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Remote Sensing in Hydrology

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Abstract: *Hydrology is the scientific study of the occurrence, distribution, movement and the physical and chemical properties of water, and its relationship with the living and material components of the environment. Due to water scarcity, population growth, improved quality of life, enhanced quality of healthcare, ever-increasing water consumption and food shortages in the future decades, many countries will face a crisis, that there will be no promising solution for it. Therefore, to investigate the various water resources and to monitor those parameters influencing the hydrological cycle, those sensors capable of estimating different patterns of these parameters are used. One of the most important applications of radar data is to use them in hydrologic models. Those methods used for the estimation of hydrometeorological fluxes, i.e. evapotranspiration and snowmelt runoff, are also described using these state variables. Remote sensing is the process of deduction of surface parameters based on the measurement of electromagnetic radiation upwelling from the Earth's surface. The present study focuses on those applications of remote sensing that are more promising in hydrology in our belief.*

Keywords: *Hydrology, Remote sensing, Meteorological fluxes, Upwelling*

INTRODUCTION

Remote sensing is a tool for estimating the hydrological cycle parameters. Remote sensing is the process of deduction of surface parameters based on the measurement of electromagnetic radiation upwelling from the Earth's surface. This radiation is both reflected and released by the Earth. The former is usually the reflected solar radiation, while the latter has a spectrum in both Thermal Infrared (TIR) and microwave sections. There is also a radiation of the microwave reflected from the imaging radars. Solar radiation reflected in hydrology is used for the survey of vegetation /land cover and water quality studies. The thermal emission in the infrared is used for surface temperature and in microwave for soil and snow moisture studies. In the present study, it is attempted to discuss the applications of radars in the precipitation studies and it is focused on the use of the visible and near-infrared (VNIR) data for snow survey and water quality; the TIR for surface temperature and energy balance studies; passive microwave for snow. The use of active microwave or radar is promising because of its high spatial resolution. However, the effects of surface roughness can make it difficult to extract the information on soil moisture. Remotely sensed observations can help us know these values, and in particular their spatial change. Using remote sensing, we not only observe the surface, but can also achieve spatial variability if the observations repeatedly determine the temporal variability.
In hydrology, the main aim of remote sensing research is to develop those methods capable of estimating hydrometeorlogical states and fluxes. The initial set of state variables includes the surface temperature, the near surface soil moisture, the balance of the snow/water cover, the water quality, the landscape roughness,

the use of land and vegetation. The hydrometeorlogical fluxes are primarily soil evaporation and plant transpiration, or evapotranspiration, and snowmelt runoff. Those variables studied in the present study are rainfall, runoff, evapotranspiration, and snow.

Theoretical Foundations

Hydrology and its elements

Hydrology is the scientific study of the occurrence, distribution, movement and the physical and chemical properties of water, and its relationship with the living and material components of the environment. Hydrology consists of two words of "Hydro", meaning water, and "logos" meaning study, and in the broad sense of the word, it is the science of water. The following figure shows the hydrological cycle. The hydrological cycle is a cycle without the beginning and the end and occurs as follows: the water evaporates from the surface of the seas and the lands and enters the atmosphere. Then, the water vapor entering the atmosphere returns to the surfaces of the Earth and the seas and oceans as precipitations during various processes.

Whenever a heavy rainfall occurs on a basin, due to the lower soil permeability at the very beginning of the rain, water flows on the earth's surface and enters rivers through watercourses. In order to estimate the surface runoff of a catchment area, the method proposed by the American Soil Conservation Service (SCS) is more likely to be used. As the result of this method, those sub-basins in areas that can produce a large amount of runoff and thereby, leading to irreparable damage to the farmers in these areas are determined (Ghoraba, 2015; Durand, Molotch and Margulis, 2008).

Rain measurement refers to the measurement of rainfall amount without infiltration or evapotranspiration. Rain gauge station is a point in an area where rainfall is measured. The results of these stations are generalized for the whole basin. Therefore, a suitable place which represents the whole area, must be selected. The purpose of all researches in this field is to estimate the precipitation in the studied area using different methods such as radiosonde, rain gauges, etc. (Baker and Miller, 2013).

Hejazizadeh (2017), studied the drought trend (intensity, continuity and the area affected by drought) in Chaharmahal and Bakhtiari province using standardized precipitation index for different periods. The results showed that drought occurs when the standardized precipitation index has negative sequences, and there is an intense drought when the standardized precipitation index values are equal to -1 or less. As this index becomes positive, a drought ends (Gajbhiye, 2015).

