

Soil Moisture Analysis over Hilly terrain for landslide warning during Heavy Precipitation

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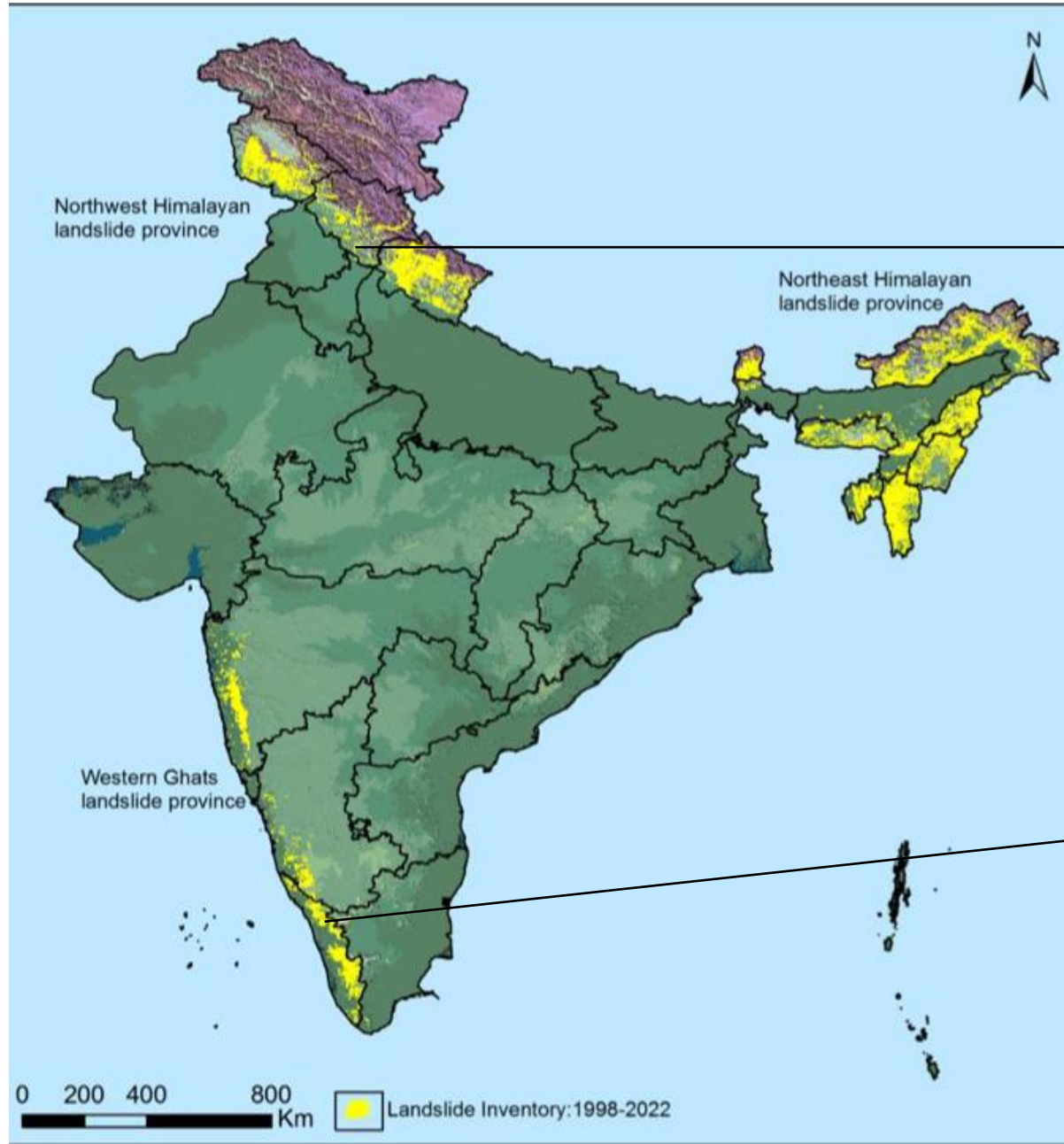
National Centre for Medium Range Weather Forecasting

Ministry of Earth Sciences

Landslides: What? Why?

- Landslide is a rapid movement of rock, soil and vegetation down the slope under the influence of gravity.
- Landslides occur most frequently in areas with steep local relief and with hillslope materials of low shear strength.
- Landslide can be triggered by heavy rainfall, undercutting of slopes due to flooding or excavation, earthquakes, snowmelt, or anthropogenic causes.
- In India, most of the landslides occur in the monsoon months (between June and September)
- Many districts in the Northernmost Indian states have high population densities.

Landslide Atlas of India (Source: ISRO)



51 killed in Himachal rains, 14 of them in Shimla landslides

More people are feared trapped under the debris of the Shiv temple in Shimla's Summer Hill area; officials said the toll may rise as the Himachal Pradesh capital is still witnessing intense rain

Updated - August 15, 2023 09:21 am IST Published - August 14, 2023 10:48 am IST - Shimla

PTI



The damage at the railway track following landslide due to incessant rains near Summer Hill in Shimla, Monday, August 14, 2023. At least nine people were killed after a temple collapsed due to the landslide. | Photo Credit: PTI

At least 51 people were killed as rains wreaked havoc in Himachal Pradesh, triggering landslides that blocked key roads, damaged homes and buried livestock in the middle of a

Wayanad landslides: How two villages vanished overnight

Chooralmala and Mundakkai, both in Wayanad's Meppadi panchayat, are nearly 50km away from the district headquarters in Kalpetta. Both places were known for their scenic landscapes and waterfalls.

Updated - August 16, 2024 01:30 pm IST Published - August 16, 2024 11:34 am IST

THE HINDU BUREAU



Army personnel with others search the Chooralmala area after a landslide triggered by heavy rainfall hit the village in Wayanad district, Kerala, Aug. 1, 2024. | Photo Credit: PTI

In the early hours of July 30, 2024, Chooralmala and Mundakkai villages in the district of Wayanad in Kerala were hit by devastating landslides triggered by torrential downpour. The massive landslides so far has claimed over 230 lives. According to the district administration, over 130 people are still missing as of August 13. This is the worst natural disaster to occur in Kerala since the 2018 floods.

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The 14 August 2023 landslides in Himachal Pradesh, India

Heavy rainfall has triggered extensive landslides in NW India, with over 50 reported fatalities.

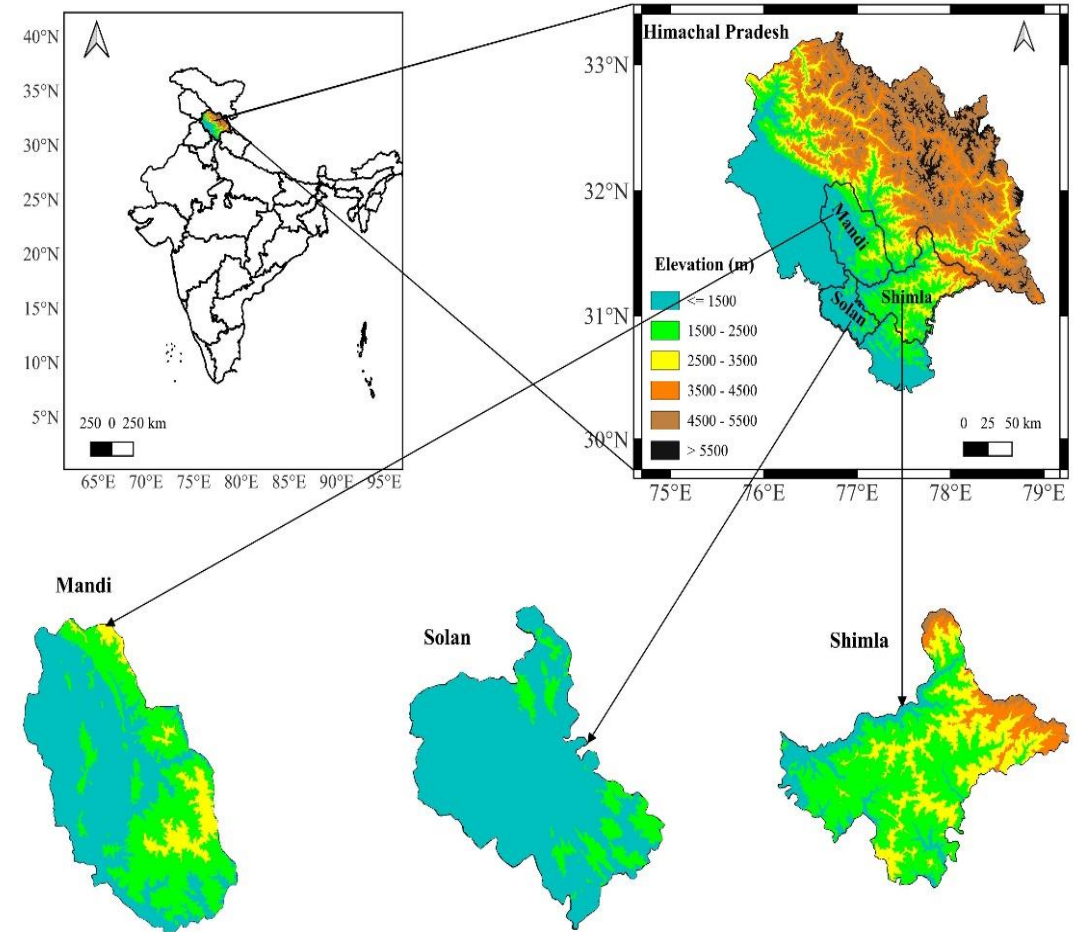
By Dave Peley 15 August 2023



Northwest Himalayan Region in India

Elevation

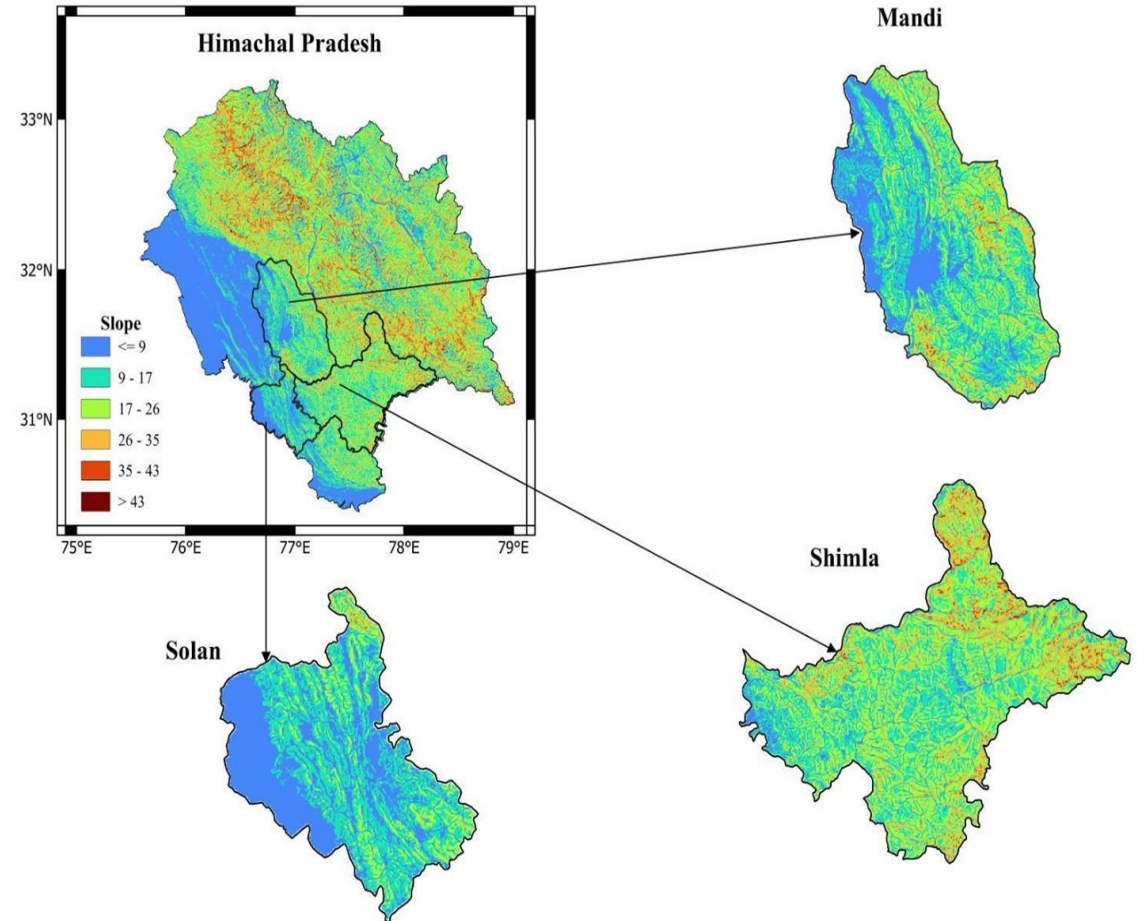
- The Shimla district has high mountain ranges and narrow, deep valleys with altitudes ranging from 1500m to 5500m. Here, the soil is generally sandy loam in valley areas of the district, which has medium water holding capacity, and in the rest of the hilly and mountainous areas, the soil is skeletal. The soil depth is generally shallow except in areas having good vegetative cover.
- The Mandi district presents a complicated terrain of hills and valleys with an elevation ranging from 550m to 3500m in the midlands of the Himalayan region, with an average elevation of 790m above mean sea level with sandy loam to clay loam soil type (Kujur et al., 2013), which has medium to high water holding capacity.
- The Solan district has terrain altitudes ranging from 300m to 2200m above mean sea level. Soil is generally sandy loam, which has low to medium water holding capacity.



