset folder, and add the reclassify layer for the AOI prepared in step 'preparing the thematic layer' (West Bengal state to the interface '\Dataset\ Classified Results \').
- To Add data, click → Add data Box will appear → click to connect dataset folder →Select location to '\Dataset\'→ Click **OK (**Figure C-93**)**.

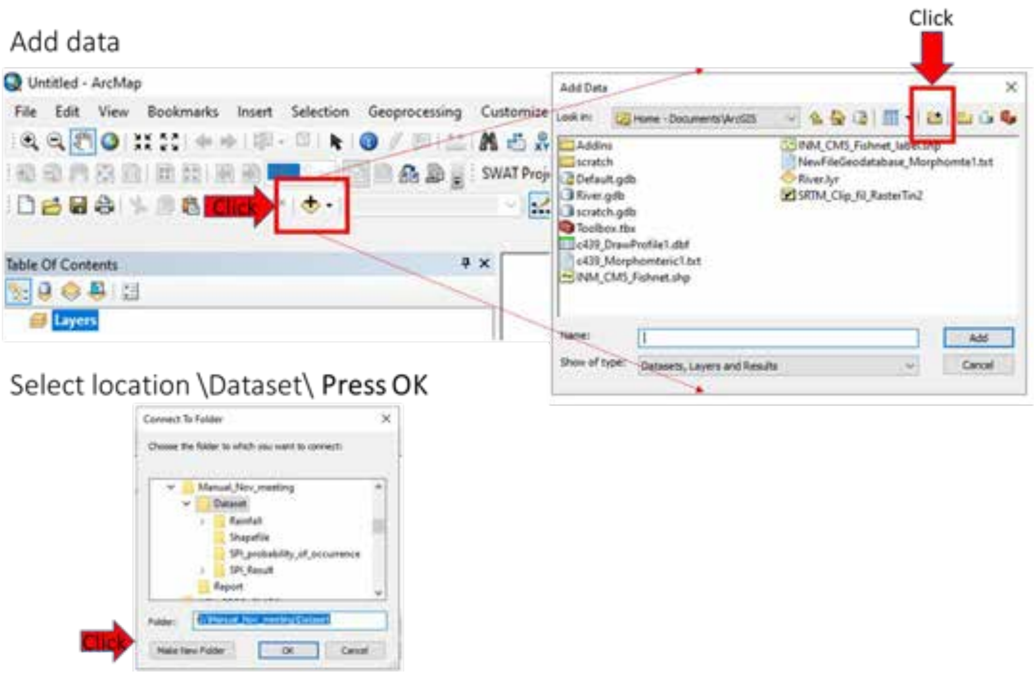


Figure C-93 Connect dataset folder

- To Add the Reclassify prepared thematic layer' → Double click on **Classified Results** folder → Select all layers and Click **ADD** (Figure C-94**).**

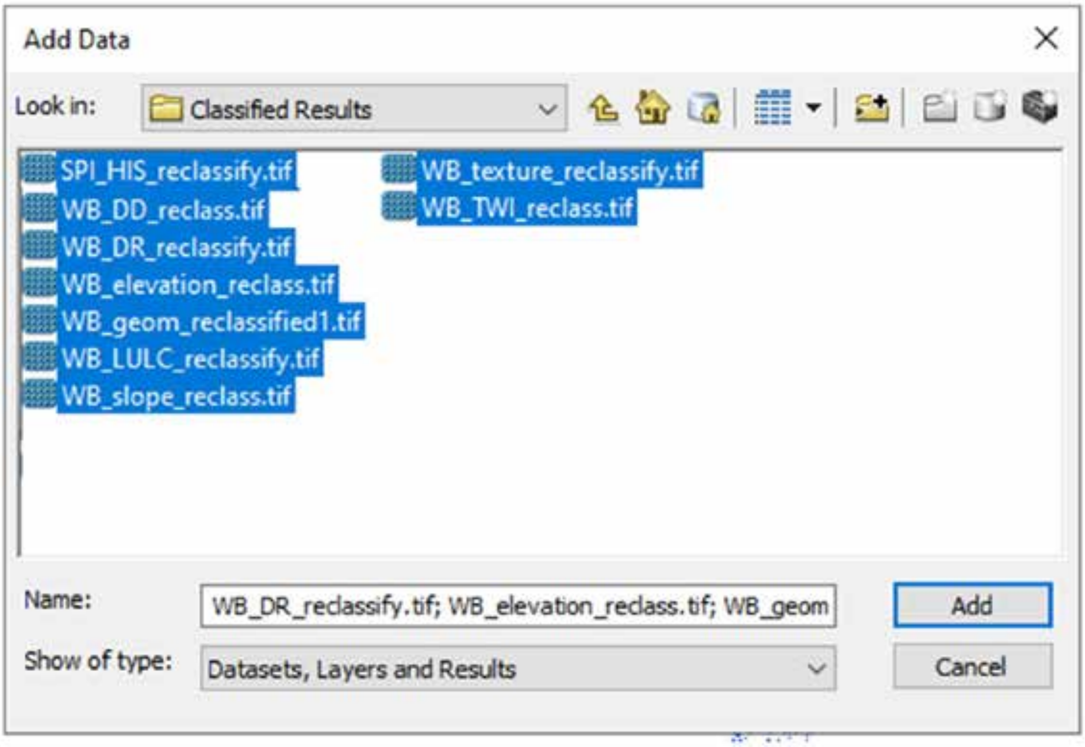


Figure C-94 Adding the reclassified flood layer to GIS

- *Weighted Overlay:* In ArcToolbox, go to 'Spatial Analysis Tools' → Select the 'Overlay' → Select the 'Weighted Overlay' tool → In the 'Weighted Overlay' window, click + to ADD layers (Figure C-95).

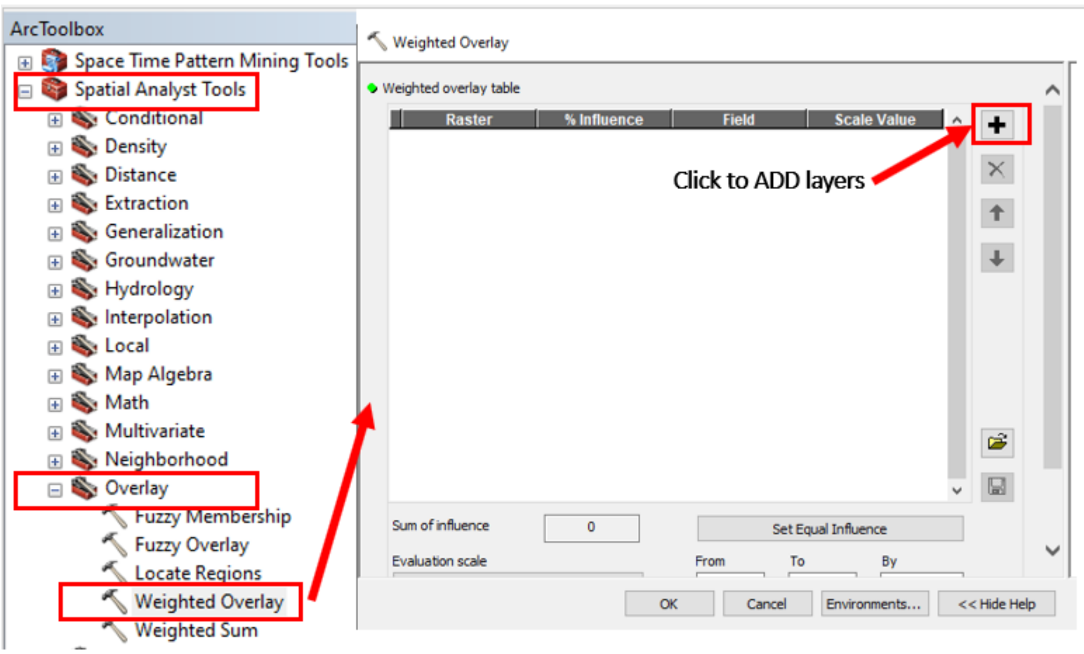


Figure C-95 Navigate to the weighted overlay tool and add layers

- ‘Add Weighted Overlay Layers’ window will pop-up, select the layers one by one in ‘Input raster’ → click **OK** → (Repeat and add all the layers by again clicking on ADD layers button) (Figure C-96).

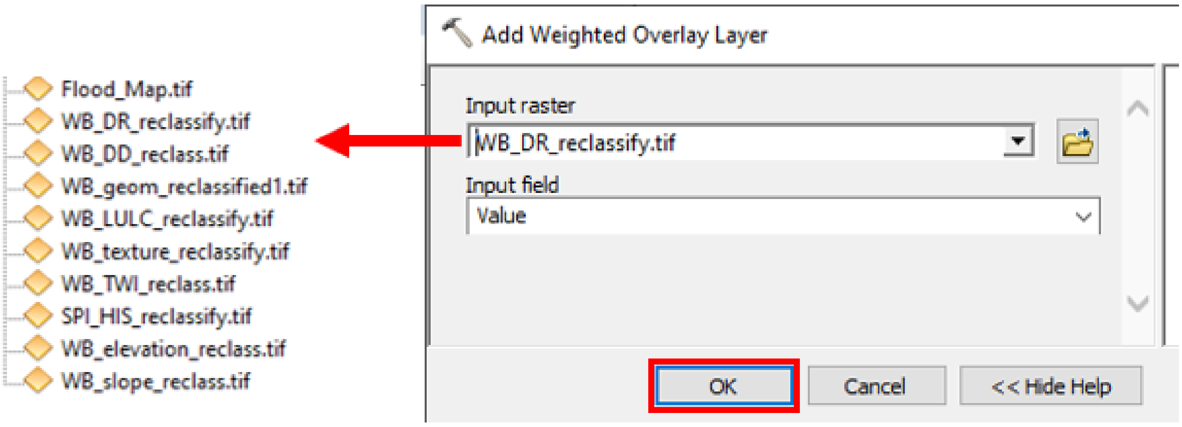


Figure C-96 Add weighted overlay layer to weighted overlay tool

- Once all the layers are added in the Weighted Overlay window insert the weight obtained by AHP (Figure C-97).