Snow is one of the important factors in controlling the hydroclimate of each geographical region. The estimation of snowfall rate in a catchment area requires a snowmelt algorithm as part of the modeling system. The Snowmelt Runoff Model (SRM) was originally designed to simulate and predict snowmelt in the small mountainous catchment areas of Europe by Martinec and Rango. It is of the models widely used in the simulation and forecast of snowmelt rate (Stisen and Sandholt, 2010). Entezami (2012) estimated the Snow Cover in the Saghez Watershed, Kurdistan province, using the MODIS satellite images and two LSU and NDSI algorithms. Based on the results of regression, LSU method is more correlated and there is no significant difference between the IRS images and the LSU method according to the results of the t-test. Therefore, the LSU method is more accurate than the NDSI method in the estimation of the snow cover (Entezami *et al.*, 2017).

On the other hand, the accurate estimation of evapotranspiration plays an important role in the regional water balance for water resources planning and management. Evapotranspiration is achieved through estimation of potential evapotranspiration at meteorological stations or directly from field measurements, but evapotranspiration is greatly influenced by the changes in time and location of precipitation, soil hydraulic properties and type and density of vegetation. One of the most important algorithms in calculating real evapotranspiration is the Surface Energy Balance Algorithm (SEBAL), which can be used to estimate the various components of the Earth's surface energy balance as well as real evapotranspiration (Yang *et al.*, 2016). Miryaqoubzadeh *et al.* (2018) determined and evaluated real evapotranspiration in the Temer Watershed, Golestan province, using remote sensing data. In this regard, the SEBAL and Penman-Monteith equation were used and the results showed that the SEBAL estimates the evapotranspiration 0.5 to 1 mm per day less than the Penman-Monteith equation, as well as groundwater is considered as other important elements of the water cycle and estimation of its changes is very important in hydrology. There are many hydrological models that describe the groundwater reserves, the Global Land Data Assimilation System (GLDAS), the Partners for Climate Protection (PCP) program, the National Centers for Atmospheric Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) and the WaterGAP (Global Assessment and Prognosis) Global Hydrological Model (WGHM) (Gallego-Elvira *et al.*, 2012). In many cases, the changes in groundwater have been determined by removing a number of factors from grace satellite data and using different tools (Morin *et al.*, 2005).

Hydrological models

1. **Stanford Watershed Model (SWM)**

This model was developed to simulate the physical phenomena of rainfall-runoff. The model has 32 parameters, and hourly rainfall and daily potential evapotranspiration data are the inputs of this model. This model has many applications, including the provision of continuous hydrographs, the determination of runoff coefficients, and the determination of urbanism impacts on the flood peak and volume. In this model, rainfall in impervious areas of the basin, such as lakes and rivers, is considered as direct runoff and interception and soil moisture storage as a potential of evapotranspiration (Audet and Dennis, 2002).

2. **Streamflow Drought Index (SDI)**

To study the hydrologic drought, several indices have been developed. The most famous index is called the Standardized Precipitation Index (SPI), which was first introduced by McKee *et al.* However, for hydrological drought, one can use another index similar to SPI, which is called the Streamflow Drought Index (SDI). It is based on the standardized monthly streamflow values and was first proposed in 1987 by Ben-Zvi. The computational principles of this index are presented in the figure below (Bashar, 2012).

3. **Sacramento model**

This model was developed in 1973 by Burnash *et al.* and is one of the most widely used rainfall-runoff models. It is suitable for large basins and uses annual recorded data for calibration (Chiew, Peel and Western, 2002). This model shows the parameters and properties of soil moisture in such a way that:

1. Distribution of soil moisture at different soil depths is reasonable.
2. The characteristics of the infiltration are reasonable.
3. It allows effective simulation of the base streamflow.

4. **Australian Water Balance Model (AWBM)**

This model was first introduced in 1993 by Walter Boughton. The model has a few parameters and each parameter specifies a particular part of the hydrologic responses of the catchment. It is one of the rainfall-runoff models and uses daily hourly rainfall. The model was completed in 1993 by Boughton. The daily results of the model are used in rainwater harvesting and management studies and its hourly results for flood design calculations.