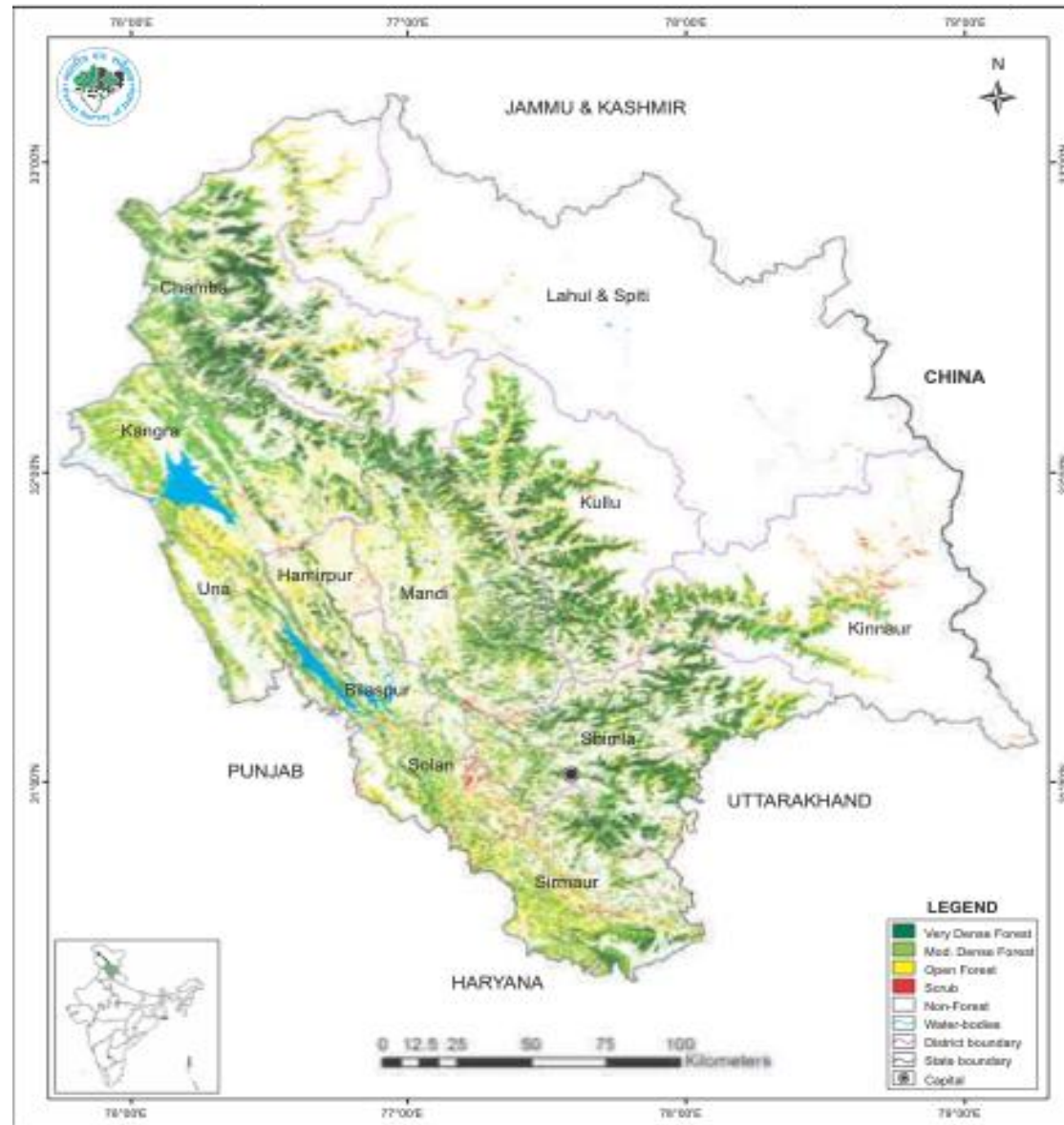
(Source: Central ground water board, Ministry of water resources)

Slope in Western Himalayan Region

- The slope measures surface steepness. The stability of slopes is a key factor in landslide risk. Steeper slopes are generally less stable and more susceptible to landslides, particularly when saturated with water or when vegetation is removed.
- Himachal Pradesh slope varies from 9-43⁰, ranging from low to high slope angle. Shimla is having most of the locations with slope, while Mandi is having some part of valley area. Solan is lowest slope among these three locations (9-35⁰).



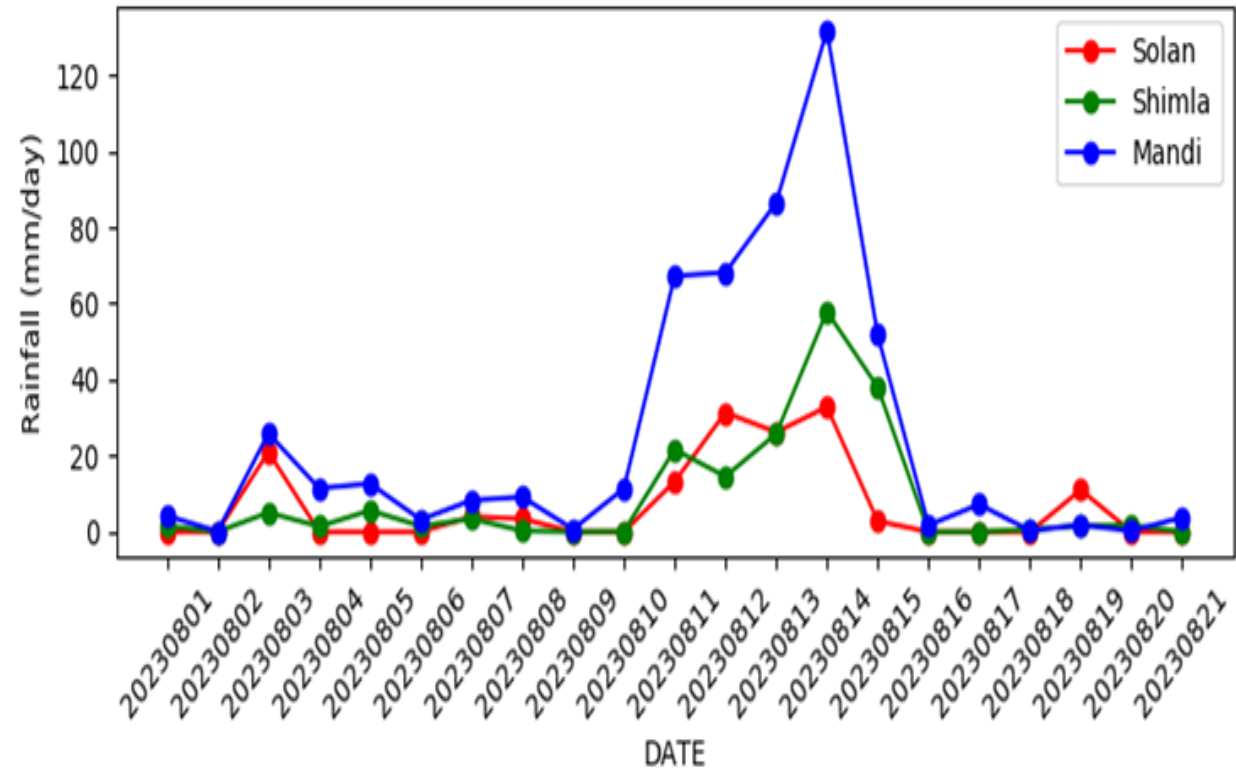
Forest Cover Map of Himachal Pradesh



Source: Forest Survey of India, Ministry of Environment

Description of the Heavy Precipitation event

- Heavy rainfall over Mandi, Shimla, and Solan in the state of Himachal Pradesh in India, started from August 10, 2023 to August 14, 2023, led to landslide events on August 14, 2023.
- The extreme rainfall event was due to the interaction of a western disturbance and a low-level moisture system from the Arabian Sea. This triggered landslides in the region (districts like Mandi, Shimla, Solan).



How soil moisture can impact landslide event?

- Soil absorbs water and increases in weight; saturated soil exerts pressure on the slope, which can lead to instability.
- As soil moisture increases, the soil's shear strength can decrease. This is because water reduces the friction between soil particles, making the soil more prone to slipping. Saturated soil is more likely to lose its cohesion and structural integrity.
- In saturated soils, the pore water pressure increases. This pressure can reduce the effective stress on the soil particles, weakening the soil structure and increasing the risk of landslides.
- Vegetation can influence soil moisture and stability. While plants help stabilize slopes by anchoring the soil with their roots, excessive moisture can overwhelm the root systems, reducing stability. Conversely, removing vegetation (e.g., deforestation or fire) can increase soil erosion and instability.
- The impact of moisture on landslides also depends on the type of soil. Clay soils, for example, are particularly sensitive to moisture changes and can become very slippery when saturated. Sandy soils might drain faster but can still become unstable if the moisture content is high enough.

Experimental Setup

- **JULES standalone** has been used at 12 km resolution with NCUM Driving data.
- The model was run from August 9, 2023 to August 17, 2023 to have a preliminary idea of JULES model predictability about variation in soil moisture for early warning of slope failure. The landslide occurred on August 14, 2023.
- JULES has been initialised for different initial conditions i.e. August 9, 2023, August 10, 2023, August 11, 2023, August 12, 2023, and August 13, 2023 respectively. Soil moisture forecasts are analysed based on initialisation days. Each simulation run ends on August 17, 2023.

Role of Hydrological Parameters

Rainfall that exceeds the soil's capacity to absorb water leads to surface runoff.