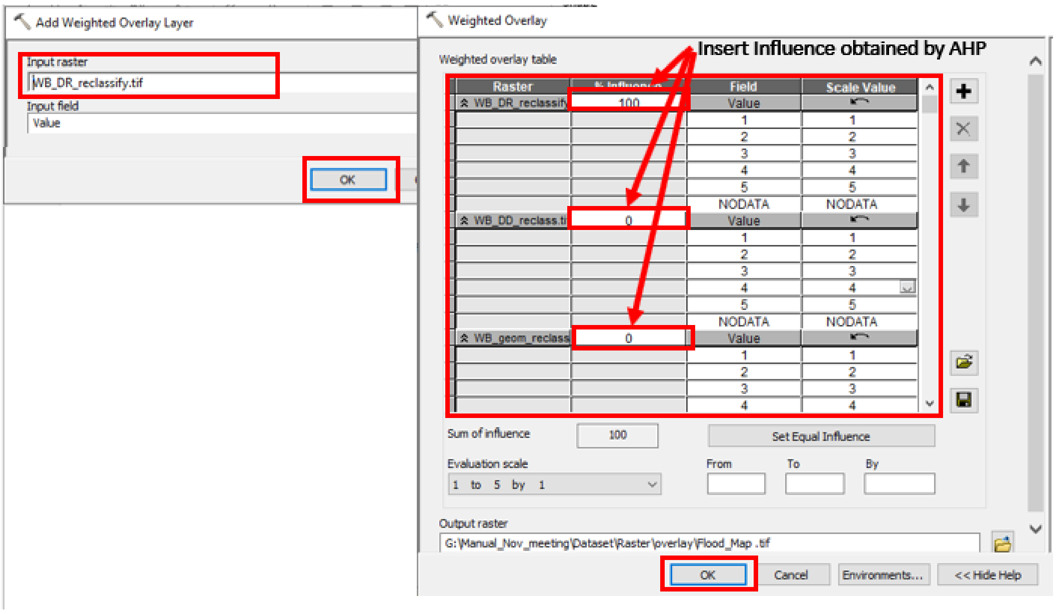


Figure C-97 Inserting weights obtained from AHP calculator for weighted overlay

- Select ‘Evaluation scale’ to ‘1 to 5 by 1’ → check all ‘Scale Value’ it should be 1 to 5 if not change it to 1 to 5 (Figure C-98) → In ‘Output Raster’ select relevant folder and assign file name (‘Dataset\Raster \Flood_map.tif‘) → click **OK (**Figure C-98**).**

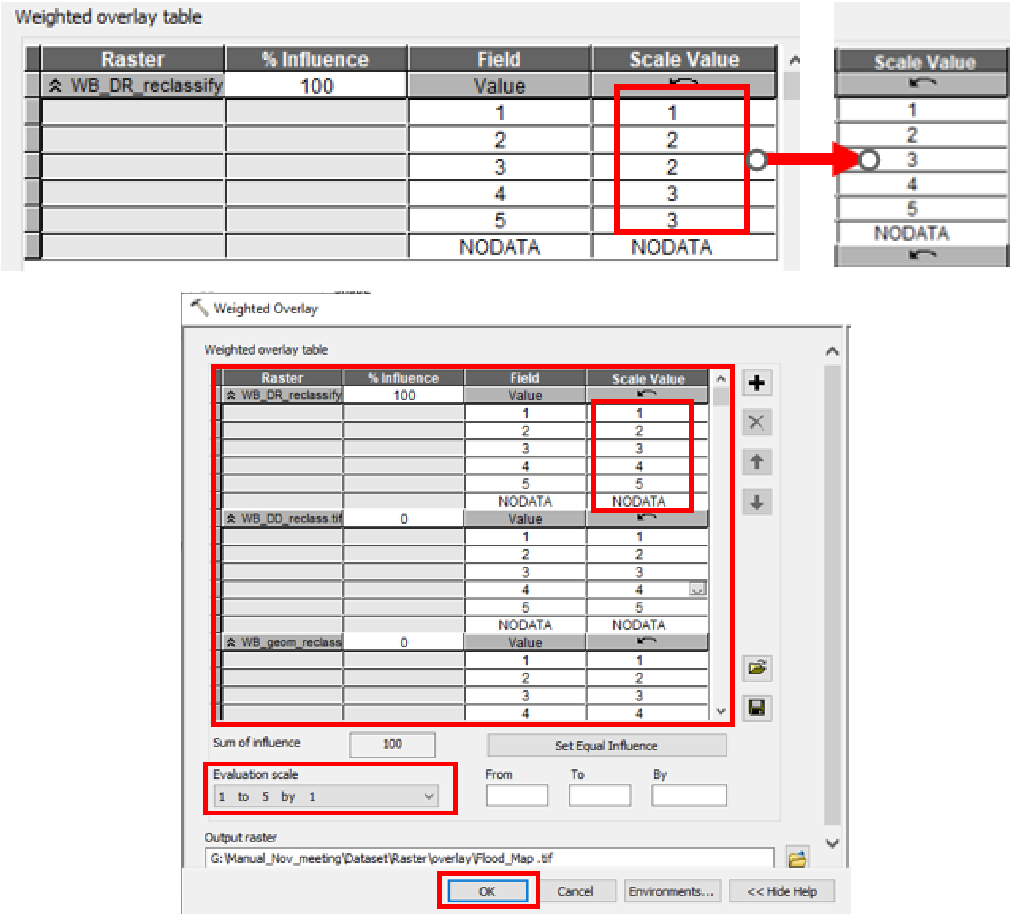


Figure C-98 Insert evaluation scale for weighted overlay

- *Changing the colour scheme of Flood Map layer:* Right click on 'Flood Map layer' layer in the 'Table of Contents' section → Click on 'Properties → A dialog box of 'Layer Properties' appear → Click on 'Symbology' → In 'Unique values' section, select a desired color palette in 'Color Scheme' → Click OK (Figure C-99).

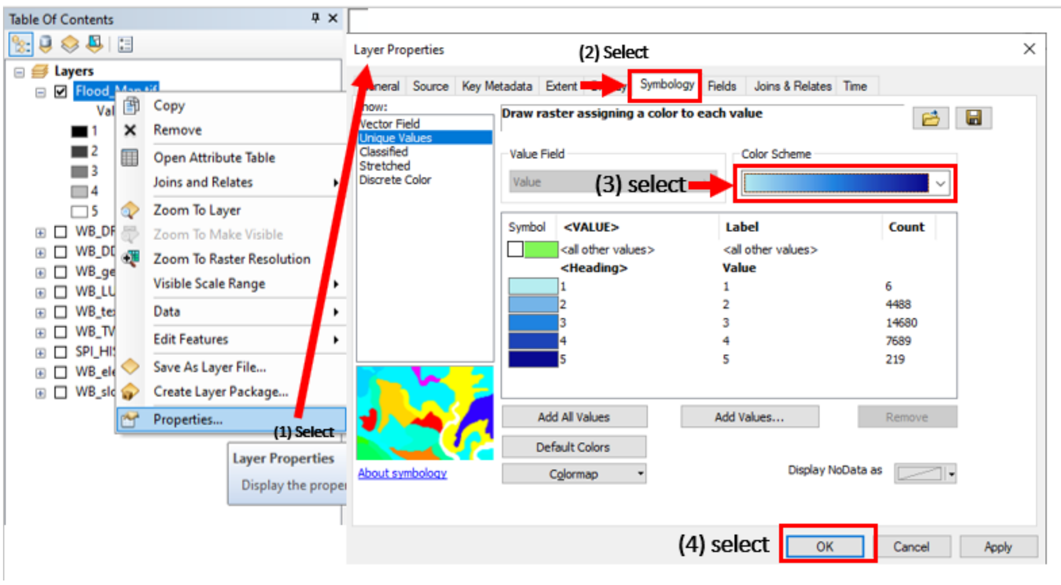


Figure C-99 Assign a colour scheme to the reclassified flood layer

Calculation of Flood Hazard

- *Converting Raster to polygon:* In ArcToolbox, go to Conversion Tools → select 'from Raster' → select 'Raster to Polygon' → Window will pop-up, select the Flood Map layer obtain in last step ('Dataset\Raster\Flood_Map.tif') in 'Input raster' → In 'Output polygon features' select relevant folder and assign file name ('Dataset\Shapefile\FloodMap.shp')→ click **OK**. (Figure C-100)