5. **Soil and Water Assessment Tool (SWAT)**

It is a continuous model and the current form of which was developed in 1996 by Arnold *et al.* This model is used for the simulation of daily river discharge, the estimation of daily sediment, and the estimation of water quality regarding the changes in the land uses. This model is used in those studies on large watersheds or at the sub-basin scale. This model is a suitable tool for simulating the hydrological processes, water quality, soil erosion, crops, rangeland management and climate change effects (Behmanesh *et al.*, 2014).

6. **HEC-1 model**

The model was developed in 1981 by the U.S. Army Engineer Hydrologic Engineering Center (HEC). To further enhance the ability of this model to study complex hydrologic issues and also to easily work with it, it was developed in a Windows environment, called HEC-HMS. This model is used for a single-occurrence storm with distributed parameters and it includes several options for modeling rainfall, losses, unit hydrographs and streamflow routing (Fan, Ko and Wang, 2009).

Results

1. Surface runoff

Using RS, GIS and SCS, it is possible to create management plans for the use and development of watershed in the following way: the spatial variation of rainfall with a certain percentage of deviation from the basic rainfall is considered for each triangular area of the studied area, which has a share in the runoff. A topographic map is used to integrate GIS and RS. To this end, the images obtained from sensors, such as LANDSAT, have been used (Abudu *et al.*, 2012).

Estimating the snowmelt runoff and the streamflow resulting from the different pond is very important for water management. Also, the results of studies in this field has proved that the SRM is the best tool for calculating snowmelt runoff in mountainous areas. The SRM can be used to estimate and predict snowmelt runoff in the mountainous watersheds of almost any size and height.

The SRM was developed using two accuracy criteria:1. The coefficient of determination, R^2; and, 2. The volume difference, D_v. The coefficient of determination is calculated as follows:

$$R^2 = 1 - \frac{\sum_{i=I}^{n}(Q_i - Q_i)^2}{\sum_{i=I}^{n}(Q_i - \bar{Q})^2} \qquad (7-2) \qquad (1)$$

Q_i: measured daily discharge
Q'_i: calculated daily discharge

$\overline{Q}$ is the mean of the measured discharge in a given year or the snowmelt season. n is the number of daily discharges. The deviation of runoff volumes, Dv, is calculated as follows:

$$D_v[\%] = \frac{V_R - V_R}{V_R} . 100 \qquad (8-2) \qquad (2)$$

The success of any water project depends on the reliable estimation of runoff volume. In the present study, the GIS and remote sensing-based SCS CN model was used to estimate the runoff from the rainfall event in an urban watershed. In the present study, it is also shown that the GIS-based SCS-CN model is an appropriate tool for calculating runoff and helps to plan and manage a watershed. The SCS CN model, combined with the Muskingu-cunge routing method, requires accurate knowledge of several spatial distribution parameters affecting runoff such as soil, land use, antecedent soil moisture conditions, channel information, and so on. The SRM is very sensitive to input data, especially temperature and precipitation and simulates runoff with the correct delay in relation to the related event. Since the metrological stations are located at very low altitudes, it is recommended to equip the rainwater catch basin with temperature inspection cameras and rain gauge stations at altitudes. Since the critical temperature and daily average temperature are two important parameters in predicting snowmelt runoff and snow hydrology, it is recommended to determine them for different places and at different times by the help of research centers and metrological organizations. Simulated runoff hydrographs were generated at the main outlet of the watershed. Continuous advances in the distributed hydrological modeling, in addition to its integration with GIS, has led to the development of robust tools for the prediction of runoff in watersheds. In particular, GIS allows the combination of remote sensing data with spatial data such as topography, soil maps, and hydrological variables such as rainfall distribution and soil moisture distribution. This study describes the importance of parameterization in predicting runoff in watersheds.

2. Rain

To estimate rainfall from satellite images, those algorithms are used. They are divided into three infrared rainfall and microwave rainfall algorithms and a combination of the two algorithms according to the wave length used by the sensors. The infrared rainfall algorithms have good spatial and temporal resolution, while rainfall can be measured directly using microwave rainfall algorithms. However, these techniques have many weaknesses, especially in those circles of the Earth at lower latitudes (Entezami *et al.*, 2017; Ahmad and Verma, 2016).

