ABSTRACT

An approach based on remote sensing (RS) and geographic information systems (GIS) has been presented to carry our snow and glacier melt runoff modeling using Landsat satellite data. It consists of five parts, the first part deals with the estimation of the land surface temperature (LST) using mono-window (MW) and split-window (SW) algorithms whereas the second part deals with the estimation of temperature lapse rate (TLR) using Landsat-8 and moderate resolution imaging spectroradiometer (MODIS) satellite data. The third part deals with the cloud and cloud shadow detection and removal techniques for optical data, and the fourth part deals with snow cover area (SCA) mapping using normalized difference snow index (NDSI) technique which can make use of the results from the third part in case of satellite data having cloud and cloud shadow. The first, second and, third parts contribute to the fourth part for precisely mapping snow cover area. Whereas the fifth part deals with snow and glacier melt runoff modeling using the degree-day method, and the results obtained from the first four parts of the methodology become input to the runoff modeling. The methodology presented has been applied to the Beas river basin in Western Himalaya, India.

Global climate change, radiation budgets, heat balance, vegetation, snowmelt, glacier hydrology, and geo-biophysical processes all benefit from LST. As a result, exact LST calculations across vast areas are critical. LST can now be estimated from satellite images using image processing-based algorithms, thanks to the advancement of remote sensing. A critical appraisal of various LST inversion algorithms is shown in this study. These algorithms include the mono- window (MW) and split-window (SW) methods. For the Beas river basin, the MW algorithm was applied to estimate LST using Landsat-8 (Path-147 and Row-38) utilising TIRS band 10 data with a 100-m resolution. For the estimation of LST, the SW method takes spectral radiance and emissivity from two bands of the TIRS as input. Using the TIRS bands 10 and 11, the spectral radiance has been calculated. Emissivity has been determined using the

normalised difference vegetation index (NDVI) proportion of vegetation technique, with bands 4 and 5 (30-m resolution) from the operational land imager (OLI). The MW LST results were also compared to air temperature data, which showed a good match. The MW methodology proposed in this study can be used to estimate LST using Landsat-8 TIRS band 10 data in an effective manner. The estimates of LST from the TIRS and OLI bands using the SW algorithm are found to be accurate and close to the in-situ air temperature measurements and the LST values obtained from the MW algorithm. Results obtained show that the values of LST are high in the barren/rocky areas and low in the snow/glacier areas. The study reveals that the LST estimates from SW and MW algorithms are linearly transferable with negligible loss of accuracy. The LST estimates from the SW algorithm differs at most by up to 5°C with the measured air temperature.

The temperature lapse rate (TLR) is an important component in snowmelt runoff modelling, and it has been computed for the Beas river basin in the Western Himalaya. The SW algorithm was used to estimate the LST of the Beas river basin using Landsat-8 data, formerly known as the Landsat data continuity mission (LDCM). The LST of the study area is negatively correlated with elevation values obtained from the United States Geological Survey's (USGS) advanced spaceborne thermal emission and reflection radiometer (ASTER) global digital elevation model (GDEM) data, indicating that the LST and elevation have an inverse relationship. The TLRs for the Beas river basin area for the period 18 April 2013 to 27 June 2015 are in the range 0.71°C/100 m to 0.87°C/100 m. The results are matched with the lapse rates estimated with the help of MODIS LST maps. The in-situ air temperature and LST from Landsat-8 and MODIS-Terra data have been found to be highly correlated, making this study immensely useful for snowmelt runoff modelling in the Himalayan region.