$$P = E - R - \Delta W$$

P = Precipitation

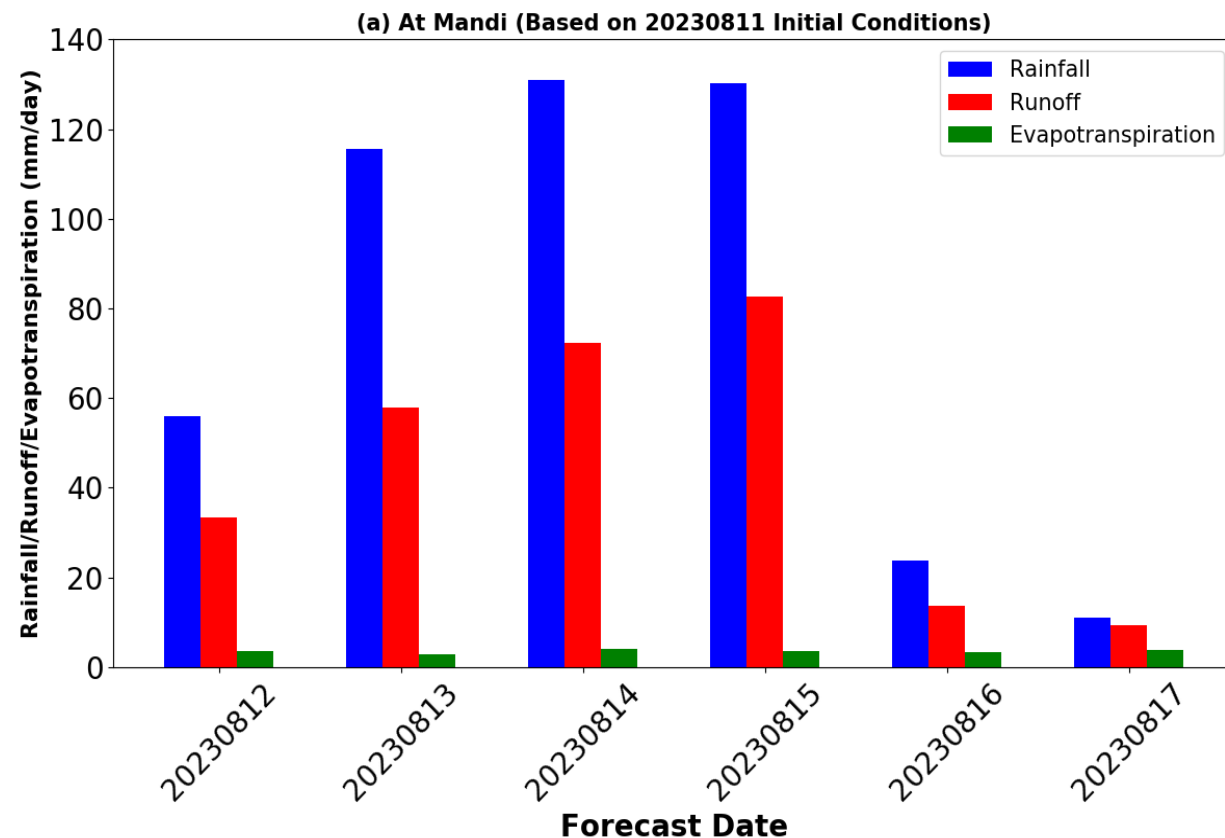
E = Evapotranspiration

- Evaporation from soil
- Transpiration from plants

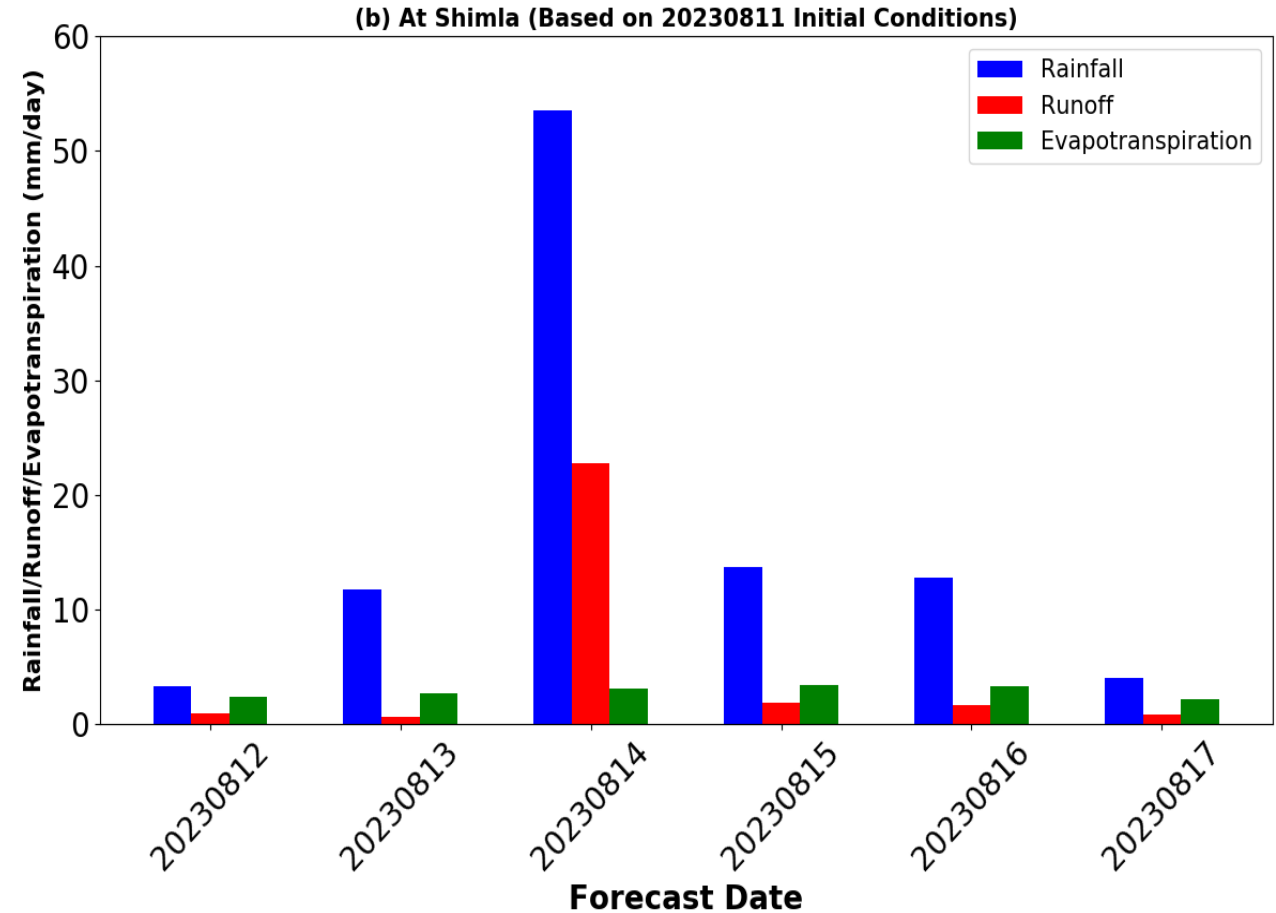
R = Runoff

ΔW = Changes in soil moisture

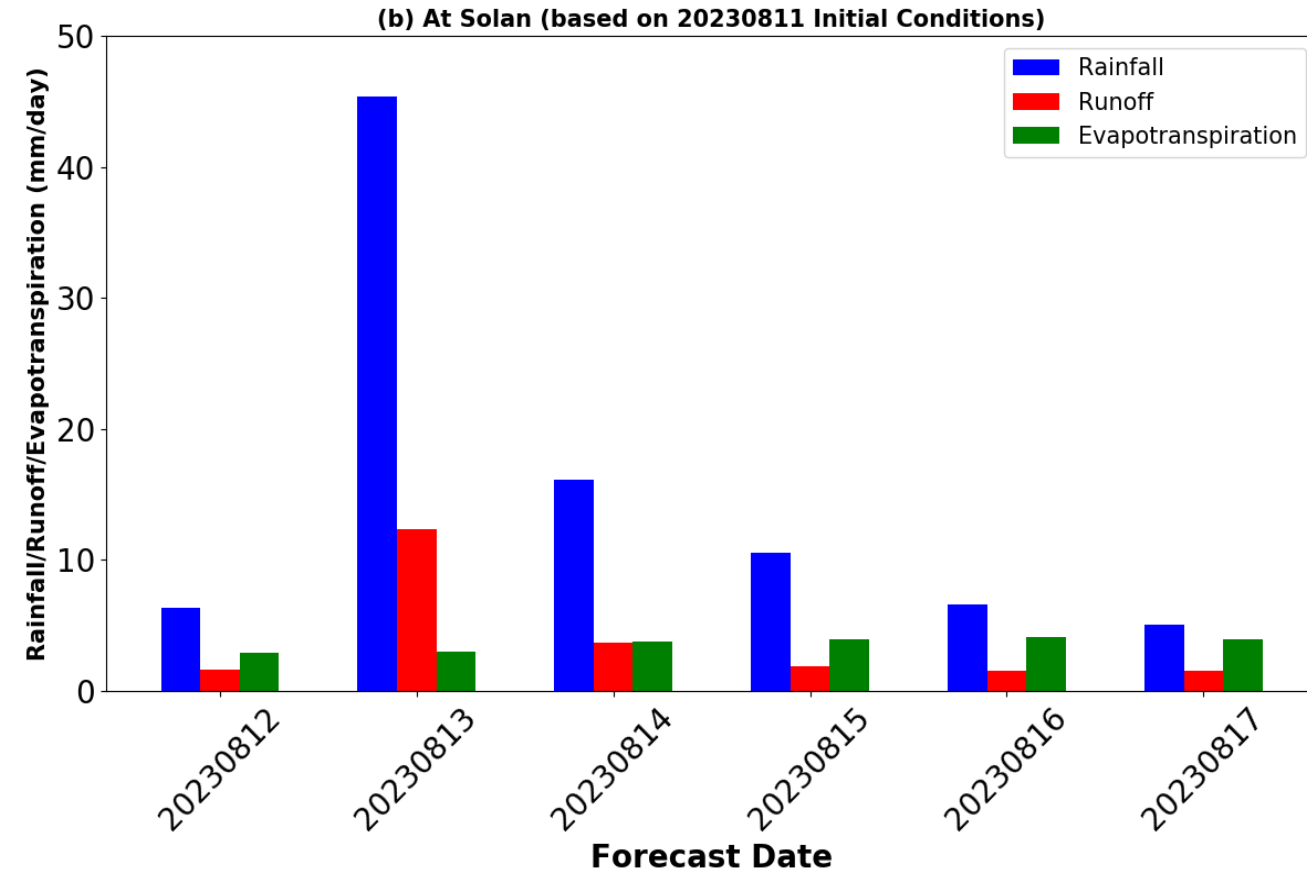
- Based on Initial Conditions August 11, 2023; rainfall and runoff is increasing as the leading time increases till August 15, 2023.
- Runoff is also high with the corresponding rainfall event.
- Evaporation is less in comparison with rainfall and runoff.
- Rest of the water is assumed to be contributed in the soil moisture.



- Based on Model simulations, day -3 forecast for August 14, 2023 is quite high as it has been observed too.
- Runoff is also high in comparison with evaporation on day-3 forecast (August 14, 2023).
- On August 13, 2023, runoff and evaporation are quite low in comparison with rainfall. So the remaining water left a significant amount of soil moisture for that region.

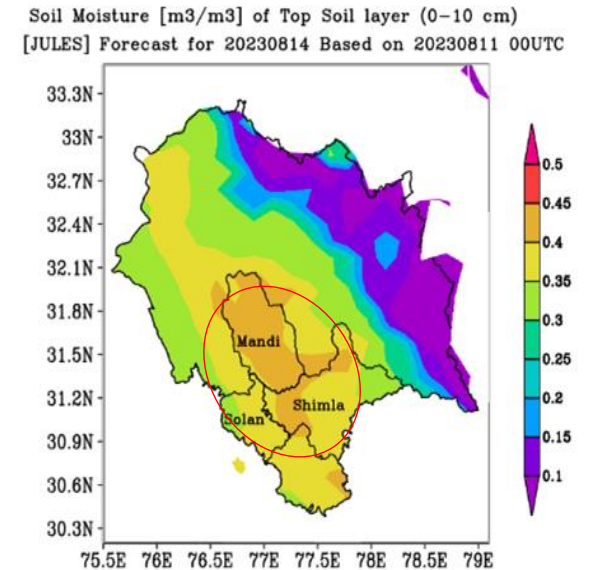
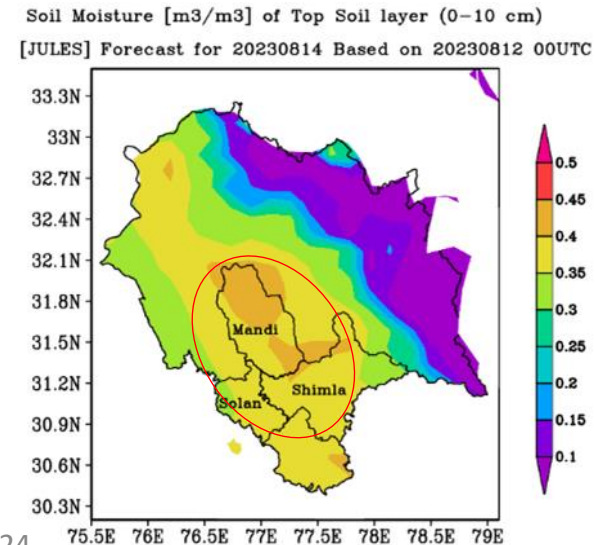
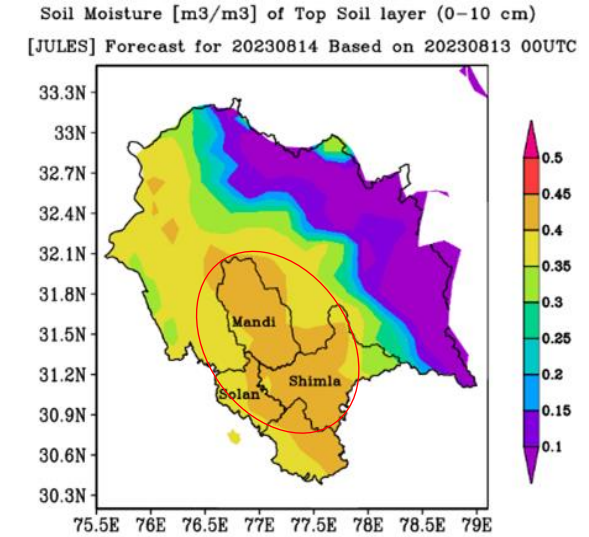
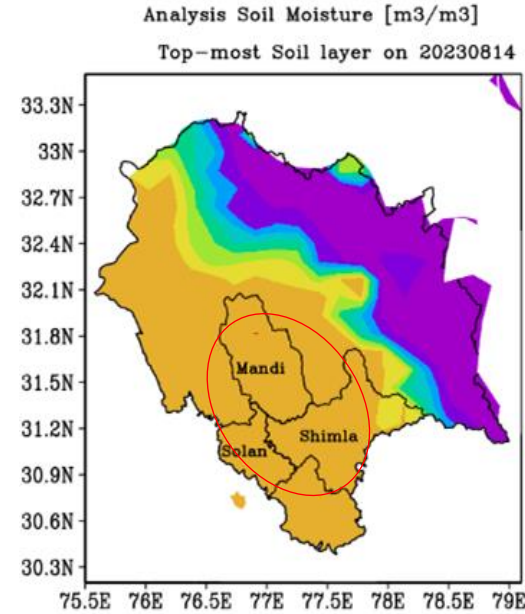


- Solan has got high amount of rainfall on day-2 (August 13, 2023).
- Less runoff and evaporation corresponding to the rainfall and remaining amount will be stored as soil moisture.
- On day -3 (August 14, 2023), rainfall has significant amount, and the corresponding runoff and evaporation are almost have same amount.
- The accumulated soil moisture plays a role in slope failure for this location.