The standardized precipitation index was first developed to monitor drought in Colorado by McKee *et al.* The only input required by SPI is monthly or weekly precipitation data. The standardized precipitation index is based on calculating the probabilities of precipitation in each time window and the gamma probability density function is used for monthly and weekly precipitation data. The following equation is related to the SPI:.

$$SPI = -\left[t - \frac{c_0+c_1+c_2t^2}{1+d_1t+d_2t^2+d_3t^3}\right] \quad for \quad 0 < H_x(X) \leq 0.5 \qquad (3)$$

$$SPI = +\left[t - \frac{c_0+c_1+c_2t^2}{1+d_1t+d_2t^2+d_3t^3}\right] \quad for \quad 0.5 < H_x(X) \leq 1.0 \qquad (4)$$

Another method is to use the runoff coefficient. The runoff coefficient is a dimensionless coefficient relating the amount of runoff to the amount of precipitation received. The concept of the runoff coefficient dates back to the early twentieth century. The runoff coefficient can be defined as the runoff depth to the full precipitation depth ratio or as the ratio of current moisture to the rainfall intensity during the concentration time. Also, in the event-based flood frequency models, rainfall is used to estimate the occurrence of the flood. At this time, rainfall-induced runoff occurs, its coefficient varies with topography, land use, vegetation, soil type and soil moisture.

Another method is to use the Runoff Curve Number (CN), which is an experimental parameter used in hydrology to directly predict runoff or infiltration using precipitation. Runoff curve number employs an empirical analysis of runoff of small basins and hills under the supervision of the US Department of Agriculture.

Remote sensing has a great potential in estimating rainfall, but it cannot be fully used for remote and inaccessible coastal areas, especially in sub-Saharan Africa, where the appropriate climate control network system is facing challenges. Therefore, this study is heavily involved with the fact that the use of remote sensing data for estimation of precipitation is a prerequisite for water resources management in these areas. In Satellite-based Rainfall Estimates (SRFEs), there are overlaps, including local rainfall data and those specifically designed for Africa. The performance of CPC-FEWS or CCD in the estimation of rainfall depends on the sensing data on the local load or local adjustment algorithm or both of them. Among the global products, CMORPH and PERSIANN have more bias than TRMM, probably due to the loss of rain gauge data in the algorithms. However, both CMORPH and PERSIANN act better after modification, indicating their ability to describe rainfall periods and inter-annual differences. The TRMM is very poor in hydrology. When working with the SRFE, the inter-annual differences are important because their ability to distinguish wet from dry years should be inherent in raw data products. This is of great importance because, in the presence of such a defect, it is difficult to overlap without a rain gauge data set. It actually eliminates the need for SRFE. The main advantage of the SRFEs in both time and space is the simulation of the model, which allows it to be used to evaluate the quality of input data of rainfall for a specific program. This study also showed the importance of calibration of the specific input model. A model cannot be calibrated with a loading input and can be used with another. This suggests that even in comparison with rainfall, the products are significantly different in temporal and spatial dynamics, affecting the prediction of the hydrologic model. There is still a need for rain gauge data. However, in areas where rainfall is low and there are data gaps, they can be used to access SRFE quality and to modify sensitivity. Therefore, SRFEs can be very useful due to their continuity in time and space, and are a prerequisite for the management of continuous, distributed hydrologic models.

3. Snow

The SRM is used to estimate snowfall. This model was originally developed by Martinec (1975) and has been used in over 100 watersheds ranging from 0.8 km² to 917.444 km² in 29 different countries, and its results have been published in about 80 journals. The SRM is a modern and definitive hydrologic model used to simulate daily rainfall-induced and snowmelt runoff in mountainous areas. It needs daily temperature, rainfall and daily snowfall as input parameters. The streamflow is calculated using the following equation:

$$Q_{n+1} = [Csn \cdot a_n(T_n + \Delta T_n)S_n + Crnp_n] \cdot A \cdot (10000/86400) \cdot (1 - K_{n+1}) + Q_n \cdot k_{n+1} \quad (5)$$

The original SRM model has been developed to model the effects of climate change and the spread of glacier melt.

Another method is the time series of the Snow-Covered Area (SCA). The Moderate Resolution Imaging Spectroradiometer (MODIS) and the Landsat Enhanced Thematic Mapper Plus (ETM +) and a dense snow avalanche model and re-rainfall model were used to reconstruct the snow water equivalent in the Rio Grande headwaters. The linear optimization was used for SCA estimates that preserve the statistical moments of higher spatial resolution.