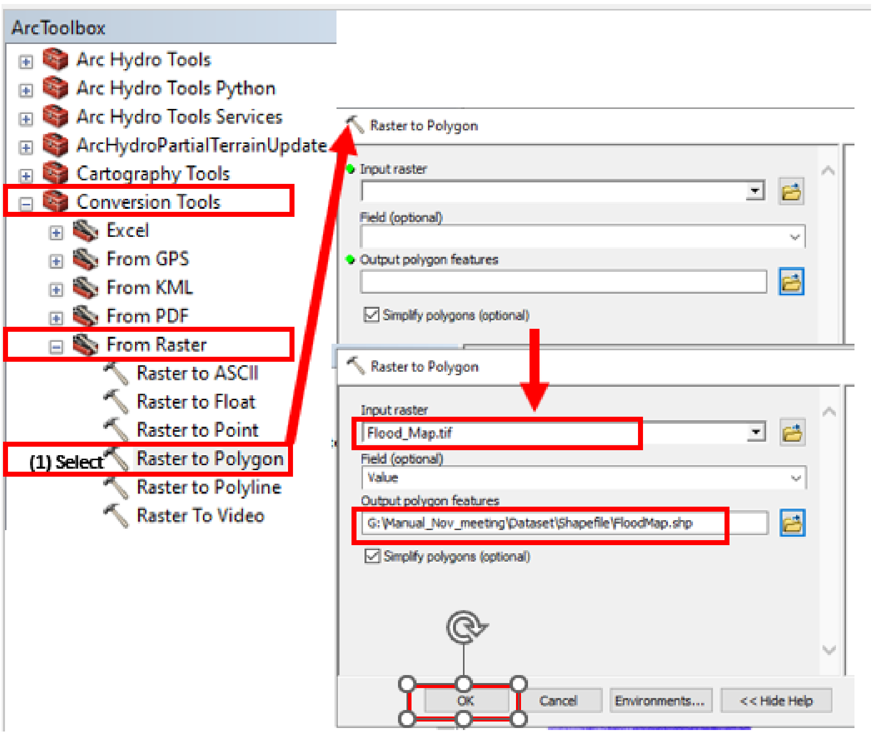


Figure C-100 Convert flood layer to shapefile

- *Dissolve polygon feature of Flood Map:* In Main Menu, go to Geoprocessing → select 'Dissolve' → ''Window will pop-up, select the Flood Map layer obtain in last step ('Dataset\Raster\Flood_Map.tif') in 'Input raster' → In 'Output polygon features' select relevant folder and assign file name ('Dataset\Shapefile\FloodMap_Dissolve.shp')→ click **OK**. (Figure C-101)

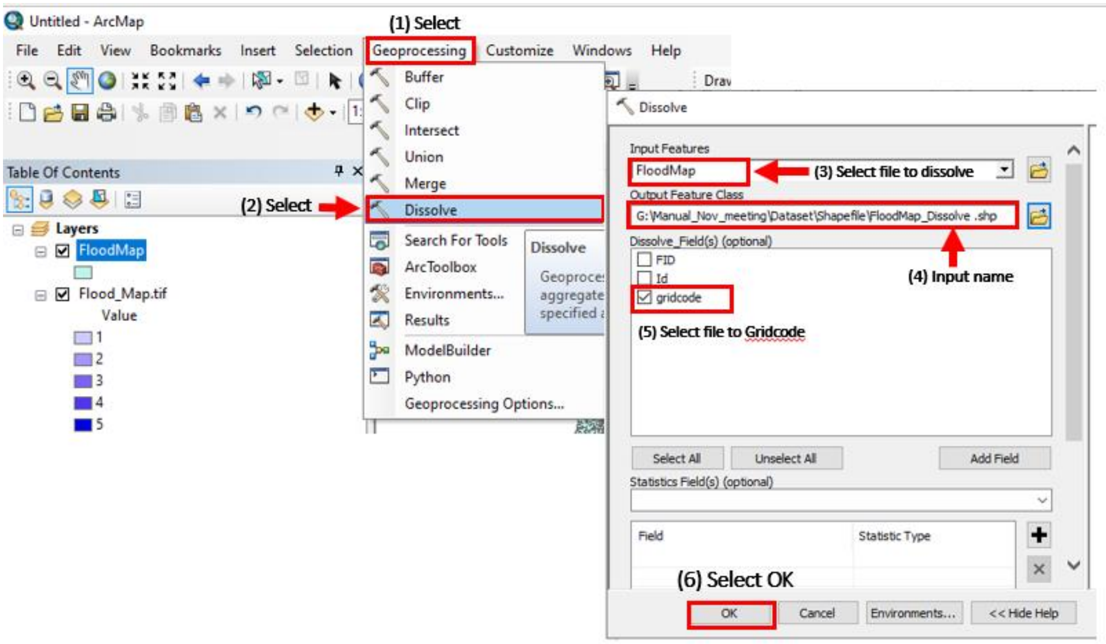


Figure C-101 Dissolve polygon feature in the flood layer

- *Extract High and Very High flood Area:* In Table of contents, Right click on Dissolve Shapefile → select 'Open Attribute Table' → select 'Gridcode' column having value 4 and 5' as shown in Figure C-102 below→ go to Table of contents, Right click on Dissolve Shapefile as shown in Figure C-103→ → select 'Data'→ select 'Export Data'→ Select 'Output features class' select relevant folder and assign file name ('Dataset\Shapefile\High_Class_flood.shp')→ click **save** → click **OK**

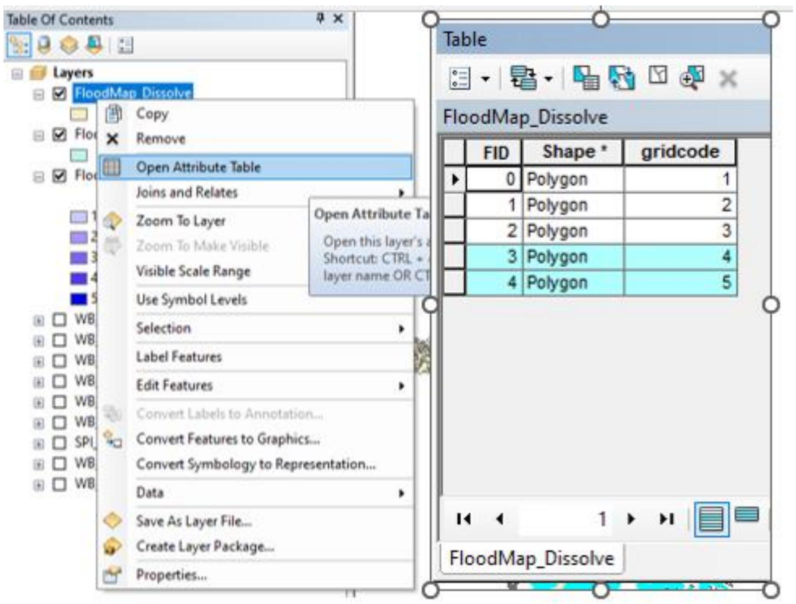


Figure C-102 Select high and very high flood area for extraction

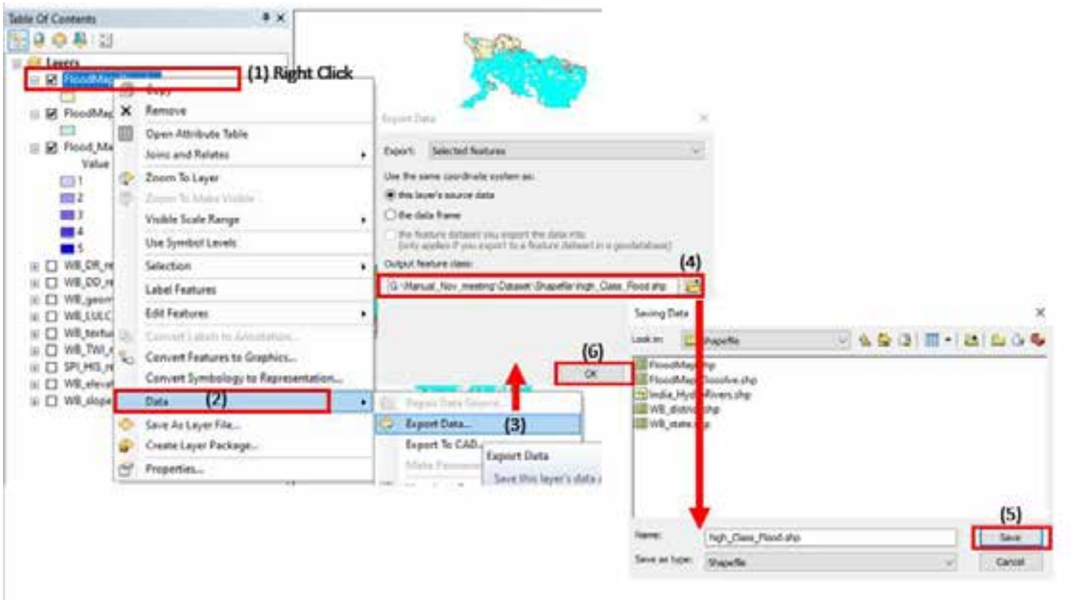


Figure C-103 Export high and very high flood area to new shapefile

- *Add Attribute for high class flood:* In Table of contents, Right click on Dissolve Shapefile → select 'Open Attribute Table' → In 'Table' window select → select 'Add Field'→ 'Add Field' window will pop-up → Insert the name of heading in table in 'Name' (for example Flood) → click **OK** the result 'Table' window will be as Figure → Go to Main Menu, go to Geoprocessing → select 'Dissolve' → ''Window will pop-up, select the High class Flood Map layer obtain in last step ('Dataset\Raster\High_Class_Flood') in 'Input Features' → In 'Output features class' select relevant folder and assign file name ('Dataset\Shapefile\FloodArea.shp')→ select 'Dissolve Field(s)' check mark the added attribute in last step ('Flood') → click **OK**. (Figure C-104)