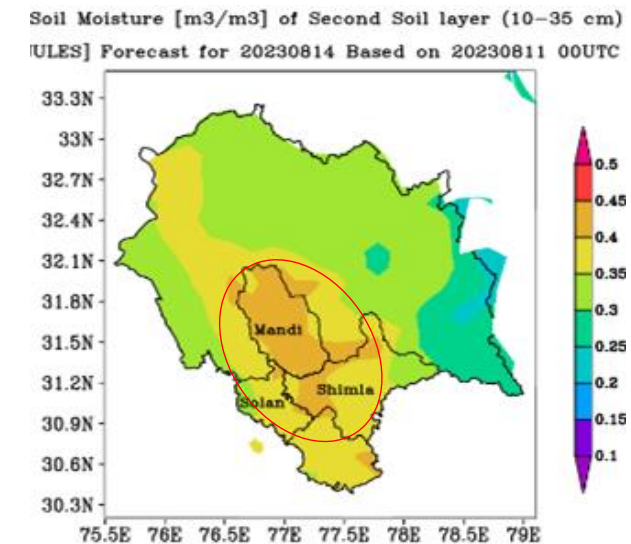
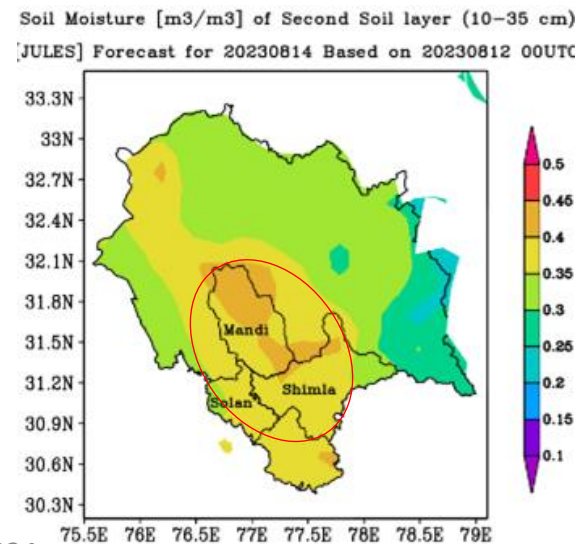
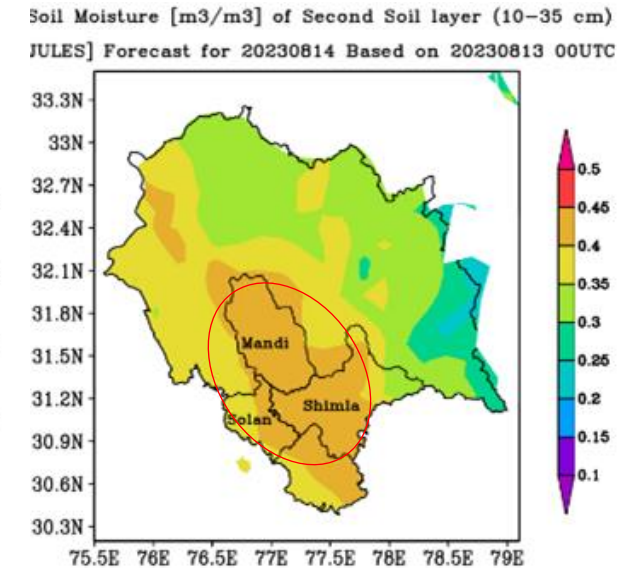
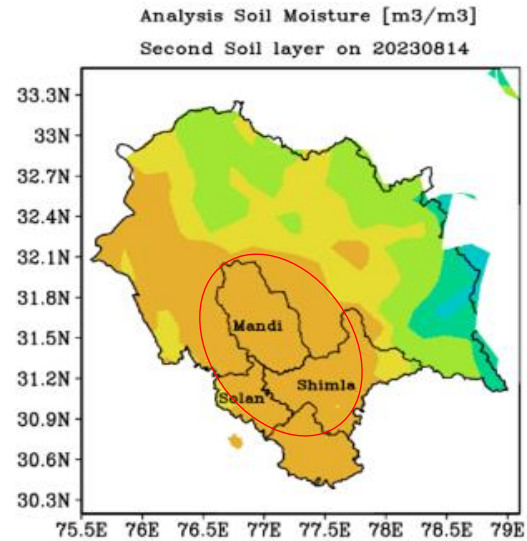
Soil Moisture in the top soil layer (0-10 cm)

- Model simulations show a low amount of soil moisture content over high elevated regions; because of low vegetation cover, this area has a thin soil layer.
- There has been a noticeable increase in soil moisture over locations where landslide occurred, specifically in the topsoil layer for day-1, day-2 and day-3 Forecasts.
- As the forecast lead time increases, soil moisture decreases in parts of Shimla and Solan. Soil moisture in Mandi persists until the day-3 forecast.
- Model is clearly indicating higher soil moisture at landslide sites compared to the rest of the Himalayan region in the state on August 14, 2023.



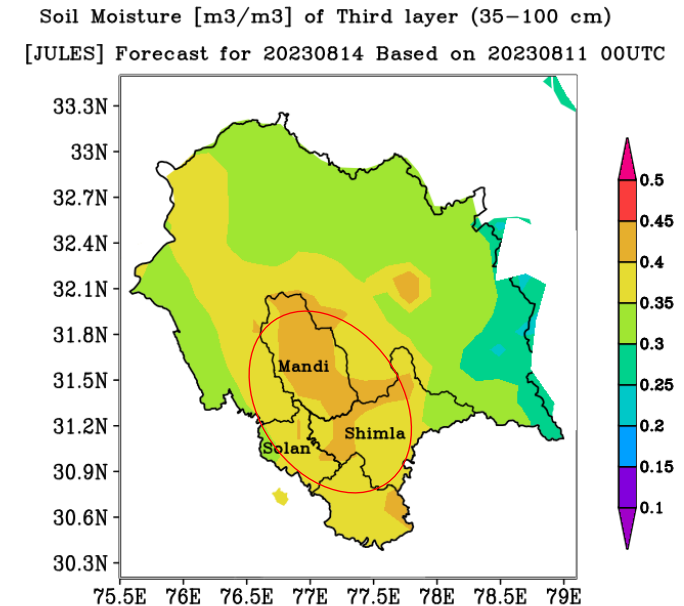
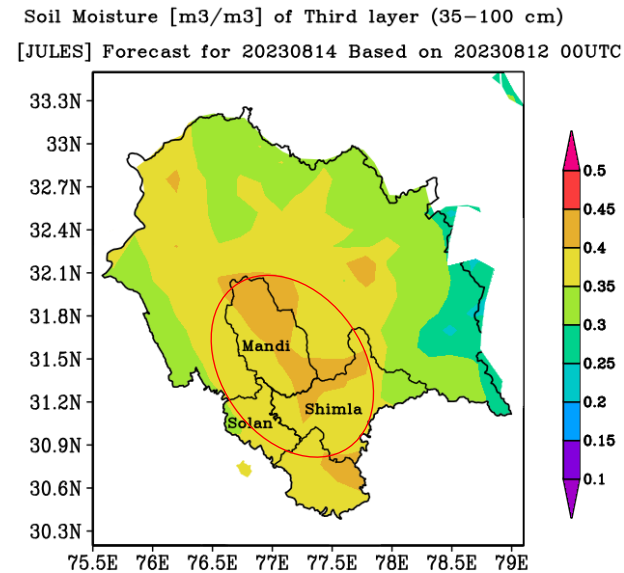
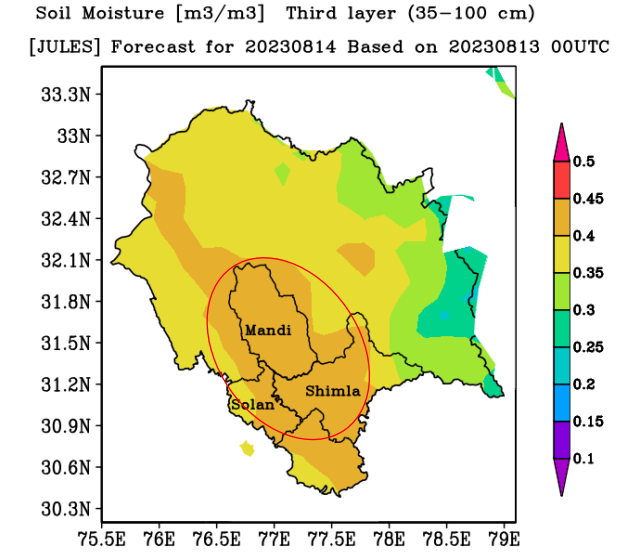
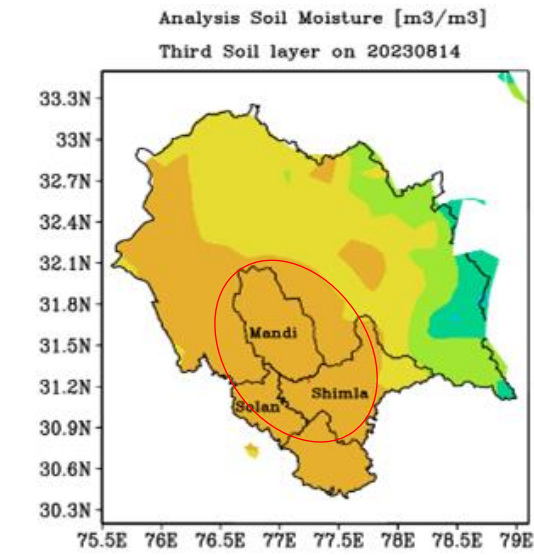
Sub-surface Soil Moisture in the Second soil layer (10 - 35 cm)

- The moisture content in the soil level-2(10-35 cm) layer ranges from 0.2 to 0.45 m³/m³ for the Himachal Pradesh.
- The analysis indicates elevated levels of soil moisture in the western part of Himachal Pradesh, while lower levels are observed in the eastern part.
- The moisture pattern in the second layer mirrors that of the topsoil layer.
- JULES models exhibit strong predictability within the given time frame.



