Satellite Based Rainfall Estimation for Runoff modelling

Advancements in hydrological and water resources assessments rely on usage and assimilation of hydro-meteorological time series data from space borne data sources. Some 20 years ago, most data used for modelling was from field measurements (*in-situ measurements*) only although there was wide consensus that such data was not always representative for areas larger than the local scale. With the advent of satellite remote sensing technology during the last two decades, much emphasis in water resource management has been on the use of various data types (read images) from remote sensing. Satellite images may serve various applications in hydrology such as, for instance, representation of rainfall patterns, observing soil moisture dynamics in a catchment, monitoring of vegetation, crop growth and land cover, monitoring of snow melt and glacier ice cover, estimation of water stress and demands for crop production, and observing flood extend in case of river or lake inundation. A review on all these applications is ignored since for this project only satellite products that are of relevance for rainfall-runoff modelling are described. Use and reliability of satellite products is briefly presented and discussed below.

Since rainfall-runoff modelling involves many aspects of our real world, a relatively large number of satellite products are available. Probably the most widely and important product used are Satellite Rainfall Estimates (SREs) since rainfall is the main driver to runoff production, as well as to water availability for lively hood support. Understanding its spatial and temporal distribution is of eminent importance for runoff modellers and for water resources assessments. Traditionally we observe and estimate surface rainfall by means of a network of rain gauges. Often, readings are taken ones per day and thus aspects of rainfall duration and intensity remain unknown. Whereas rain gauges represent the most direct way to measure rainfall, the spatial coverage of rain gauges in many catchments is inadequate with often low network density and gauges that are unevenly distributed. Moreover, observations by a gauge are considered point observations and thus observations are not well representative for larger areas.

Satellite rainfall products overcome part of these constrains since satellite images cover large areas, and since observations can be systematically repeated over time. As such satellite remote sensing is a viable option to observe rainfall from convective cloud systems. At earliest development of satellite rainfall estimation during the late nineties, estimates commonly rely on either infrared (IR) or passive microwave (PMW) based remote sensing. IR observations commonly are at relatively high temporal resolution (15-30 min) and have large spatial coverage (i.e., large swath width). MW observations commonly are intermittent in time (e.g. 1 per day) at small swath widths and provide relatively accurate estimates of rain rate.

The merit for use of IR channels for rainfall estimation is that cloud top temperature of convective systems can be related to surface rain rates. However, research showed that relations only are weak and that rainfall production in a cloud system is not necessarily associated with cold clouds. PMW based algorithms rely on brightness temperatures of a cloud which relate to ice scattering inside the convective cloud systems. Errors in observing rainfall by PWM are known to be large when observing warm orographic rain which may not produce much ice aloft.

Following the earliest findings on reliability and accuracy of satellite rainfall estimation, nowadays information from various sensors and satellites is merged and has resulted in more accurate SRE's. Examples are the morphed and/or merged product such as CMORPH, TRMM3B42, and MSG-MPE rainfall products. Most merged products exploit information from IR and PWM channels ánd from analysis of cloud wind vectors, to track cloud systems over space and time. Numerous algorithms have been developed over the past decade to estimate rainfall rates from satellite observations. Examples include the Tropical Rainfall Measuring Mission (TRMM) product 3b42, Climate Prediction Center (CPC) morphing technique (CMORPH; Joyce et al., 2004), Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis (TMPA; Huffman et al., 2007), Precipitation Using Artificial Neural Networks (PERSIANN; Sorooshian et al., 2000), and National Research Laboratory Global Blended-Statistical Precipitation Analysis (NRLgeo; Turk and Miller, 2005). Rainfall products from these algorithms are available at near-global coverage at 8 km × 8 km and $0.25^o \times 0.25^o$ spatial resolutions and at 30 min, 3-h, daily and monthly temporal resolutions. These resolutions provide potential benefit for applications in water resources management, climate studies and agriculture