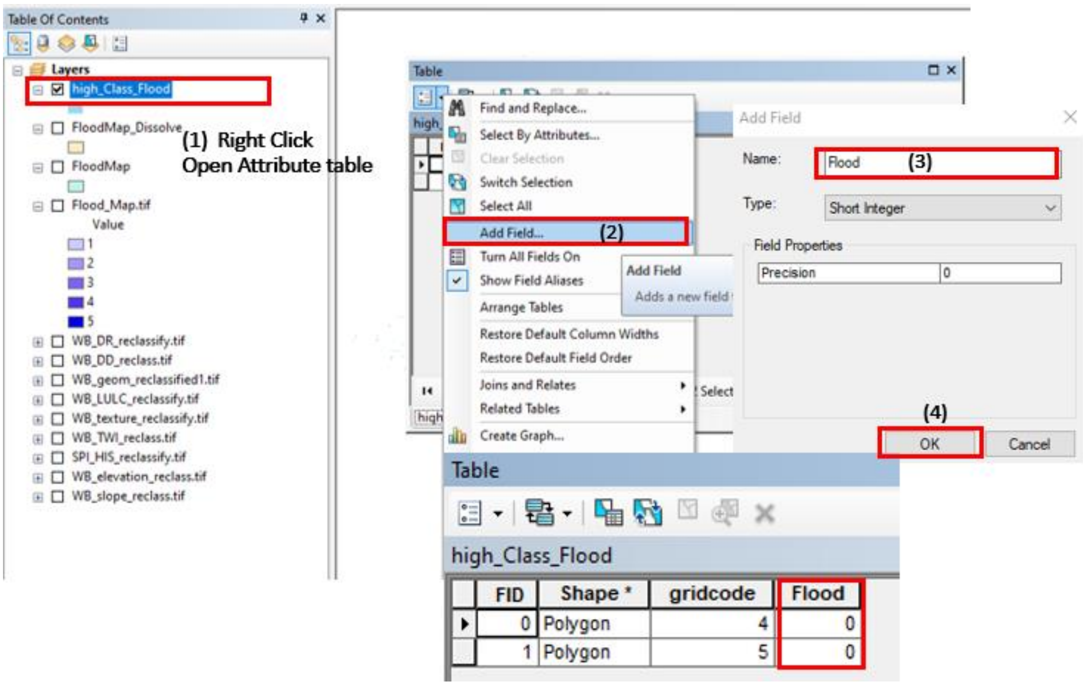


Figure C-104 Adding a field to the shapefile attribute table for high class flood

- *Dissolving Shapefile for High-Class Flood:* In Table of contents, Right click on Dissolve Shapefile → select 'Open Attribute Table' → In 'Table' window select → select 'Add Field'→ 'Add Field' window will pop-up show in Figure C-105→ Insert the name of heading in table in 'Name' (for example Flood) → click **OK** the result 'Table' window will be as Figure C-105

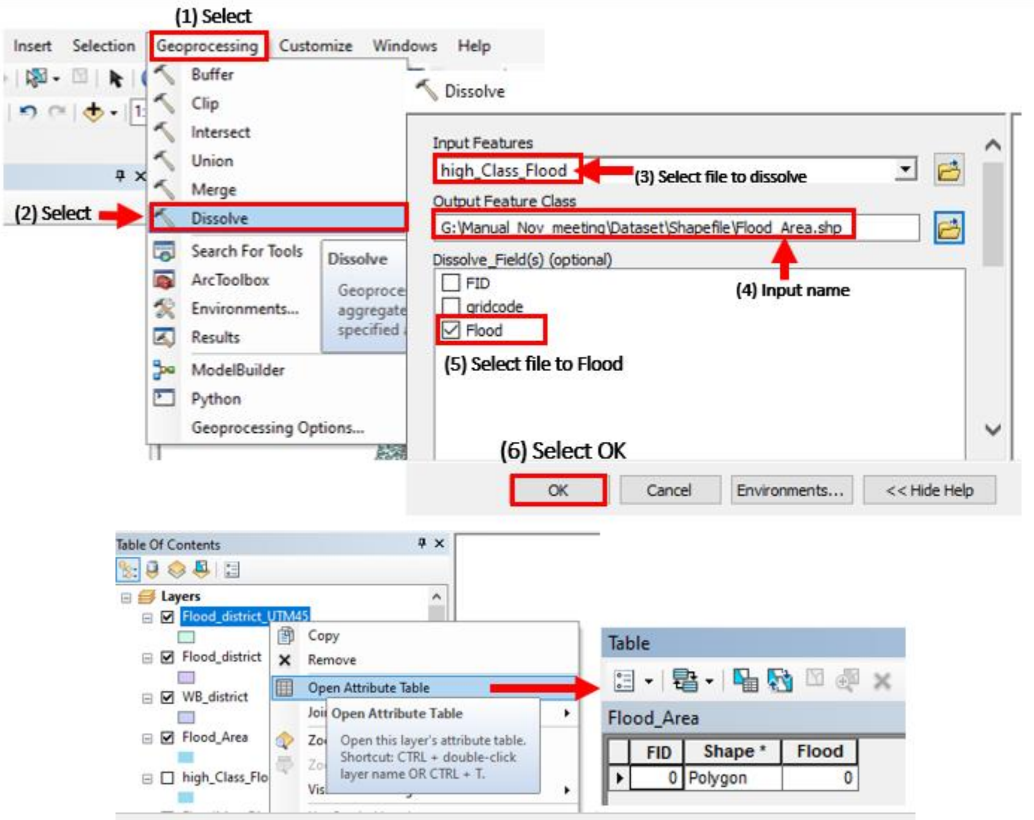


Figure C-105 Dissolving shapefile with high and very high flood classes into a single flood area

- *Projecting district shapefile to UTM Coordinate system:* In ArcToolbox, go to Data Management Tools → select 'Projection and Transformations' → select 'Project' → 'Project' window will pop-up, select the AOI/State district file shapefile 'Input Feature class' ('WB_district.shp') →As show in Figure C-106 in 'Output Coordinate System' select → 'Spatial Reference Properties' window will pop-up, select the 'Projected Coordinate Systems' → select the 'UTM' → select the 'Northen Hemisphere' → select the 'WGS 1984 UTM Zone 45N' → click **OK** → In 'Output feature class' select relevant folder and assign file name ('Dataset\Shapefile\WB_District_UTM.shp')→ click **OK**. (Based on the UTM Zone where our AOI lies, select the corresponding UTM zone. To check your UTM zone here https://www.dmap.co.uk/utmworld.htm)