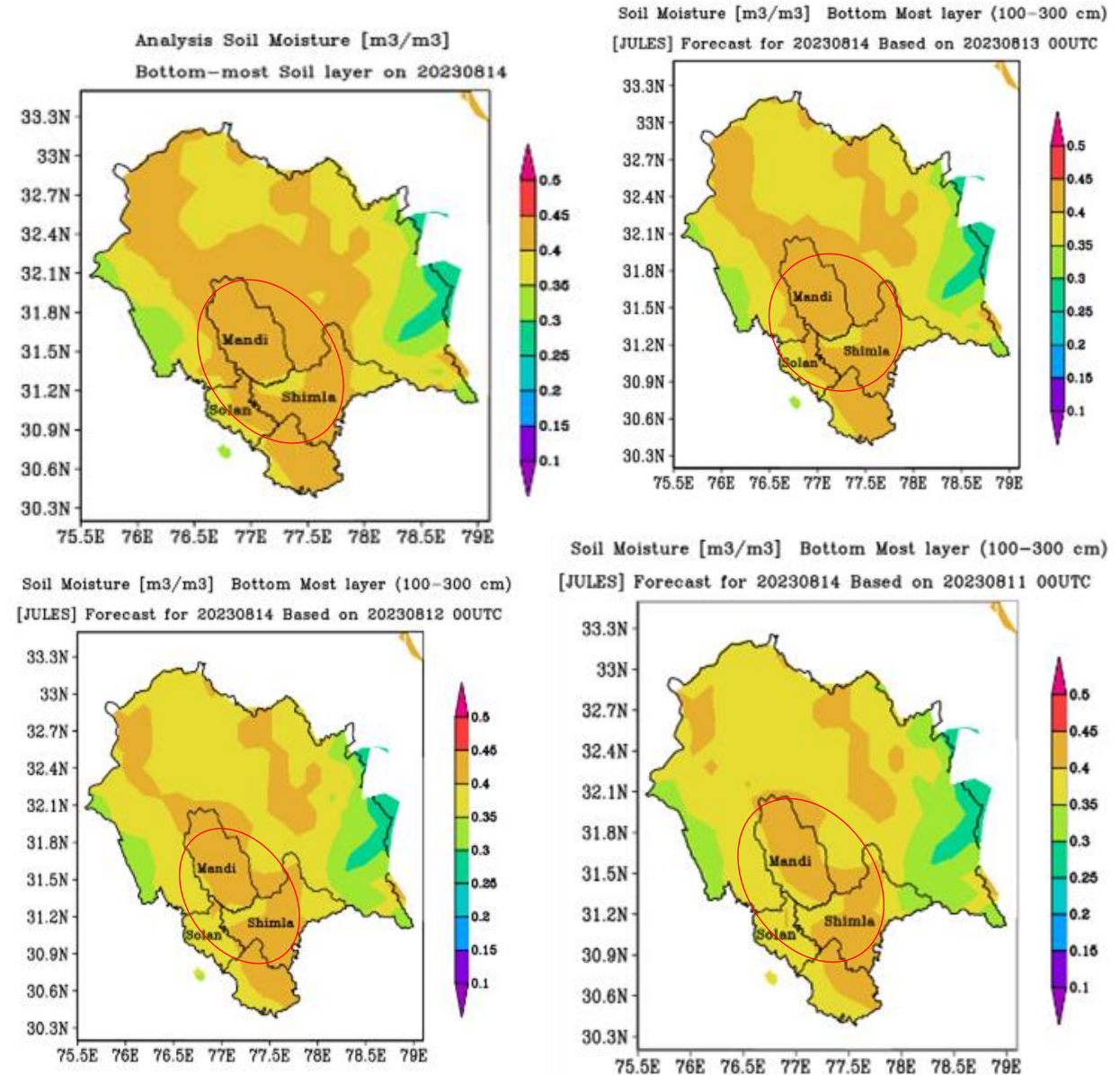
Sub-surface Soil Moisture in the Third soil layer (35 - 100 cm)

- Soil moisture in the soil level-3 (35 - 100 cm) indicate a range of 0.35-0.45 m³/m³, except for a small portion on the eastern side of the state.
- Over the areas where landslide happened, model is showing elevated amount of soil moistures in comparison to the rest of the area in that state.
- Changes in soil moisture forecasts follow a similar pattern to soil layers 1 and 2 as the leading time progresses.



Sub-surface Soil Moisture in the Bottom-most soil layer (100 - 300 cm)

- Soil layer 4 (100-300 cm) shows adequate soil moisture across the most of the area, except for some border areas on the western and eastern sides.
- The moisture in the fourth layer is not solely due to rainfall on that day, but also due to previous rainfall in those areas.
- Therefore, Monitoring the soil moisture trend is crucial prior to slope failure events occurring in these locations.



The JULES standalone analysis was conducted using different initial conditions for the dates August 9, 2023, August 10, 2023, August 11, 2023, August 12, 2023, and August 13, 2023 to assess the predictability of soil moisture in the event of severe weather.

The landslide occurred on August 14, 2023.

In reference to this date,

August 13, 2023 signifies day -1,

August 12, 2023 signifies day -2,

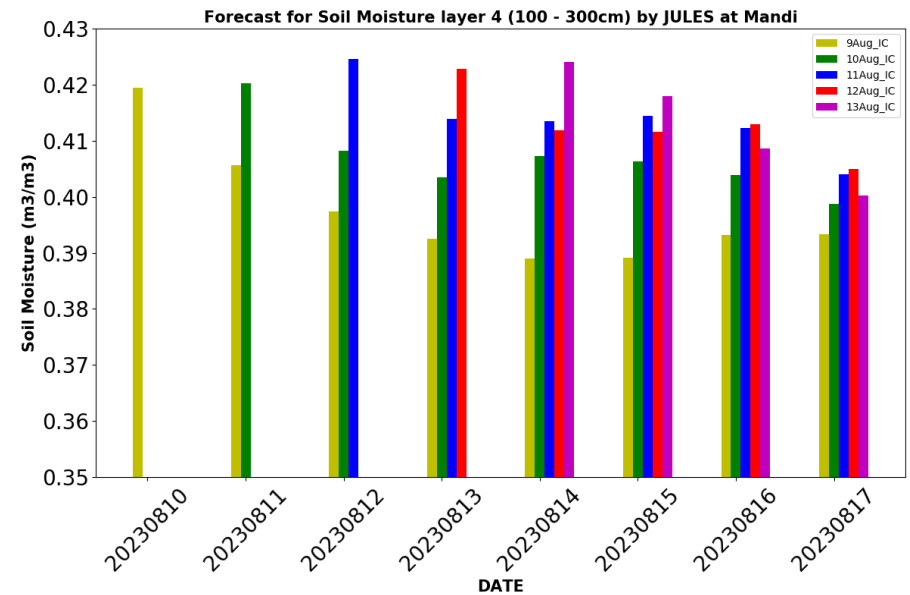
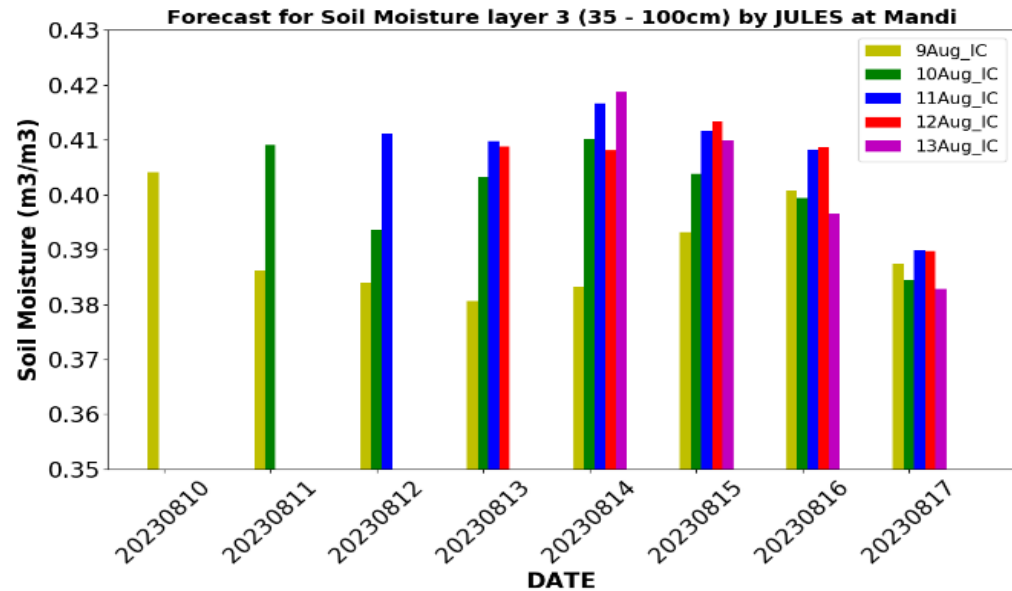
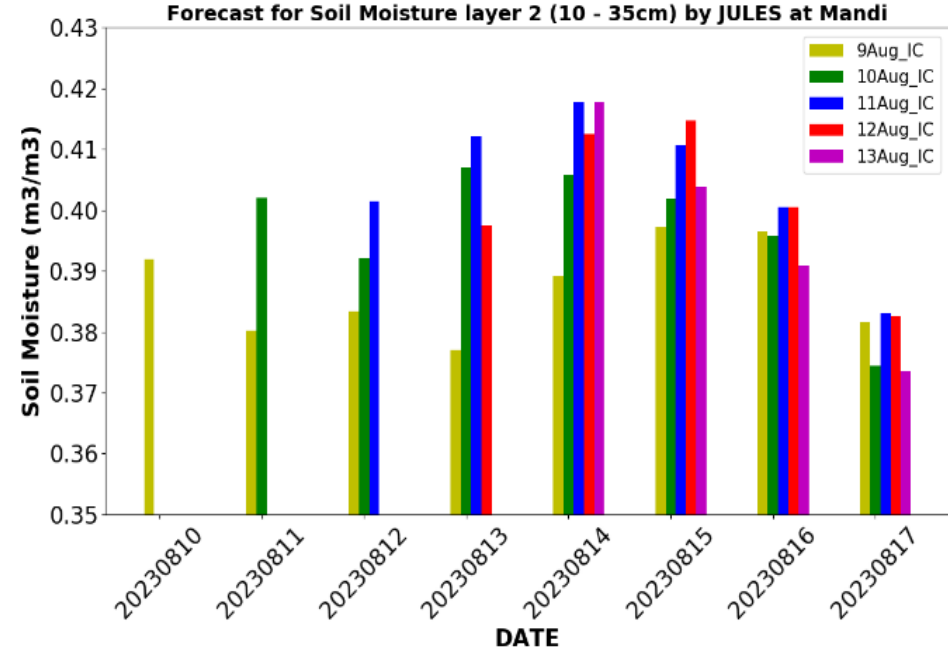
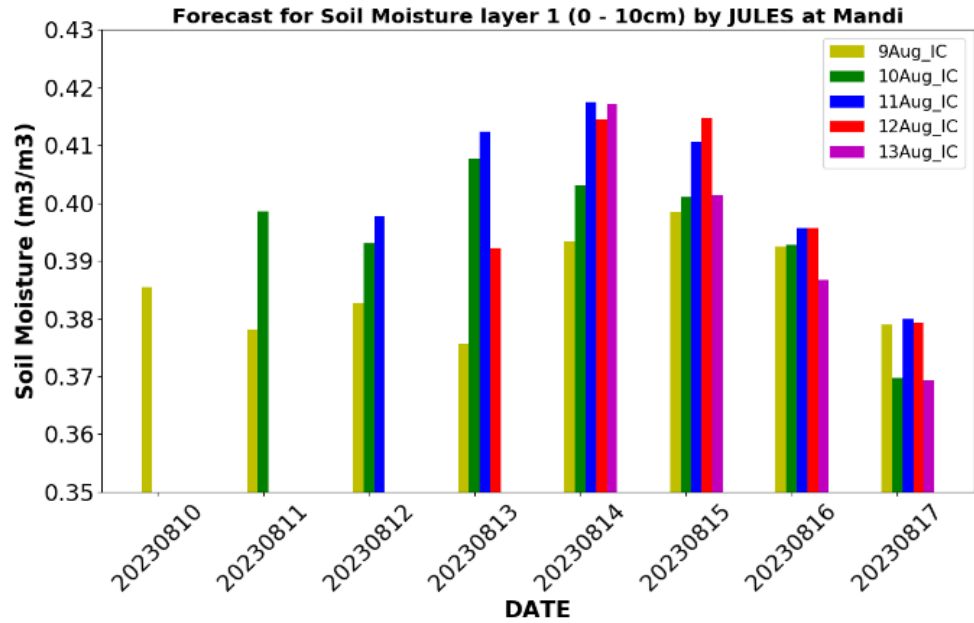
August 11, 2023 signifies day -3,

August 10, 2023 signifies day -4,

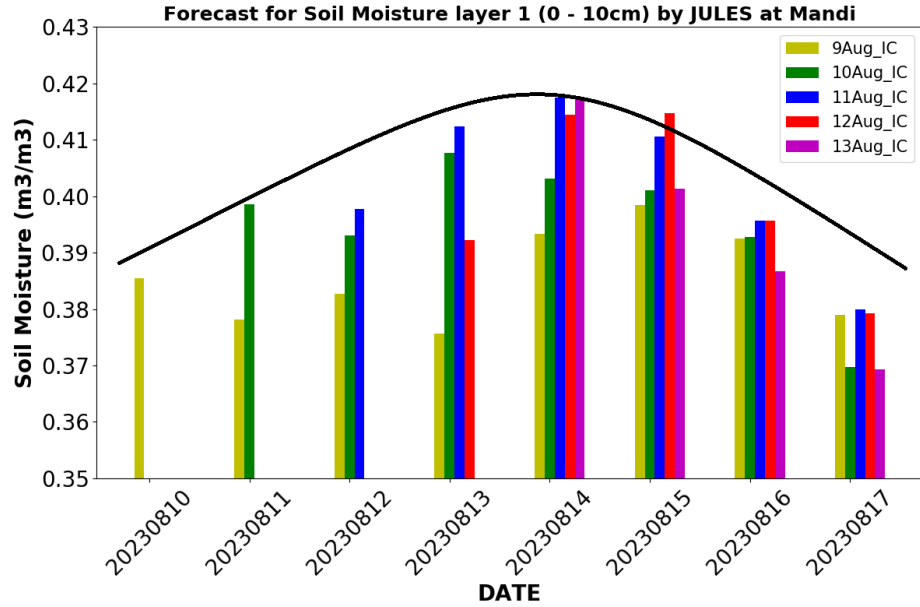
and August 9, 2023 signifies day -5.