Satellite based rainfall time series from merged products often is considered to be more representative than data from raingauges which need to be interpolated to arrive at spatial coverage effective for water resources assessments and modelling. Whereas merged rainfall products are considered to be most accurate and most promising for application, consensus has been reached that SRE's require correction. Whereas there is wide consensus in science on this aspect of satellite imagery, in certain work fields, and in many organisations there is still much debate and unawareness. The latter is partly caused by everlasting high expectations by data users on i) advancements in satellite observation techniques and availability of well-performing retrieval algorithms, and ii) the fact that estimates of satellites are available at recurrent or fixed time intervals with coverage over large spatial domains. Actually, the same observation characteristics triggered the high expectations on the use of satellite data for water resource management and modelling in the late nineties. Currently much emphasis is on combining different information streams to improve reliability and accuracy.

A first step to assess accuracy and reliability of any satellite product is to collect ground truth data at selected locations in a catchment. Ground truth observations (i.e. *in-situ* measurements) should be at selected instants in time which should be close to the satellite overpass time. By comparing the satellite observations to ground truth data that, actually, simply must be interpreted as 'counterpart data' from the real world such as rainfall depth, flood extend, moisture content or elevation height, a first impression is gained how well the satellite observes the respective real world property. Satellite observations rarely match "one to one" to *in-situ* based counter parts and thus the information supplied by the images potentially is relatively low. Each satellite product requires some specific reliability and/or accuracy assessment. For instance, accuracy of satellite based land cover analysis relies on a so called 'confusion matrix' (see the MSc report by Kebebe 2011) whereas accuracy analysis of rainfall estimates rely on e.g. scatter plots and histograms showing frequency distributions (see Haile et al., 2011). Scatter plots signify that SRE require correction in time and space domains to make the data effective for practical use. In correcting, much emphasis is on assessing effects on cumulative distribution of daily rainfall, occurrence of normal, dry and wet years, representation of rainfall anomalies and rainfall volumes that largely affect the hydrologic catchment behaviour. An example of use of uncorrected and bias corrected data in a rainfall-runoff model is shown in Habib et al., (2015) for the Gilgel Abay catchment, Lake Tana basin, Ethiopia. Findings indicate pronounced differences in the simulated hydrographs when in-situ data is used as compared to SREs. Recent studies on various satellite rainfall products indicate similar findings and signify the need to further develop advanced bias-correction techniques, to improve retrieval algorithms and to improve satellite sensors with the overall aim to improve estimation reliability and accuracy.

Other satellite products used for rainfall-runoff modelling are for representing terrain properties such as vegetation, land use and elevation. Vegetation effects evaporation that is commonly considered the main water loss term from a catchment, and subsequently from a rainfall-runoff model. In rainfall-runoff modelling, elevation of a catchment is often represented by means of a Digital Elevation Model (DEM). Such DEMs are very useful in distributed rainfall –runoff models in which the model domain is partitioned by means of a grid. Elements that make up a grid may be of equal and of similar size (i.e. rectangles) or be of different size and shape such as triangles. For modelling the use of a DEM with equally sized elements is commonly preferred since all satellite data used for a rainfall-runoff model needs to be of similar spatial resolution to allow the model algorithm to read and utilize the data. Since most satellite products are of different resolution, resampling of the satellite data is a major step in the setup of a satellite based rainfall-runoff model. It is noted that observation frequency of hydro-meteorological satellite products commonly does not match to observation frequency of ground truth data and as such some aggregation, or disaggregation in time, is needed as well. All above steps commonly need to be performed before a satellite based rainfall-runoff model can be run and operated.

In conclusion there is still much need to improve estimates of hydro-climatological variables by space technology. Although the current available satellite products largely improved assessments in water resources and hydrology, much effort is still needed to improve reliability and accuracy of the products. For such sensors need to be improved, observation algorithms needs to be improved and satellite constellations (e.g. the ESA Sentinels) need to be well designed. Lastly bias correction techniques need to be improved.

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