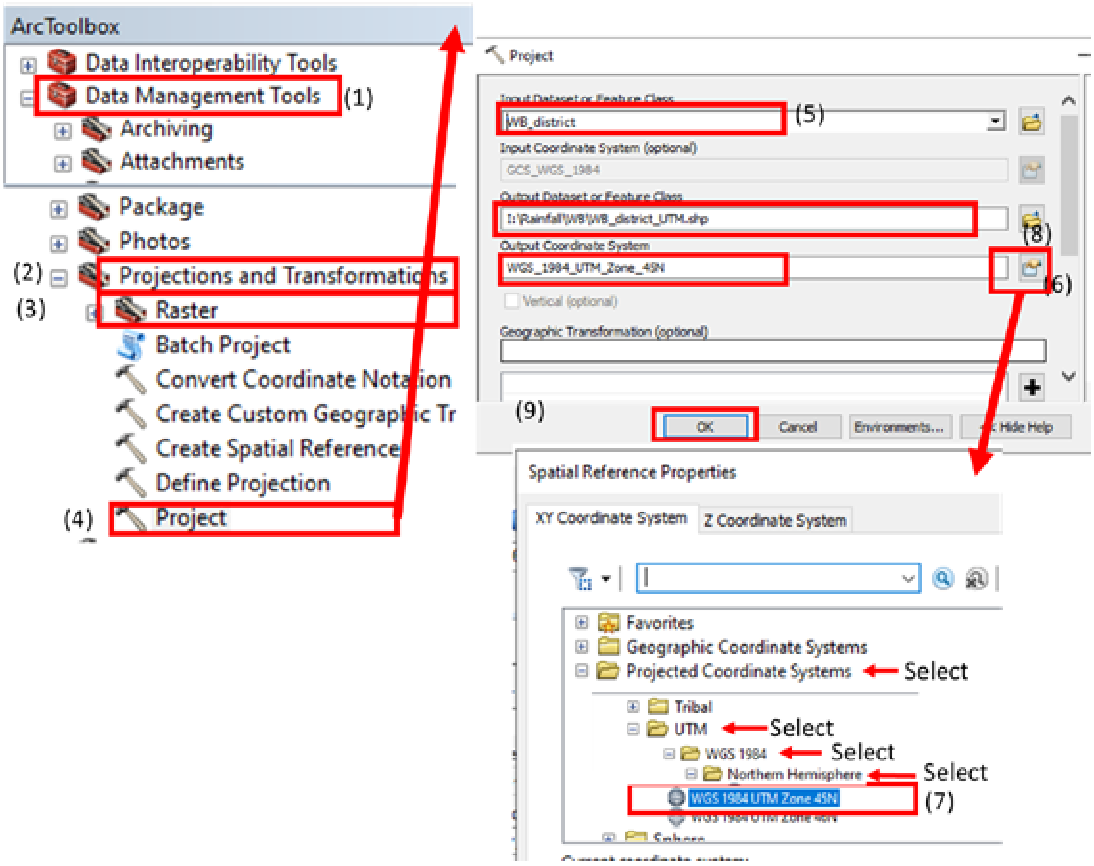


Figure C-106 Projecting district shapefile to UTM Coordinate System

- *Projecting to Dissolve Flood Area shapefile to UTM Coordinate system:* In ArcToolbox, go to Data Management Tools → select 'Projection and Transformations' → select 'Project' → 'Project' window will pop-up, select the dissolve flood area shapefile obtained in last step in 'Input Feature class' ('Flood_Area.shp') →As show in Figure C-107 in 'Output Coordinate System' select → 'Spatial Reference Properties' window will pop-up, select the 'Projected Coordinate Systems' → select the 'UTM' → select the 'Northen Hemisphere' → select the 'WGS 1984 UTM Zone 45N' → click **OK** → In 'Output feature class' select relevant folder and assign file name ('Dataset\Shapefile\Flood_Area_UTM45.shp')→ click **OK**.

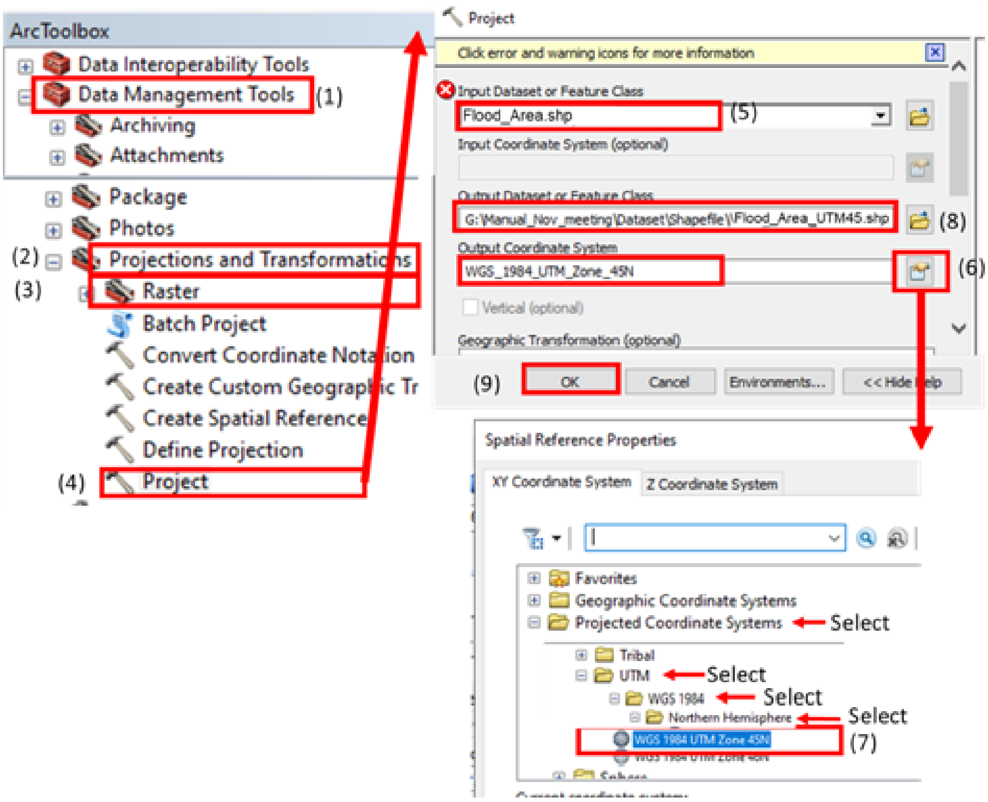


Figure C-107 Projecting flood shapefile to UTM Coordinate System

- *Linking district with flood area:* In ArcToolbox, go to Analysis Tools → select 'Overlay' → select 'Intersect' → 'Intersect' window will pop-up, select the projected AOI district shapefile and also the projected dissolved flood area output layer obtain in last step in 'Input Feature' as shown in Figure→ In 'Output feature class' select relevant folder and assign file name ('Dataset\Shapefile\Flood_District_UTM45.shp')→ click **OK**. (Figure C-108)

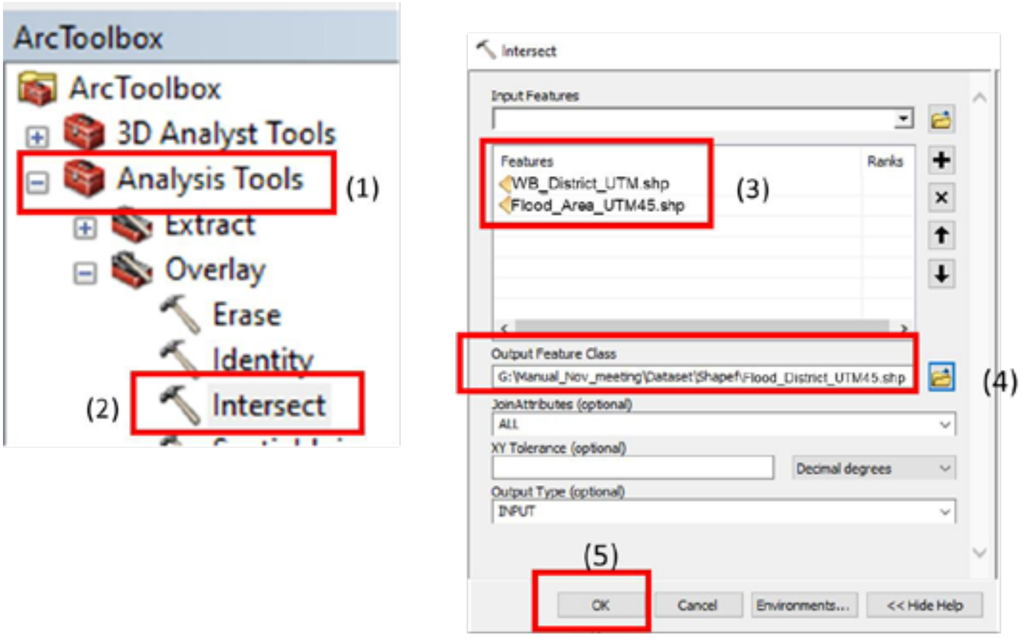


Figure C-108 Linking district with flood area

- *Calculate flood area:* In Table of contents, Right click on Projected Shapefile ('Flood_District_UTM45.shp')→ select 'Open Attribute Table' → In 'Table' window select → select 'Add Field'→ 'Add Field' window will pop-up → Insert the name of heading in table in 'Name' (for example Flood_Area) → select 'Type' as 'Float' →click **OK** →the result 'Table' window will be as Figure C-109 → go to the added field column name in 'Table' → Right click Column 'Flood_Area') → select 'Field Calculator' → 'Calculate Geometry 'Window will pop-up, select the 'Units' as 'sq km' click **OK**.