Location-1 (Mandi)

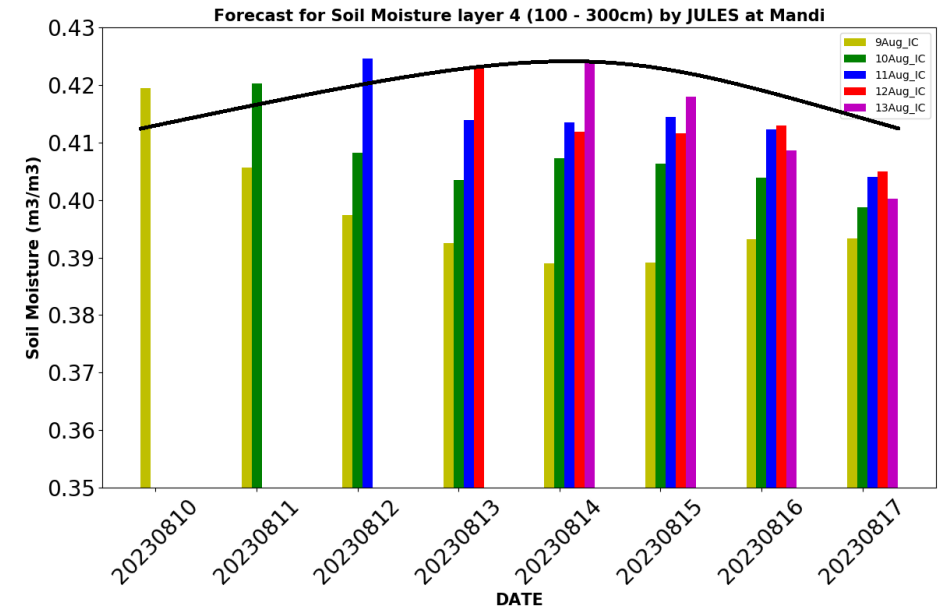
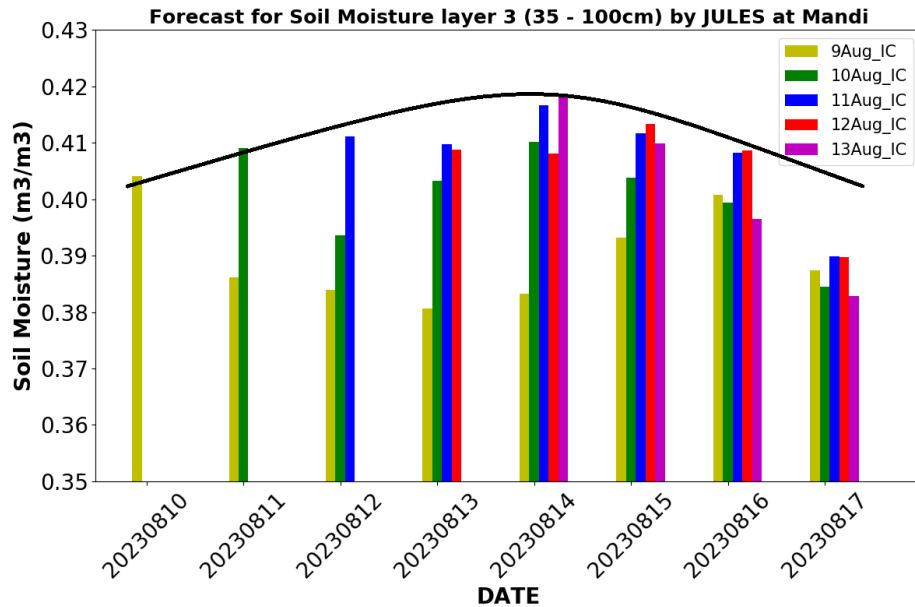
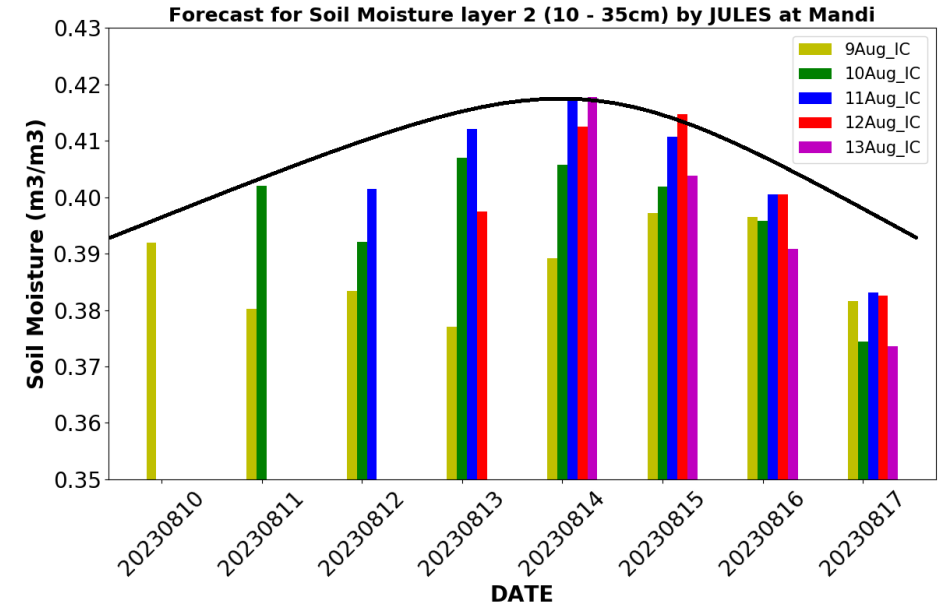
Based on day-3 forecast:
Correlation between rainfall
and top layer soil moisture
~0.94



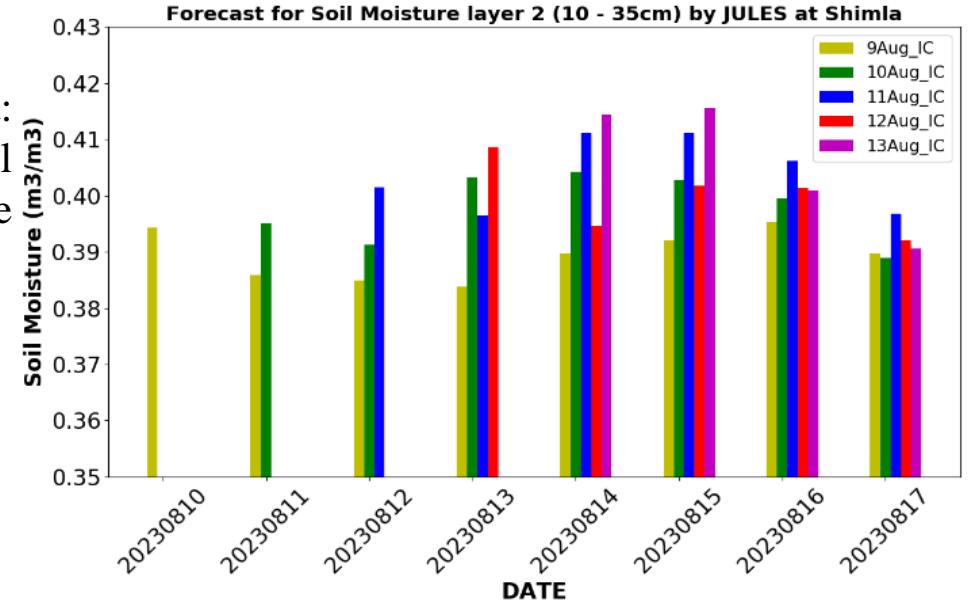
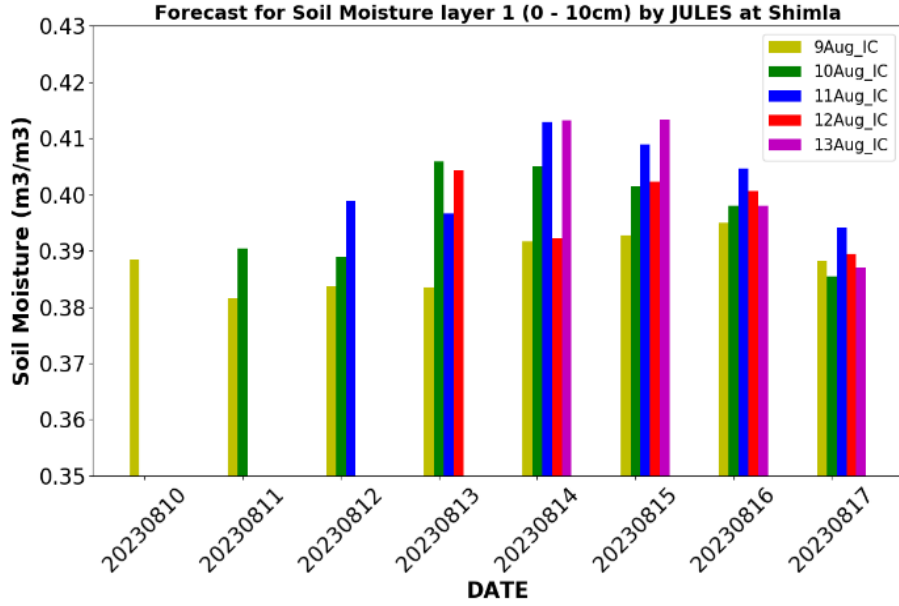
Location-1 (Mandi)



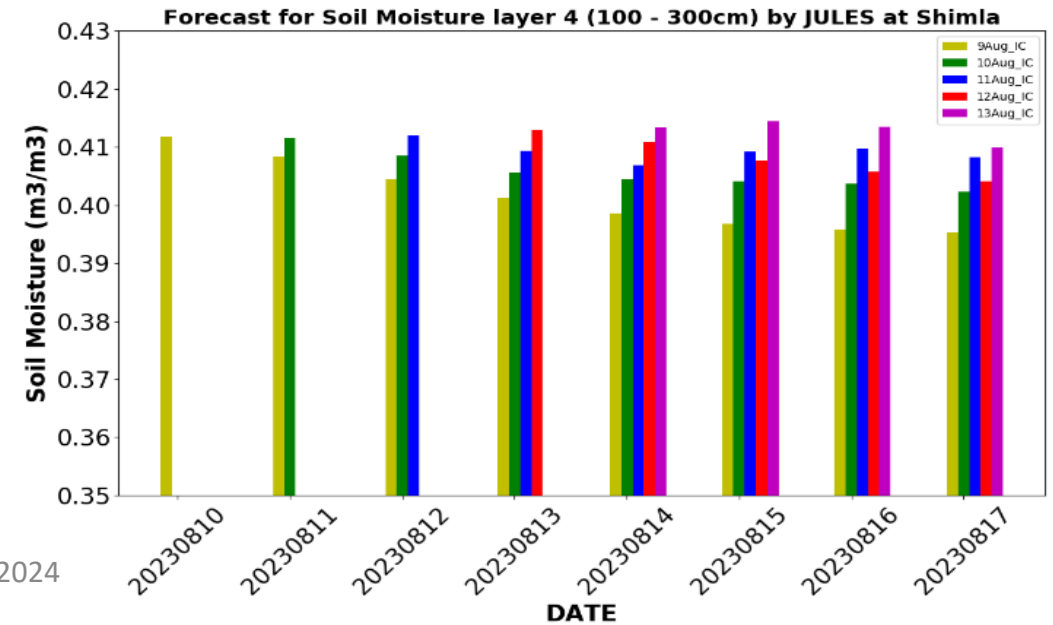
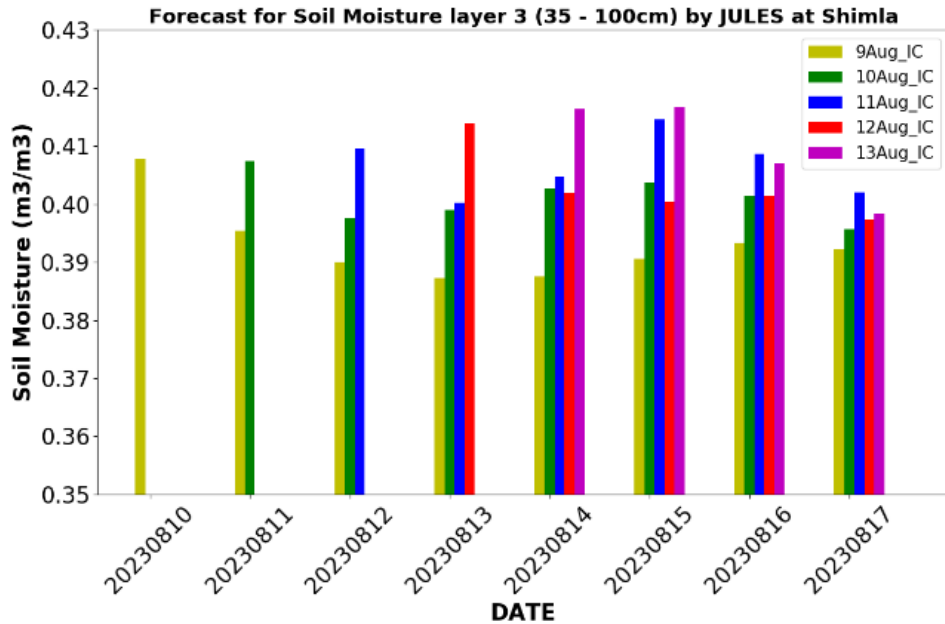
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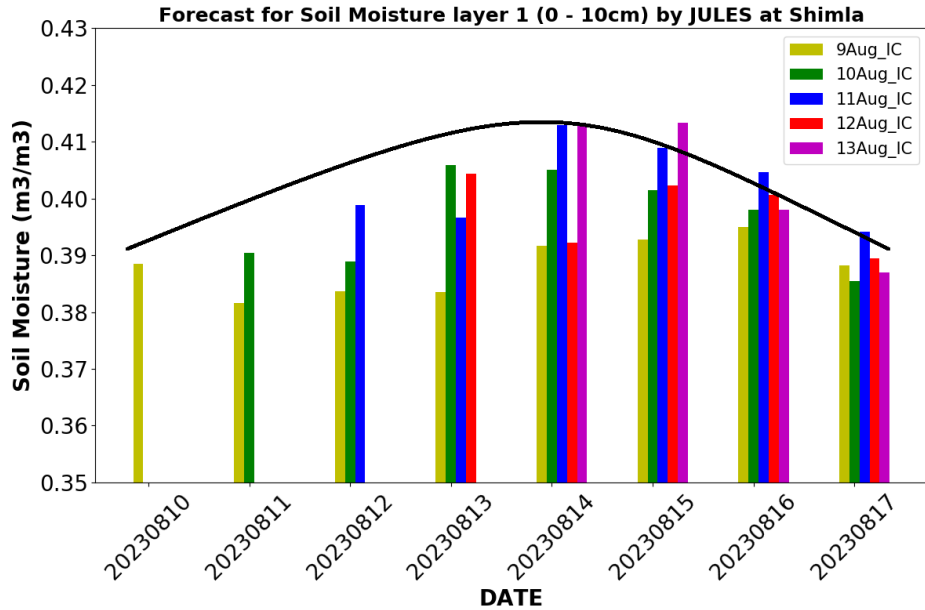
Location - 2 (Shimla)