The third method is the LSU method. It is assumed that the radiances measured by the sensor are a linear combination of the radiances reflected by EMs, each of which has a unique spectral sign. Each EM denotes the reflection of the pure pixels of a phenomenon. In this method, first, the bands suitable for the spectral separation of phenomena were selected. Then, based on the spectral reflection of the three phenomena, the Ems were determined and several phenomena including snow were specified by selecting the pure pixel of those phenomena. Finally, the output of the LSU algorithm is four images, one of which is RMS, and the rest are related to surface terrains that represent the percentage of each terrain within each pixel. In this method, the amount of snow within each pixel is between zero and one, which indicates the probability of snow within each pixel.

The NDSI is obtained by the following equation:

$$NDSI = \frac{MODIS4 - MODIS6}{MODIS4 + MODIS6} \quad (6)$$

where MODIS4 and MODIS6 are the reflection of the bands NO.4 (545-560 nm) and NO.6 (1628-1625 nm) of the MODIS sensor.

The NDSI determines three criteria for the role of the snow: 1. The threshold of NDSI; 2. The reflection rate in the band NO.2 (687-841 nm), which should be greater than 11% to be known as snow; and, 3. The reflection rate in the band NO.4 (687-841 nm), which should be greater than or equal to 10% to be known as snow.

Based on the results of this study, the use of the models measuring snow at the sub-pixel scale increases the ability to gauge snow. To compare the accuracies of the two LSU and NDSI, the MODIS satellite image, i.e. the IRS image of the same day that has a better spatial resolution (24 meters), was used.

4. Evapotranspiration

The Normalized Difference Vegetation Index (NDVI), satellite images, energy balance components, Very Small Aperture Terminal (VSAT) satellite data, SEBAL algorithm data and tangible heat flux are of the data needed for evapotranspiration study. The energy balance of a water body can be expressed as a balance of energy and loss as follows:

$$R_n + \gamma E_{EB} + G + H = 0 \qquad (7)$$

Where R_n is pure radiation at the water surface, kEEB is a hidden thermal flux, G is heat and H is a reasonable heat transferred between the air and the water surface. G can be considered equal to the heat storage, assuming that the contribution of other conditions (the transfer of heat to the substrate and the preservatives, the flow, the output, etc.) in the energy storage is negligible.

In 1939, remote sensing was used for the first time to determine the changes in water resources in Egypt by Bastiaanssen and Menenti, and then, the algorithm linking land, soil, vegetation and water at the ground level was presented by Bastiaanssen. This is an image processing algorithm that calculates the actual evapotranspiration for each pixel at the time of imaging.

The most accurate device used for estimating the plant-based evapotranspiration is called Lysimeter. However, since the construction of the lysimeter is costly and the statistics from this device are not generally available, empirical methods are often used for the estimation of evapotranspiration and the obtained results are compared with those of a standard method. Today, due to the advancement of satellite technology, it is possible to estimate actual evapotranspiration on a large scale using a remote sensing technique.

Conclusion

Among natural disasters, flood, earthquake and drought are of particular importance in terms of financial losses and casualties. Rain, snow, surface runoff, evapotranspiration are considered as those natural phenomena that can be very effective in meeting human needs if used correctly and timely. One of the most important applications of radar data is the use of them in the hydrologic models. Radars are able to estimate rainfall, runoff, evapotranspiration and snow in a basin. These factors are used to determine the Earth's surface energy balance and water balance. Due to the fact that there are spatial variations in the surface, especially in vegetation and meteorological parameters, such parameters cannot be calculated using a limited number of terrestrial and synoptic observations. Therefore, there is a need for high-performance algorithms. In the present study, it was attempted to use common methods or those methods used in the last 5 years to estimate various factors of hydrology as well as their relationship with remote sensing. Iran is a country with limited water resourced. It is located in an arid and semi-arid region. Therefore, snowfall and rainfall, especially in the summer, are the most important factors for water supply and are considered as one of the important hydro-climatic factors in the geological study of a region. In the northwest of Iran, precipitation mostly occurs as snow in cold seasons and due to the mountainous characteristics of these areas, snow resources remain throughout the year. Therefore, scientific management of the water resources which are in this form of snow or rain, or even runoff induced by them, is necessary to maintain water supply in these areas. In addition, precipitation plays a critical role in hydrology. Therefore, paying attention to various dimensions of precipitation studies and presenting comprehensive results in this regard are of great importance for decision-making, planning and policy-making on the implementation of projects and executive plans related to the comprehensive and integrated watershed management..

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