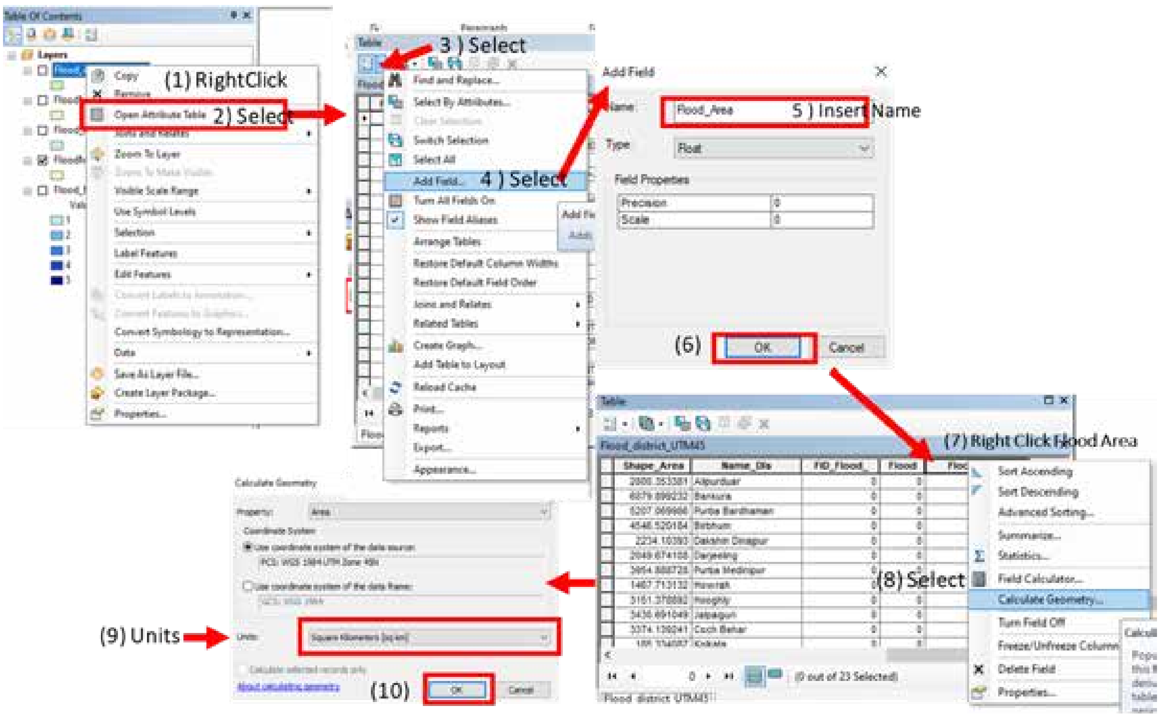


Figure C-109 Calculate flood area

- *Export Flood area to Excel:* In Table of contents, Right click on calculated flood area shapefile in last step ('Flood_District_UTM45.shp')→ select 'Open Attribute Table' → In 'Table' window select → select 'Select All'→ Right click on row of the Table window click 'Copy selected' → Open new excel sheet and **paste (**Figure C-110**)**.

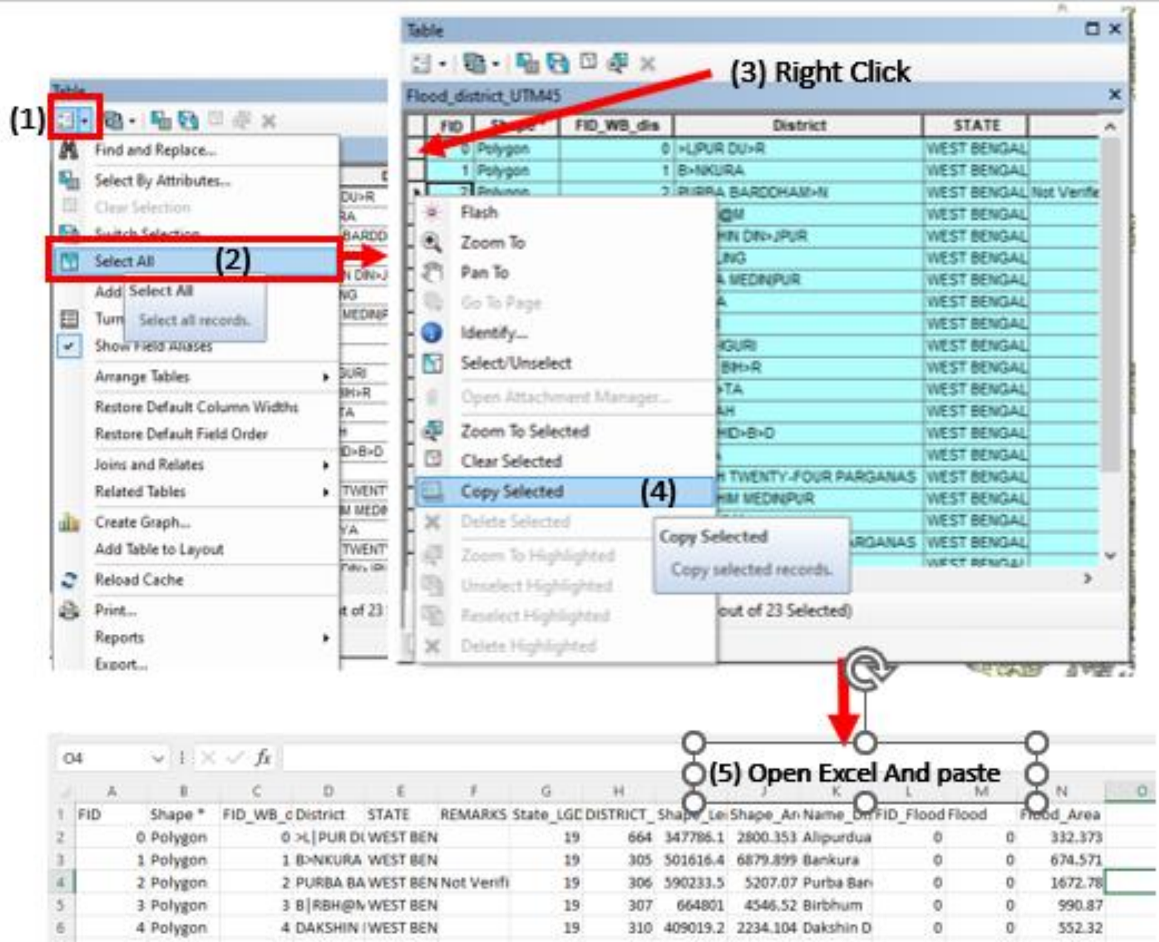


Figure C-110 Export Flood area to Excel

- *Calculate percentage flood area in Excel:* In Excel add new column name percentage area use formula **100 x Flood Area / District area** to calculate example shown below Figure C-111.

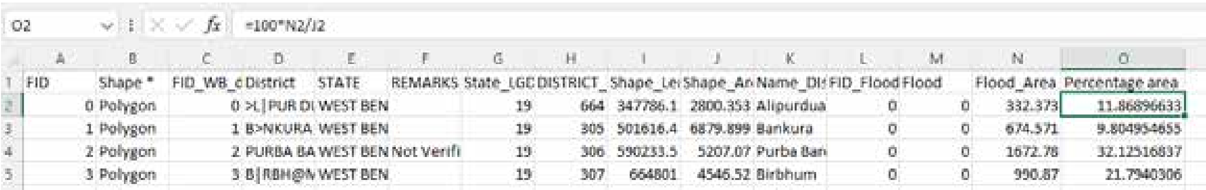


Figure C-111 Calculate percentage flood area in Excel

- This FHI value would then be combined with the normalized hazard-specific exposure and vulnerability indicator values to calculate the final Flood Risk Index (FRI) of each district within the state “WB”.

PART D

STEP-BY-STEP PROCEDURE FOR CALCULATION OF HAZARD-SPECIFIC EXPOSURE INDEX

Calculation of Hazard-specific Exposure Index

Since all the indicators have positive relationship with exposure, i.e., a higher value of the indicator is associated with a higher level of exposure, the normalisation is based on Equation D-1. The Exposure Indices (EI) are calculated by taking a simple Arithmetic Mean of the normalised values after assigning equal weights to all the indicators. The values thus obtained suggest the relative exposure of the districts within a state to floods and drought.

$$x_{ij}^{P} = \frac{X_{ij} - Min_i\{X_{ij}\}}{Max_i\{X_{ij}\} - Min_i\ \{X_{ij}\}} \qquad \text{(Equation D-1)}$$

Where, x_{ij}^{P} is the normalized value of the j^{th} indicator of the i^{th} district, X_{ij} is the actual value, $Max_i\{X_{ij}\}$ is the maximum value, and $Min_i\{X_{ij}\}$ is the minimum value.

Two exposure indicators have been considered for both hazards. For drought exposure, these indicators are “Population density and Proportion of area under rainfed agriculture”, whereas for flood exposure, they are “Population density and Percentage land under agricultural use”.

- **Example showing normalization for flood related indicators for District A[1].**

  Percentage of land under agricultural use: The maximum and minimum values as shown in Table D-1, are 86.65 (District V) and 24.45 (District J), respectively. So, the denominator is (X_{max} – X_{min}) = (86.65-24.45) = 62.20. [Note that the denominator will be identical for all districts under consideration].

  The numerator for District A is (X_{actual} – X_{min}) = (48.76-24.45) =24.31.

  Hence, the normalized value of the indicator population density for District D = 24.31/62.20 = 0.39.

  Deploying the same formula, we will get the normalised value of all other indicators. The normalised values for overall districts will vary between 0 and 1, and are unit free.

  The Actual and Normalized values for the flood related indicators for all the districts are shown in Table D-1.

  Similarly, we can calculate the normalized values of each of the drought exposure indicators for each district.

- **Example showing normalization for drought related indicators for district A.**

  Proportion of area under rainfed agriculture: The maximum and minimum values are 0.94 (District J) and 0.01 (District V), respectively (Table D-2). So, the denominator is (X_{max} – X_{min}) = (0.94-0.01) = 0.93. [The denominator will be identical for all districts under consideration].

  The numerator for District A is (X_{actual} – X_{min}) = (0.74 - 0.01) = 0.73.

  Hence, the normalized value of the indicator population density for District A = 0.73/0.93 = 0.78.

  Deploying the same formula, we will get the normalised value of all other indicators as shown in Table D-2.

[1]District A is a hypothetical district and does not represent a real district in India.

- **Aggregation of Indicators and Developing the Exposure Index:** The normalized values can be aggregated to build the Exposure Index. If different weights are attached to different indicators, then a weighted average will be considered to calculate the exposure index (i.e., normalized values are to be multiplied by their respective weights and then added up). However, in this case, since equal weights are given, a simple arithmetic mean will do.