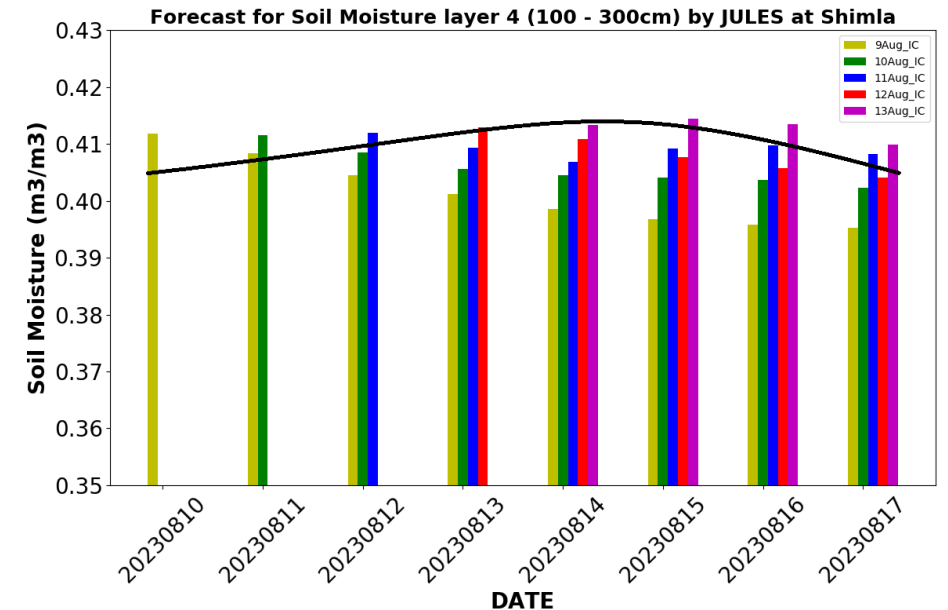
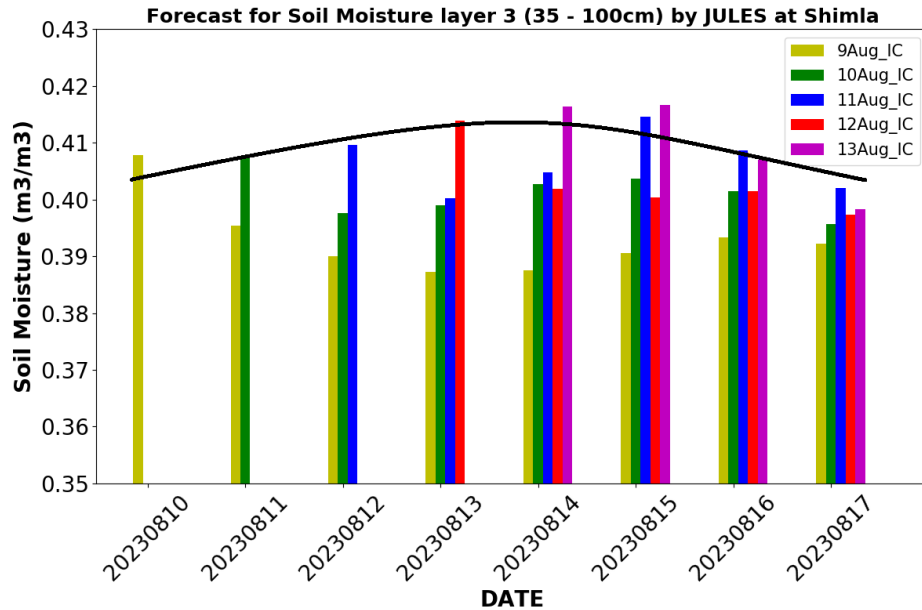
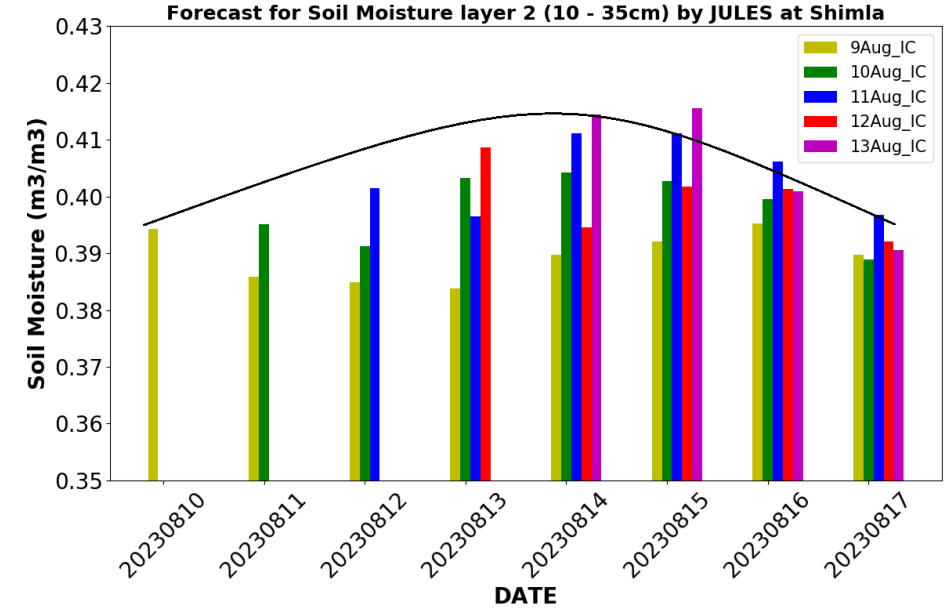
Based on day-3 forecast:
Correlation between rainfall
and top layer soil moisture
~0.78



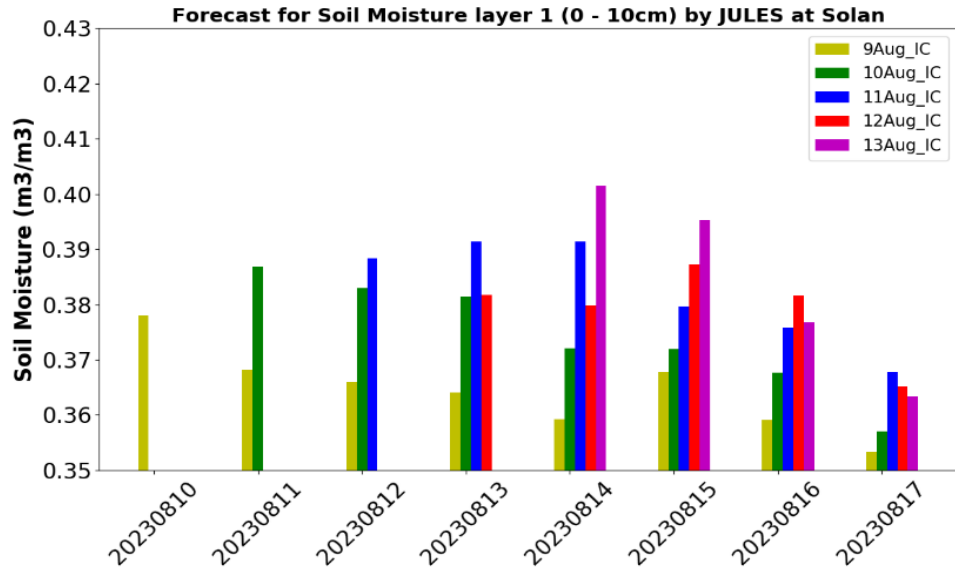
Location - 2 (Shimla)