SCA plays a significant role in high-altitude regions of mountainous hydrology. The Beas river basin, which is a mainly snow-fed river, is in the Western Himalayas and is a part of the

Indus river system. The spatiotemporal flow and avalanche episodes are influenced by the river basin's SCA variability. By taking this into consideration, the current study emphasises SCA variability and its association with numerous topographical parameters such as height, slope, and aspect. Snowmelt runoff modelling, in particular, uses SCA data as a crucial element in a variety of scientific investigations and management applications. The present study has investigated the accuracy of the MODIS-Terra (MOD10A1) and Landsat-8 data in snow cover mapping under Himalayan conditions. Total SCA has been estimated with the help of these two datasets over 3 years. In this study, snow cover in the Beas river basin region has been determined by applying the NDSI algorithm from Landsat-8 and MODIS-Terra satellite data which detects snow cover area. The snow cover mapping, which is an essential process in snow hydrological modelling, involves distinguishing snow pixels from non-snow pixels. It has been implemented in the Beas river basin of the Western Himalayas, India. Totally twelve Landsat-8 and MODIS images have been used for the snow cover mapping during the melting seasons on a monthly basis from April to October of the years 2013 to 2015. The ASTER GDEM with a spatial resolution of (30 m) has been used to delineate the catchment boundary, stream network, slope, and aspect maps. The NDSI method was used for the snow cover mapping. The NDSI maps have been further classified into snowy and snow-free areas based on a threshold value. For a threshold value greater than 0.4, the area is regarded as snowy, otherwise, it is deemed as a snow-free area. This type of categorization has the benefit of SCA estimation under mountain shadow conditions. The mean SCA in this region of the Beas river basin has been found to be between 40 and 51 %, with a mean of around 44 % of the overall basin area of 5382 sq. km. For determining the SCA of the study area, snow accumulation and depletion curves have also been produced.

Clouds and their associated cloud shadows typically obscure land surfaces and make it difficult to analyse shift trends over time. Using the Landsat-8 initial image data (WRS2:

Path/Row =147/38, collected on April 24, 2015), this study illustrates a new way for detecting and removing cloud and cloud shadows. This method uses six of the nine bands for modification in order to calculate the intensity of cloud and cloud shadows, which is then removed. The spectral information of the various bands is utilised in this manner. According to the validation, the cloud and cloud shadows contaminated pixels are properly recognised, with overall accuracies of 97 and 96 percent, respectively. However, this method's usefulness is limited when dealing with dense clouds and cloud shadows. This methodology has the potential to be used for atmospheric corrections to improve landscape change detection with further development.

Rainfall, snowmelt, and glacial melt are the primary sources of discharge for large Himalayan rivers. A large population is reliant on the runoff from Himalayan rivers with considerable hydroelectric potential; floods are also common in these rivers. Snowmelt runoff estimation is critical for India's western Himalayan rivers, which are critical for hydropower generation and water storage during the non-monsoon season. A degree-day method based snowmelt runoff model (SRM) has been presented to estimate snow and glacier melt runoff on a daily basis in the Beas river basin up to Pandoh dam during April, 2013 and October, 2015. The model's input parameters are derived from existing maps, satellite data, metrological, and hydrological data. The basin's relief has been divided into 12 zones having 500-meter elevation. TLR has been derived from the observed temperature at three locations inside the basin to estimate the temperature for these elevation zones.

The basin's SCA is calculated using Landsat-8 satellite data. For each elevation zone, the runoff created by snow-covered and snow-free areas is estimated individually. For the simulation period of April 2013–October 2015, the average coefficient of determination (R^2) for the snowmelt season in the Beas river basin is 0.77. The average measured runoff volume is 24009.40 (10^6 m^3) and, the average measured runoff is 802.47 (m^3/s), whereas the average computed runoff volume is 25784.04 (10^6 m^3) and, the average computed runoff is 772.51 (m^3/s). The average volume difference is (+) 6.68%.

For better modelling, more focus is needed to strengthen the spatial and temporal hydro-meteorological database for the study area. The SRM model is a degree-day model that is more sensitive to temperature differences at various elevations. Because snow is the region's primary supply of water, a precise estimate of snow equivalent is required. This necessitates the installation of meteorological stations inside the study area. The SRM model is adequate for flood forecasts and water resource management in the study area, based on the values of R^2 and D_v for the melting season simulation.