  Example showing calculation of Flood Exposure Index (FEI) for District A.
  FEI = (0.43+0.39)/2 = 0.68

  Example showing calculation Drought Exposure Index (DEI) for district A.

  DEI = (0.43+0.78)/2 = 0.61

  - **Exposure Ranking:** Once the EIs are calculated for all districts, a comparative ranking is carried out based on the index value. Higher the value of EI for a particular district, higher will be its exposure. These exposure rankings are usually presented in tabular form. Here, we have ranked the 14 hypothetical districts according to their EI based on the two indicators that we have considered. Actual values and Normalized values for the flood and drought related indicators for all the districts are shown in Tables D-1 and D-2, respectively.

Table D-1: Actual values (AVs) and Normalized values (NVs) of indicators and Flood Exposure Index

District*	Population density		% Land under agricultural use		FEI	Rank
	AV	NV (+)	AV	NV (+)		
A	1463.16	0.43	48.76	0.39	0.41	17
B	553.58	0.02	54.02	0.48	0.25	22
C	826.97	0.14	72.57	0.77	0.46	14
D	787.25	0.13	82.71	0.94	0.53	11
E	960.53	0.20	60.36	0.58	0.39	18
F	2739.36	1.00	55.77	0.50	0.75	2
G	1821.69	0.59	66.82	0.68	0.64	3
H	1196.81	0.31	59.82	0.57	0.44	16
I	2033.53	0.68	54.35	0.48	0.58	8
J	1799.19	0.58	24.45	0.00	0.29	21
K	883.49	0.17	76.73	0.84	0.51	13
L	1216.58	0.32	77.75	0.86	0.59	7
M	1452.38	0.42	74.14	0.80	0.61	5
N	1396.13	0.40	75.57	0.82	0.61	6
O	2626.32	0.95	61.88	0.60	0.78	1
P	2739.36	1.00	30.18	0.09	0.55	10
Q	1003.06	0.22	65.68	0.66	0.44	15
R	948.98	0.20	76.19	0.83	0.52	12
S	1368.69	0.39	71.87	0.76	0.57	9
T	503.61	0.00	69.48	0.72	0.36	19
U	1148.74	0.29	47.54	0.37	0.33	20
V	1057.23	0.25	86.65	1.00	0.62	4

**The listed districts are hypothetical cases and do not represent any real district in India*

Table D-2: Actual values (AVs) and Normalized values (NVs) of indicators and Drought Exposure Index

District*	Population density		Proportion of area under rainfed agriculture		DEI	Rank
	AV	NV (+)	AV	NV (+)		
A	1463.16	0.43	0.74	0.78	0.61	5
B	553.58	0.02	0.2	0.20	0.11	21
C	826.97	0.14	0.01	0.00	0.07	22
D	787.25	0.13	0.56	0.59	0.36	16
E	960.53	0.20	0.94	1.00	0.60	6
F	2739.36	1.00	0.45	0.47	0.74	4
G	1821.69	0.59	0.28	0.29	0.44	12
H	1196.81	0.31	0.74	0.78	0.55	8
I	2033.53	0.68	0.85	0.90	0.79	2
J	1799.19	0.58	0.94	1.00	0.79	3
K	883.49	0.17	0.68	0.72	0.45	11
L	1216.58	0.32	0.52	0.55	0.43	13
M	1452.38	0.42	0.49	0.52	0.47	10
N	1396.13	0.40	0.25	0.26	0.33	17
O	2626.32	0.95	0.23	0.24	0.59	7
P	2739.36	1.00	0.85	0.90	0.95	1
Q	1003.06	0.22	0.27	0.28	0.25	18
R	948.98	0.20	0.27	0.28	0.24	19
S	1368.69	0.39	0.42	0.44	0.41	15
T	503.61	0.00	0.78	0.83	0.41	14
U	1148.74	0.29	0.69	0.73	0.51	9
V	1057.23	0.25	0.01	0.00	0.12	20

**The listed districts are hypothetical cases and do not represent any real district in India*

PART E

STEP-BY-STEP PROCEDURE FOR CALCULATION OF VULNERABILITY INDEX

Calculation of Hazard-specific Vulnerability Index

The IPCC AR5 (2014) emphasizes that reducing vulnerability and exposure to current climate variability is a critical first step towards adapting to future climate change. Vulnerability, as an internal property of a system, reflects its susceptibility to harm due to climate hazards. Assessing vulnerability under the current climate helps identify the weaknesses of natural or socio-economic systems, uncovering the underlying drivers of these weaknesses. Such assessments provide valuable insights for devising strategies to address these vulnerabilities and adapt to the influencing drivers effectively. While long-term objectives like mitigating climate hazards and minimizing exposure are essential, governments and development agencies can achieve substantial short- to medium-term progress by focusing on vulnerability reduction. This approach enables a pragmatic pathway to enhance resilience and adaptive capacity, paving the way for robust responses to future climate impacts. By addressing systemic weaknesses and reducing vulnerability in the near term, stakeholders can build a strong foundation for sustainable, long-term climate adaptation strategies.

The concept of vulnerability could be operationalized in two ways:

- Starting point/contextual approach (O'Brien, Eriksen, Nygaard, &Schjolden, 2007): Vulnerability is considered as a pre-existing condition in anticipation of a hazard.

- Endpoint/outcome approach (Kelly & Adger, 2000; O'Brien, Eriksen, Nygaard, & Schjolden, 2007): Vulnerability of a system is assessed before and after exposure to a hazard.

In this manual, our focus is on the flood and drought-specific starting point/contextual vulnerability of states and districts in India.

This section presents the method of normalizing and calculating the hazard-specific vulnerability at the district level based on the illustrative data for hypothetical districts given in Table E-1. It represents the actual values of the indicators (AV), normalised values (NV) and the composite vulnerability index for all districts. Similar to the calculation of EI, the Vulnerability Indices (VI) are calculated by taking a simple Arithmetic Mean of the normalised values after assigning equal weights to all the indicators. After that, all the districts are ranked based on their VIs.

However, the process of normalization differs according to the indicator's functional relationship with vulnerability.

- **For positively related indicators**, i.e., indicators representing 'sensitivity', where an increase in the value of the indicator increases vulnerability, normalization is carried out using Equation E-1.

$x_{ij}^{P} = \frac{Xij - Min_i\{X_{ij}\}}{Max_i\{X_{ij}\} - Min_i\{X_{ij}\}}$ (Equation E-1)
Where X_{ij} is the actual value of the j^{th} indicator if the i^{th} district, $Max_i\{X_{ij}\}$ is the maximum value, and $Min_i\{X_{ij}\}$ is the minimum value.

Example of normalization of an indicator representing sensitivity:

Normalization of "Proportion of small and marginal landholdings" for District A: The proportion of small and marginal landholdings is considered an indicator of sensitivity and is thus positively related to vulnerability. The maximum and minimum values are respectively 1.00 (District S) and 0.89 (District O), as shown in Table E-1. So, the denominator is (X_{max} - X_{min}) = (1.00-0.89) = 0.10.

[Note that the denominator will be the same for all districts under consideration].

The actual value of the indicator for District A is 0.98; therefore, the numerator will be (X_{actual}- X_{min}) = (0.98-0.89) = 0.09.

Hence, the normalized value of proportion of small and marginal landholdings indicator for this district = 0.09/0.10 = 0.9

Similarly, we can calculate the normalized values of each of the positive indicators for each of the districts by applying the same normalization method.

- **For negatively related indicators**, i.e., indicators representing 'adaptive capacity', where vulnerability decreases with an increase in the value of the indicator, normalization is achieved by using Equation E-2.

$x_{ij}^{N} = \frac{Max_i\{X_{ij}\} - Xij}{Max_i\{X_{ij}\} - Min_i\ \{X_{ij}\}}$	(Equation E-2)
Where X_{ij} is the actual value of the j^{th} indicator of the i^{th} district, $Max_i\{X_{ij}\}$ is the maximum value, and $Min_i\ \{X_{ij}\}$ is the minimum value.	

Example of normalization of an indicator representing adaptive capacity:

Normalization of "Livestock to human ratio" for District A: The livestock to human ratio is considered an adaptive capacity indicator and is negatively related to vulnerability**.** The maximum and minimum values are 0.28 (District B) and 0.03 (District F), respectively as shown in Table E-1. So, the denominator is (X_{max} -X_{min}) = (0.28 - 0.03) = 0.25. Once again, the denominator will remain constant for all districts under consideration.

Accordingly, the numerator for District A is (X_{max} - X_{actual}) = (0.28 - 0.21) = 0.07.

Hence, the normalized value of the livestock to human ratio indicator for this district = 0.07/0.25 = 0.28.

Similarly, we can calculate the normalized values for all negative indicators using the same normalization method.

- **Aggregation of Indicators and Developing the Vulnerability Index (VI):** The normalized indicators need to be aggregated to come up with the Vulnerability Index. If different weights are attached to different indicators, then a weighted average will be taken to calculate the index (i.e., normalized values are to be multiplied by their respective weights and then added up). However, in this case, since equal weights are given, a simple arithmetic mean will do.

  Example showing calculation of Vulnerability Index (VI) for District A.