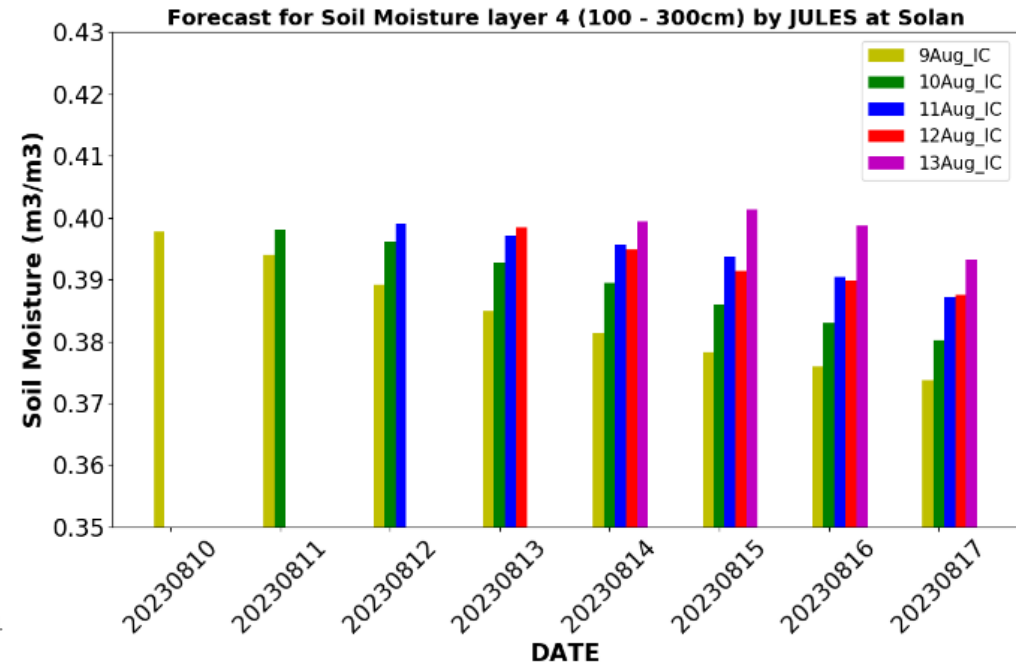
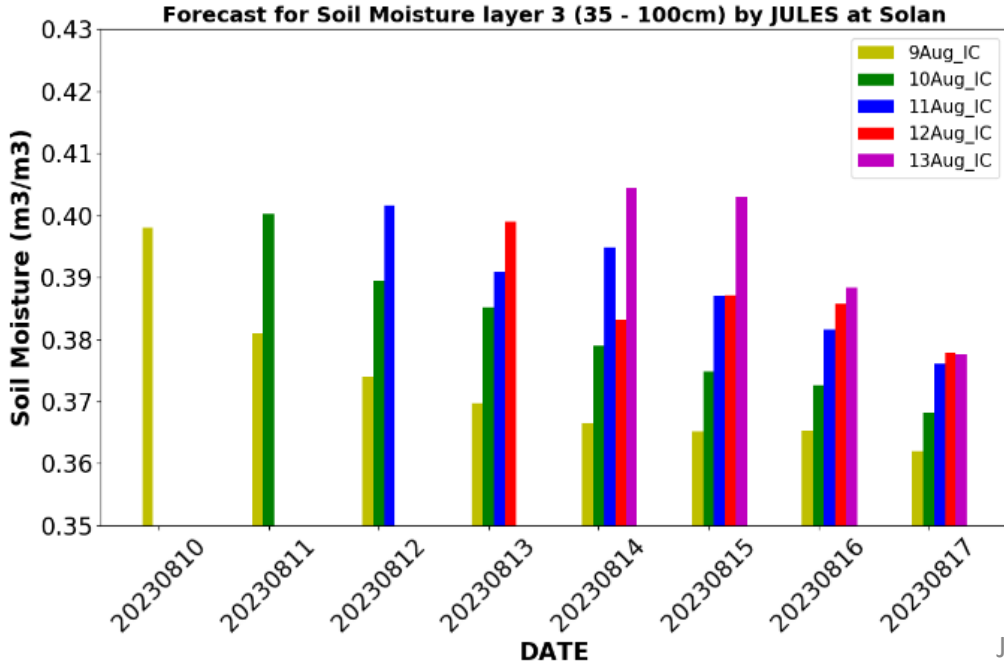
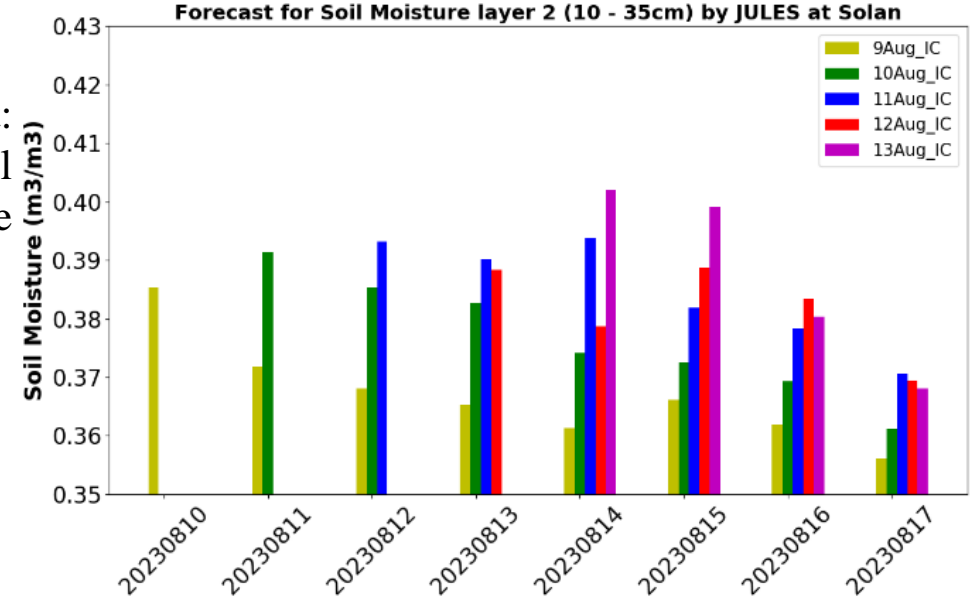
Based on day-3 forecast:
Correlation between rainfall
and top layer soil moisture
~0.78



Location -3 (Solan)

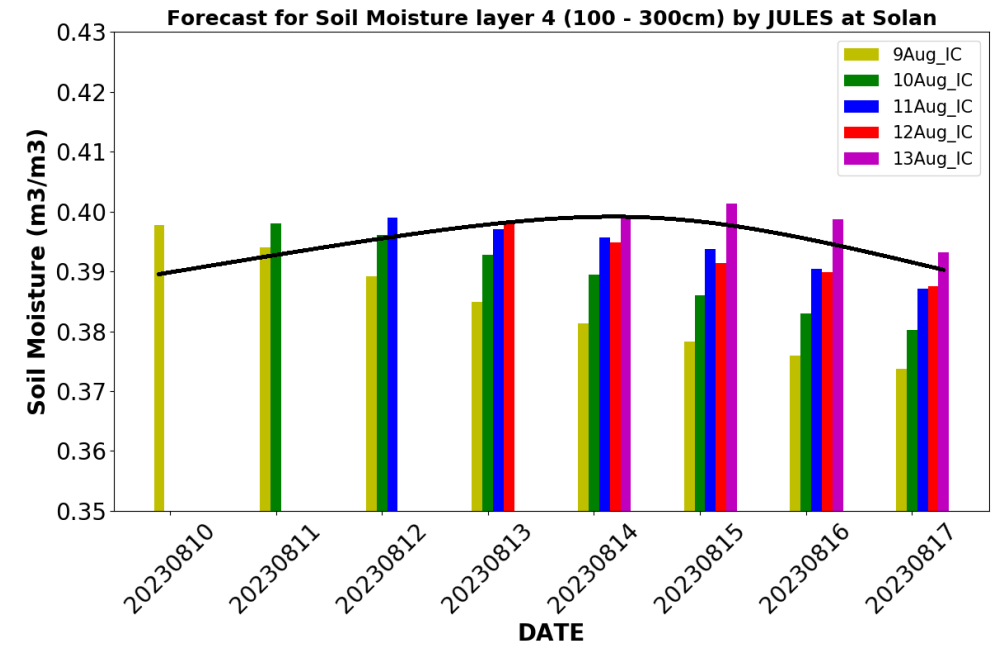
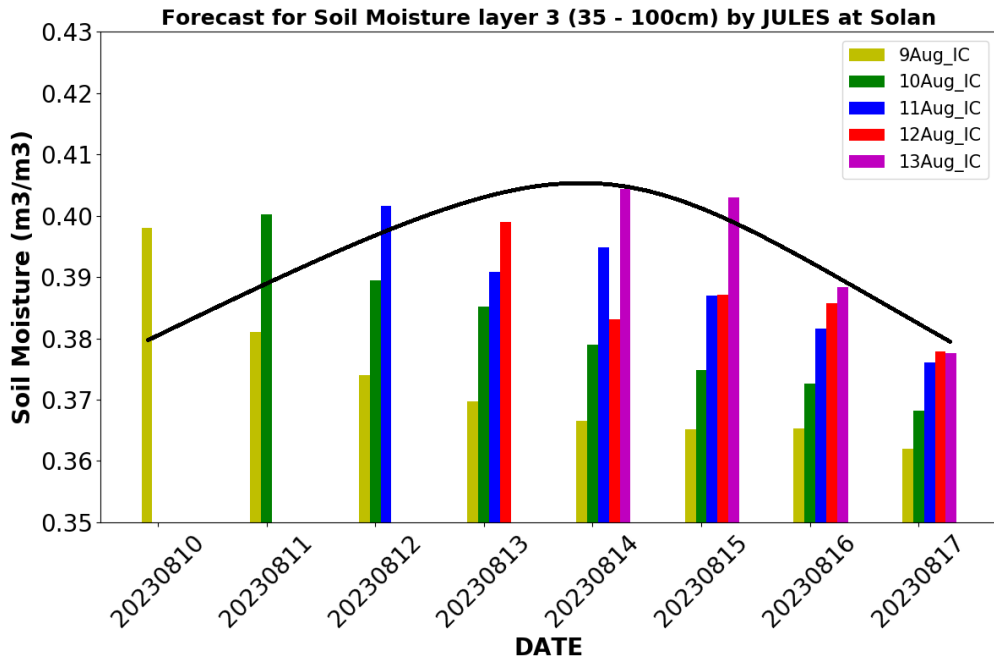
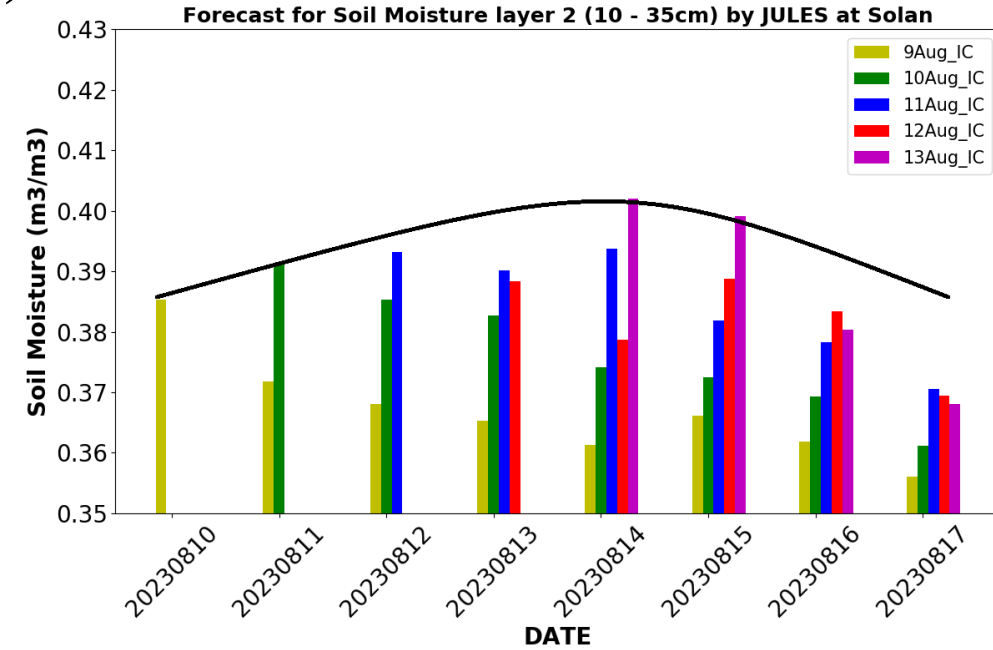
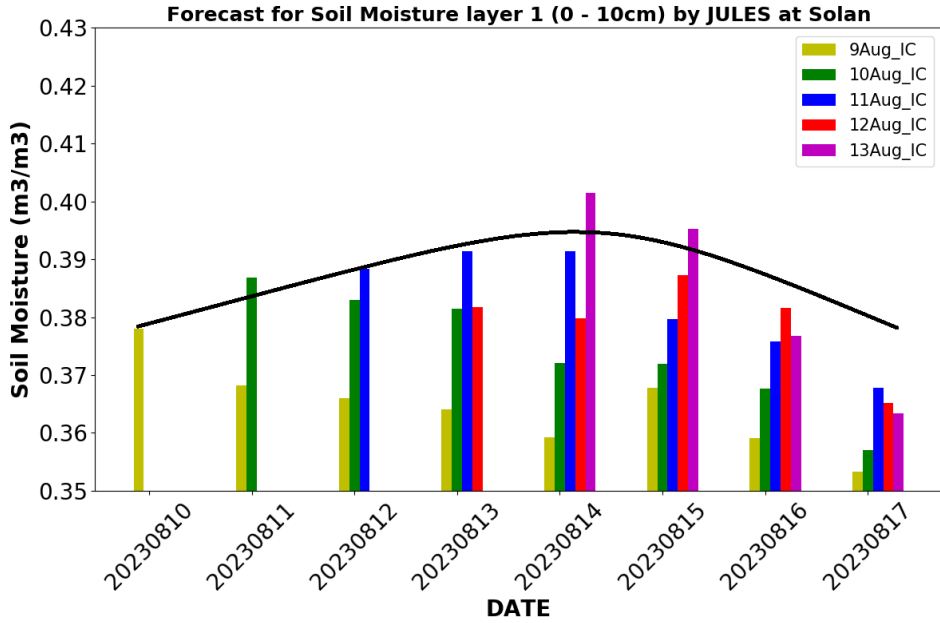


Based on day-3 forecast:
Correlation between rainfall
and top layer soil moisture
~0.60



Location -3 (Solan)

Based on day-3 forecast:
Correlation between rainfall
and top layer soil moisture
~0.60



Conclusions and future roadmap

- The study examines the use of model-derived soil moisture forecasts in predicting landslides. Limited soil moisture observations in complex terrain regions has led to a stronger reliance on observed rainfall data.
- Simulated soil moisture is available at all locations irrespective of its elevation, slope or other characteristics.
- All three locations have experienced a notable increase in soil moisture due to sustained heavy rainfall. The heavy rainfall has led to a higher surface runoff and rest of the water consequently elevated the soil moisture content.
- According to the JULES model forecast, there has been a discernible increase in soil moisture for August 14, 2023 in these locations (Solan, Shimla, and Mandi) specifically in the soil layers.
- The integration of soil moisture data with rainfall and other pertinent parameters demonstrates the potential to markedly mitigate the occurrence of false and overlooked landslide warning forecasts.
- This work is under review in *Natural Hazard* journal.