  VI = (0.35+0.11+0.39+0.59+0.81+0.28+1.00+0.79+1.00+0.72)/10 = 0.60

  Once VIs have been calculated for all the districts, a comparative ranking can be carried out based on the index values similar to the exposure ranking.

Table E-1: District-wise Actual Values (AVs), normalised values (NVs) of indicators and the Vulnerability Index

District*	MDPI		Forest area per 100 rural ppn		Population living in households with an improved drinking-water source (%)		Women who are literate (%) (15-49)		Proportion of small and marginal landholdings		Livestock to human ratio (old data)		Proportion of net sown area under horticulture (old data)		Yield variability of food grains (old data)		Road density (km/100 sq km)		Average person days per household employed under MGNREGA		VI	Rank
	AV	NV (+)	AV	NV (-)	AV	NV (-)	AV	NV (-)	AV	NV (+)	AV	NV (-)	AV	NV (-)	AV	NV (+)	AV	NV (-)	AV	NV (-)		
A	0.10	0.35	0.04	0.11	95.20	0.39	73.60	0.59	0.98	0.81	0.21	0.28	0.00	1.00	0.21	0.79	59.26	1.00	48.26	0.72	0.60	4
B	0.12	0.47	0.04	0.20	96.30	0.30	68.30	0.86	0.90	0.04	0.28	0.00	0.00	0.96	0.19	0.68	185.19	0.61	45.86	0.81	0.49	17
C	0.13	0.49	0.01	0.97	99.40	0.05	70.80	0.73	0.92	0.20	0.23	0.20	0.00	0.94	0.16	0.53	120.54	0.81	42.57	0.92	0.58	6
D	0.10	0.34	0.01	0.97	99.70	0.02	74.30	0.56	0.94	0.43	0.20	0.32	0.00	0.97	0.11	0.26	273.63	0.33	52.57	0.57	0.48	19
E	0.05	0.06	0.04	0.11	90.80	0.74	77.00	0.43	0.98	0.84	0.09	0.76	0.00	0.73	0.20	0.74	250.55	0.41	68.72	0.00	0.48	18
F	0.06	0.10	0.02	0.71	99.50	0.04	80.50	0.25	1.00	1.00	0.03	1.00	0.00	1.00	0.25	1.00	256.46	0.39	50.96	0.63	0.61	3
G	0.07	0.15	0.00	1.00	98.10	0.15	77.40	0.41	0.98	0.85	0.10	0.72	0.00	0.75	0.09	0.16	381.60	0.00	40.34	1.00	0.52	13
H	0.10	0.35	0.04	0.11	95.20	0.39	73.60	0.59	0.96	0.67	0.21	0.28	0.00	1.00	0.21	0.79	348.17	0.10	48.26	0.72	0.50	15
I	0.10	0.37	0.01	0.74	95.50	0.36	70.90	0.73	0.97	0.72	0.23	0.20	0.00	0.97	0.14	0.42	61.01	0.99	48.17	0.72	0.62	2
J	0.05	0.06	0.04	0.11	90.80	0.74	77.00	0.43	0.94	0.49	0.09	0.76	0.00	0.73	0.20	0.74	97.18	0.88	68.72	0.00	0.49	16
K	0.10	0.35	0.01	0.79	99.30	0.06	79.20	0.32	0.94	0.45	0.21	0.28	0.00	1.00	0.25	1.00	111.42	0.84	44.96	0.84	0.59	5
L	0.16	0.71	0.01	0.79	99.00	0.08	72.30	0.66	0.96	0.67	0.17	0.44	0.01	0.00	0.25	1.00	158.91	0.69	52.59	0.57	0.56	11
M	0.13	0.49	0.01	0.98	99.10	0.07	67.60	0.89	0.97	0.72	0.10	0.72	0.01	0.45	0.10	0.21	151.95	0.71	56.64	0.43	0.57	9
N	0.05	0.04	0.01	0.81	98.20	0.15	76.20	0.47	0.97	0.77	0.10	0.72	0.01	0.41	0.21	0.79	153.36	0.71	44.44	0.86	0.57	8
O	0.04	0.00	0.02	0.71	99.50	0.04	85.50	0.00	0.98	0.84	0.04	0.96	0.01	0.42	0.14	0.42	381.60	0.00	59.44	0.33	0.37	22
P	0.10	0.32	0.01	0.83	95.20	0.39	73.50	0.60	0.89	0.00	0.15	0.52	0.00	0.97	0.10	0.21	376.35	0.02	44.16	0.87	0.47	20
Q	0.10	0.37	0.01	0.74	95.50	0.36	70.90	0.73	0.98	0.80	0.23	0.20	0.00	0.97	0.14	0.42	276.59	0.33	48.17	0.72	0.56	10
R	0.10	0.32	0.01	0.83	99.10	0.07	73.20	0.61	0.93	0.33	0.15	0.52	0.00	0.97	0.10	0.21	242.90	0.43	44.16	0.87	0.52	14
S	0.06	0.12	0.04	0.00	87.80	0.98	77.00	0.43	1.00	0.99	0.12	0.64	0.00	0.97	0.06	0.00	107.83	0.85	52.59	0.57	0.55	12
T	0.21	0.98	0.03	0.28	87.60	1.00	65.40	1.00	0.95	0.52	0.25	0.12	0.00	0.97	0.11	0.26	64.86	0.98	57.66	0.39	0.65	1
U	0.13	0.51	0.04	0.06	100.00	0.00	85.60	0.00	0.99	0.90	0.07	0.84	0.00	0.85	0.22	0.84	245.50	0.42	68.72	0.00	0.44	21
V	0.21	1.00	0.01	0.91	99.80	0.02	65.40	1.00	0.95	0.55	0.22	0.24	0.00	0.90	0.12	0.32	225.10	0.49	57.40	0.40	0.58	7

**The districts listed in the table are hypothetical cases and do not represent any real district in India or elsewhere.*

PART F

STEP-BY-STEP PROCEDURE FOR CALCULATION OF HAZARD-SPECIFIC RISK INDEX

Calculation of Hazard-specific Risk Index

The risk index for both drought and flood are calculated based on the geometric mean of the specific Hazard Index (HI), Exposure Index (EI), and Vulnerability Index (VI) given as:

$$\text{Risk Index} = \sqrt[3]{(HI * EI * VI)} \qquad \text{(Equation F-1)}$$

Use of geometric mean is the best way of calculating the average value of components when they are in ratios. Various important global indicators, such as the Human Development Index (UNDP, 2021) is calculated based on exactly the similar method of normalization and taking geometric mean.

- Example showing calculation of Flood Risk Index (FRI) for a hypothetical district A from values given in Table F-1

$$\text{FRI} = \sqrt[3]{(0.27 * 0.41 * 0.60)} = 0.41$$

- Example showing calculation of Drought Risk Index (DRI) for district A from values given in Table F-2

$$\text{DRI} = \sqrt[3]{(0.27 * 0.41 * 0.60)} = 0.45$$

Similarly, we can calculate the risk index for all districts for both flood and drought as shown in Tables F-1 and F-2 and rank them according to their relative values.

Table F-1: Flood Hazard, Exposure, Vulnerability, and Flood Risk Index

District	FHI	FEI	VI	FRI
A	0.27	0.41	0.60	0.41
B	0.20	0.25	0.49	0.29
C	0.49	0.46	0.58	0.51
D	0.47	0.53	0.48	0.49
E	0.20	0.39	0.48	0.34
F	0.93	0.75	0.61	0.75
G	0.69	0.64	0.52	0.61
H	0.39	0.44	0.50	0.44
I	0.18	0.58	0.62	0.40
J	0.01	0.29	0.49	0.11
K	0.77	0.51	0.59	0.61
L	0.68	0.59	0.56	0.61
M	0.96	0.61	0.57	0.69
N	1.00	0.61	0.57	0.70
O	0.89	0.78	0.37	0.64
P	0.10	0.55	0.47	0.29
Q	0.38	0.44	0.56	0.46
R	0.61	0.52	0.52	0.54
S	0.82	0.57	0.55	0.64
T	0.01	0.36	0.65	0.15
U	0.77	0.33	0.44	0.48
V	0.40	0.62	0.58	0.52

Table F-2: Drought Hazard, Exposure, Vulnerability and Drought Risk Index

District	DHI	DEI	VI	DRI
A	0.25	0.61	0.60	0.45
B	0.70	0.11	0.49	0.34
C	0.49	0.07	0.58	0.27
D	0.76	0.36	0.48	0.51
E	0.67	0.60	0.48	0.58
F	0.33	0.74	0.61	0.53
G	0.63	0.44	0.52	0.52
H	0.58	0.55	0.50	0.54
I	0.75	0.79	0.62	0.72
J	0.20	0.79	0.49	0.43
K	0.57	0.45	0.59	0.53
L	0.43	0.43	0.56	0.47
M	0.85	0.47	0.57	0.61
N	0.65	0.33	0.57	0.50
O	0.01	0.59	0.37	0.13
P	0.71	0.95	0.47	0.68
Q	0.58	0.25	0.56	0.44
R	0.90	0.24	0.52	0.48
S	0.57	0.41	0.55	0.51
T	0.79	0.41	0.65	0.60
U	0.49	0.51	0.44	0.48
V	1.00	0.12	0.58	0.42